An Examination of the Potential for Improving Carbon/Energy Balance of Bioethanol

A REPORT TO IEA BIOENERGY TASK 39

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Executive Summary

IEA Bioenergy is an international collaborative agreement set up in 1978 by the International Energy Agency (IEA) to improve international co-operation and information exchange between national bioenergy RD&D programmes. The IEA Bioenergy Vision is "To realise the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, to provide a substantial contribution to meeting future energy demands."

The IEA Bioenergy aim is "To facilitate, co-ordinate and maintain bioenergy research, development and demonstration through international co-operation and information exchange, leading to the deployment and commercialization of environmentally sound, sustainable, efficient and cost-competitive bioenergy technologies."

As part of IEA Bioenergy Task 39's ongoing program of promoting the commercialization of biofuels, the Task commissions reports that help to address specific areas of interest to the members. Task 39 is an ideal mechanism for bridging the Atlantic and transferring knowledge between member countries.

The energy balance and greenhouse gas emissions of biofuels remain a controversial topic in the popular press, with government policy makers, and within the academic community. Most of the discussion is based on the existing (or past) performance of biofuel technologies and therefore may not be representative of future developments in the industry. The energy balance and life cycle greenhouse gas (GHG) emissions of corn ethanol plants have been extensively studied and reported on and there is a wide variety of results that have been published. This work has concentrated on that technology, and an effort to determine if one of the reasons for the variation might be that the data that others have used has been taken from different periods of time and if that has any influence on the wide range of results that are presented.

It is known that the 1st generation ethanol industry has made some significant progress in reducing costs and the energy inputs into the process but those changes and improvements have not been translated into energy balance results or life cycle green house gas emissions.

The past and current state of the art of starch ethanol plants has been documented with respect to their energy and environmental performance (particularly GHG emissions). This includes a description of the advances that have been made over the past two decades to arrive at the current level of technology. The potential for future improvements in the process and technology have been investigated. This considered the identification of the current primary energy needs of the process and the means of reducing that energy through the application of technology from other industries, through technology breakthroughs, through advances in enzymes and yeasts, etc. The impact of these improvements on the energy balance and GHG emissions for biofuel performance has been documented.

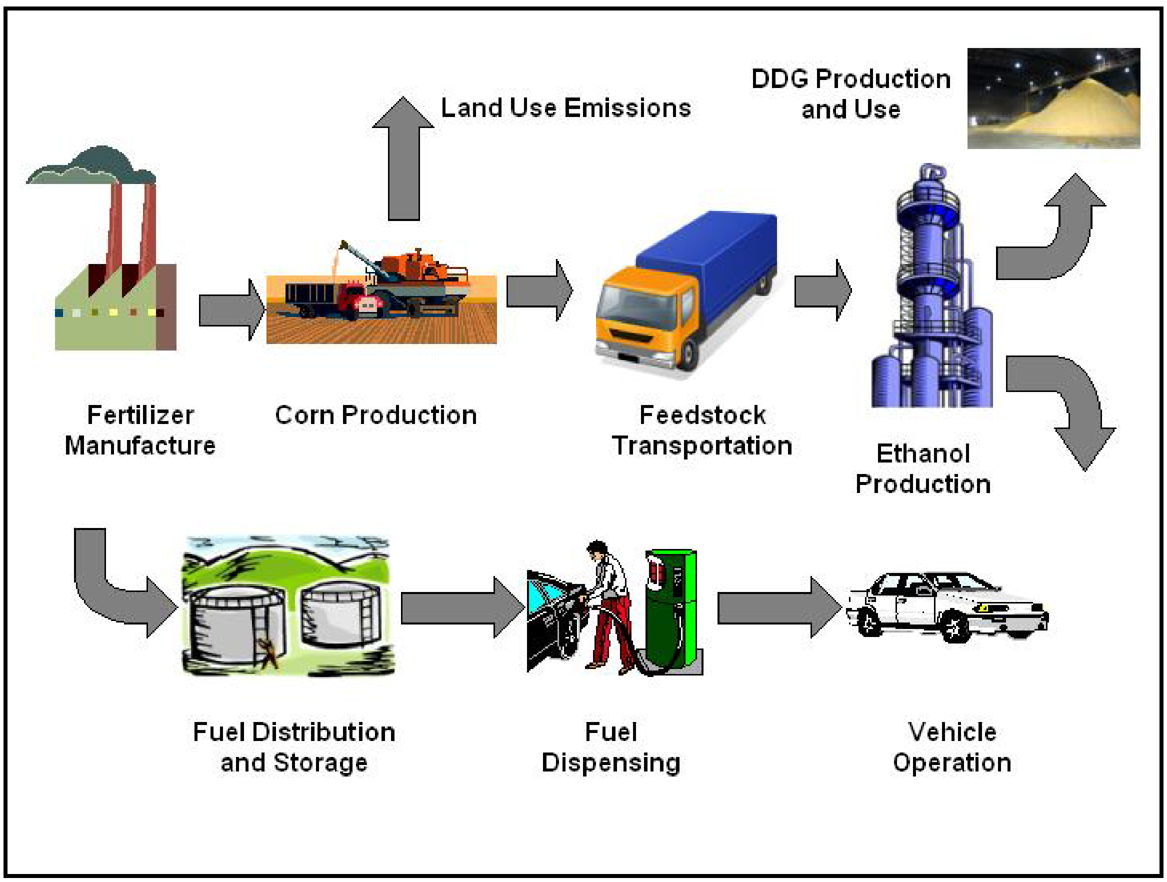
As environmental awareness increases, governments, industries and businesses have started to assess how their activities affect the environment. Society has become concerned about the issues of natural resource depletion and environmental degradation. The environmental performance of products and processes has become a key operational issue, which is why many organizations are investigating ways to minimize their effects on the environment. Many have found it advantageous to explore ways to improve their environmental performance, while improving their efficiency, reducing costs and developing a "green marketing" advantage. One useful tool is called life cycle assessment (LCA). This concept considers the entire life cycle of a product.

Life cycle assessment is a "cradle-to-grave" (or "well to wheels") approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product selection.

The ethanol system includes the emissions associated with the manufacture of fertilizer, emissions arising from the application of the fertilizer and other land use changes are additional sources included. The production of distillers' grains is a co-product. An emissions credit is calculated based on the emissions associated with the displacement of other feed sources. As with the gasoline system emissions associated with the construction of the ethanol plant are not included but the emissions associated with the manufacture of the transportation systems are included.

Neither the gasoline reference system nor the ethanol system considers energy or emissions associated with the human activity required to undertake each of the activities.

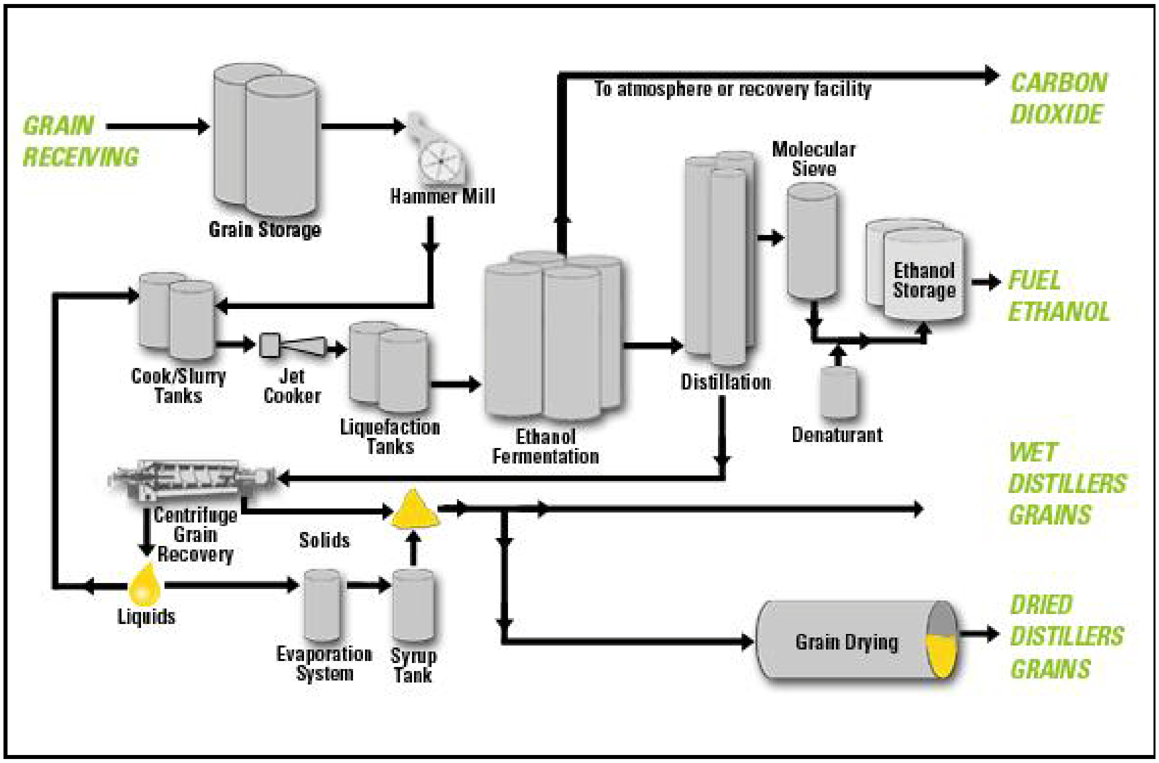
Figure ES- 1 Ethanol Lifecycle Stages



The basic ethanol production process involves the enzymatic hydrolysis of starch to sugars and the fermentation of the sugars to ethanol via yeast. The weak ethanol solution known as beer is then distilled and dried to produce anhydrous ethanol, which is suitable for blending with gasoline. There are a number of process variations that are employed such as dry or wet milling, batch or continuous fermentation, etc.

Most new ethanol plants being considered are dry mill ethanol plants. The basic process flow for one of these plants is shown in the following figure. Thermal energy is added to the system in the cooking, distillation, evaporation, and drying stages. Thermal energy is removed from the system prior to fermentation, during fermentation, after distillation, after co-product drying. Processes that optimize this addition and removal of energy can lower the need for the net energy into the system.

Figure ES- 2 Ethanol Process Flow Schematic



The results of the modelling for energy balances and GHG emissions are presented below. The gasoline energy balance is projected to continue to decline as more synthetic crude oil is incorporated into the refining slate. The ethanol energy balance continues to improve as efficiency gains are made both with feedstock production and ethanol manufacturing. Note that the value of the co-product credit also declines as efficiencies are realized with corn and soybean production. This illustrates the dynamic nature of the GHGenius model.

Table ES- 1 Total Energy Balance Comparison – Gasoline and Ethanol

Fuel	Gasoline		Ethanol		
Feedstock	Crude Oil		Corn		
	1995	2015	1995	2005	2015
	Joules consumed/joule delivered				
Fuel dispensing	0.0024	0.0023	0.0037	0.0038	0.0036
Fuel distribution, storage	0.0065	0.0067	0.0147	0.0150	0.0154
Fuel production	0.1510	0.1716	0.6402	0.5208	0.3650
Feedstock transmission	0.0128	0.0119	0.0127	0.0130	0.0135
Feedstock recovery	0.0916	0.1299	0.1061	0.0950	0.0681
Ag. Chemical manufacture	0.0000	0.0000	0.1295	0.1144	0.1035
Co-product credits	-0.0008	-0.0016	-0.0616	-0.0572	-0.0500
Total	**0.2634**	**0.3208**	**0.8452**	**0.7048**	**0.5192**
Net Energy Ratio (J delivered/J consumed)	**3.7961**	**3.1174**	**1.1831**	**1.4189**	**1.9262**

The GHG emissions for gasoline and ethanol are shown in the following table. The emissions are presented on energy unit basis. For gasoline, the increase in energy use is mostly offset by the efforts to reduce fugitive emissions from operating wells. This has been the focus of significant efforts in Canada and other crude oil producing countries in recent years. The GHG emissions savings from ethanol production and use have more than doubled between 1995 and the projected level in 2015. This indicates the danger of making policy decision based on historical data without taking into account learning experiences and the potential gains that can be expected as industries develop. The GHG emissions reductions in 2015 from corn ethanol would qualify as advanced biofuels under proposed US regulations.

Table ES- 2 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline		Ethanol		
Feedstock	Crude Oil		Corn		
Year	1995	2015	1995	2005	2015
	g CO_2 eq/GJ (HHV)				
Fuel dispensing	118	90	185	181	142
Fuel distribution and storage	656	507	1,107	1,109	1,124
Fuel production	11,181	12,162	35,012	28,294	19,085
Feedstock transmission	1,084	903	1,004	1,009	1,031
Feedstock recovery	7,257	8,724	12,012	10,550	7,348
Land-use changes, cultivation	8	15	21,827	20,987	20,369
Fertilizer manufacture	0	0	8,261	7,033	6,215
Gas leaks and flares	3,486	1,688	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0
Emissions displaced	-65	-137	-18,490	-17,934	-17,219
Sub-Total	23,725	23,951	60,919	51,229	38,095
Combustion emissions	62,917	64,813	3,058	2,237	1,973
Grand Total	86,642	88,764	63,977	53,466	40,068
% Reduction			26.2	39.0	54.9

When the ethanol is blended with gasoline and the emissions reported on a distance-travelled basis then the lifecycle emissions benefits improve as shown in the following table.

Table ES- 3 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline		E10		
Feedstock	Crude Oil		Corn		
Year	1995	2015	1995	2005	2015
	g CO_2 eq/km				
Vehicle operation	210.1	210.2	206.2	209.4	208.0
C in end-use fuel from CO_2 in air	0.0	0.0	-13.5	-14.0	-14.0
Net Vehicle Operation	210.1	210.2	192.6	195.4	194.0
Fuel dispensing	0.4	0.3	0.4	0.4	0.3
Fuel storage and distribution	2.2	1.7	2.2	1.9	1.8
Fuel production	37.3	40.2	46.4	44.8	41.4
Feedstock transport	3.6	3.0	3.6	3.3	3.0
Feedstock and fertilizer production	24.3	28.9	27.0	27.8	29.7
Land use changes and cultivation	0.0	0.0	5.1	4.9	4.7
CH_4 and CO_2 leaks and flares	11.6	5.6	10.7	6.8	5.1
Emissions displaced by co-products	-0.2	-0.5	-4.5	-4.4	-4.4
Sub total (fuelcycle)	289.3	289.4	283.5	280.8	275.7
% Changes (fuelcycle)			-2.0	-3.7	-4.7
GHG Reductions g CO_2 eq/litre of ethanol			840	1,100	1,413

This work has shown that the GHG emissions related to producing ethanol from corn are not static and have shown continual improvement over time. This is one possible explanation for some of the differences reported in the literature for different LCA results for corn ethanol. The results found in this work are much more significant than just helping to explain why the results of past studies have varied. They show that the benefits of relatively immature technologies can change quite rapidly as the technologies develop and mature.

This reduction in emissions is due to the learning experience that is common to the development of many innovations. This learning experience can be expected to continue into the future as even more experience is gained with the technology. While the learning rate will be constant when measured on a logarithmic scale, it usually declines when measured against time. Nevertheless, the rapid expansion of the ethanol industry in the past few years will see the cumulative production in North America increase by a factor of four between 2005 and 2015.

This work shows that policy development based solely on historical data, without considering future developments, is a flawed approach and could lead to the rejection of some options that could eventually be very attractive options for GHG emission reductions. As governments around the world try to establish the GHG emissions benefits of various biofuels the use of methodologies such as default emission factors could lead to a significant underestimation of the benefits unless the factors are updated on a frequent basis. Furthermore, the default emission factors will only be relevant if the data used to calculate them can be verified as being from the same time period and that time period needs to be stated.

The biofuels industry will need to do a better job of benchmarking its performance than it traditionally has done if the GHG emissions benefits that it provides are to be credible. The industry will also need better visibility over the entire supply chain which will mean that biofuel producers will need much better visibility on feedstock supply than exists in many regions of the world.

While this analysis has focused on corn ethanol, it is likely that the same directional trend would be found for other feedstocks such as sugar cane, wheat, and sugar beet. All crops are likely benefiting from the improvements found in the agriculture sector, and some of the improvements in the ethanol production process (such as improved enzymes) are generic in nature and applicable to all feedstocks.

A similar analysis should be considered for biodiesel produced from rapeseed and soybeans to determine how those emissions may have changed over time and how they might be expected to change in the future.

Opportunities exist to direct technology development with appropriate policy instruments. The improvements seen to date in the biofuels industry have developed because they also reduce production costs as they reduce emissions. Governments should consider policy instruments that would accelerate the adoption of new technology in the biofuel sector so that greater GHG emissions benefits are achieved sooner than would otherwise be the case. In some cases, it may be possible to achieve GHG emission benefits for 1st generation biofuels that are similar to those that are expected from the 2nd generation processes at a lower cost and in a shorter time frame.

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1. INTRODUCTION

IEA Bioenergy is an international collaborative agreement set up in 1978 by the International Energy Agency (IEA) to improve international co-operation and information exchange between national bioenergy RD&D programmes. The IEA Bioenergy Vision is “To realise the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, to provide a substantial contribution to meeting future energy demands.”

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Twenty countries plus the European Commission, take part in IEA Bioenergy: Australia, Austria, Belgium, Brazil, Canada, Croatia, Denmark, Finland, France, Ireland, Italy, Japan, The Netherlands, New Zealand, Norway, South Africa, Sweden, Switzerland, the United Kingdom, the USA and the European Commission. Work in IEA Bioenergy is carried out through a series of Tasks, each having a defined work programme. Each participating country pays a modest financial contribution towards administrative requirements, shares the costs of managing the Tasks and provides in-kind contributions to fund participation of national personnel in the Tasks.

1.1 TASK 39 LIQUID BIOFUELS

One of the Tasks is Task 39, Liquid Fuels from Biomass. The objectives of this Task are to:

- Provide information and analyses on policy, regulatory and infrastructure issues that will help participants encourage the establishment of the infrastructure for biofuels as a replacement for fossil-based biofuels.
- Catalyze cooperative research and development projects that will help participants develop improved, cost-effective processes for converting lignocellulosic biomass to ethanol.
- Provide information and analyses on specialized topics relating to the production and implementation of biodiesel technologies.
- Provide for information dissemination, outreach to stakeholders, and coordination with other related groups.

As part of Task 39’s ongoing program of promoting the commercialization of biofuels, the Task commissions reports that help to address specific areas of interest to the members. Task 39 is an ideal mechanism for bridging the Atlantic and transferring knowledge between member countries.

1.2 SCOPE OF WORK

The energy balance and greenhouse gas emissions of biofuels remain a controversial topic in the popular press, with government policy makers, and within the academic community. Most of the discussion is based on the existing (or past) performance of biofuel technologies and therefore may not be representative of future developments in the industry. The energy balance and life cycle greenhouse gas (GHG) emissions of corn ethanol plants have been extensively studied and reported on and there is a wide variety of results that have been published. This work has concentrated on that technology, and an effort to determine if one of the reasons for the variation might be that the data that others have used has been taken from different periods of time and if that has any influence on the wide range of results that are presented.

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The past and current state of the art of starch ethanol plants has been documented with respect to their energy and environmental performance (particularly GHG emissions). This includes a description of the advances that have been made over the past two decades to arrive at the current level of technology. The potential for future improvements in the process and technology have been investigated. This considered the identification of the current primary energy needs of the process and the means of reducing that energy through the application of technology from other industries, through technology breakthroughs, through advances in enzymes and yeasts, etc. The impact of these improvements on the energy balance and GHG emissions for biofuel performance has been documented.

The outcomes of the report provide not only a potential technology development road map for the industry but also a valuable resource for policy makers as they continue to develop national biofuels policies that encourage innovation and improved environmental performance.

2. LIFE CYCLE ASSESSMENT

As environmental awareness increases, governments, industries and businesses have started to assess how their activities affect the environment. Society has become concerned about the issues of natural resource depletion and environmental degradation. The environmental performance of products and processes has become a key operational issue, which is why many organizations are investigating ways to minimize their effects on the environment. Many have found it advantageous to explore ways to improve their environmental performance, while improving their efficiency, reducing costs and developing a “green marketing” advantage. One useful tool is called life cycle assessment (LCA). This concept considers the entire life cycle of a product.

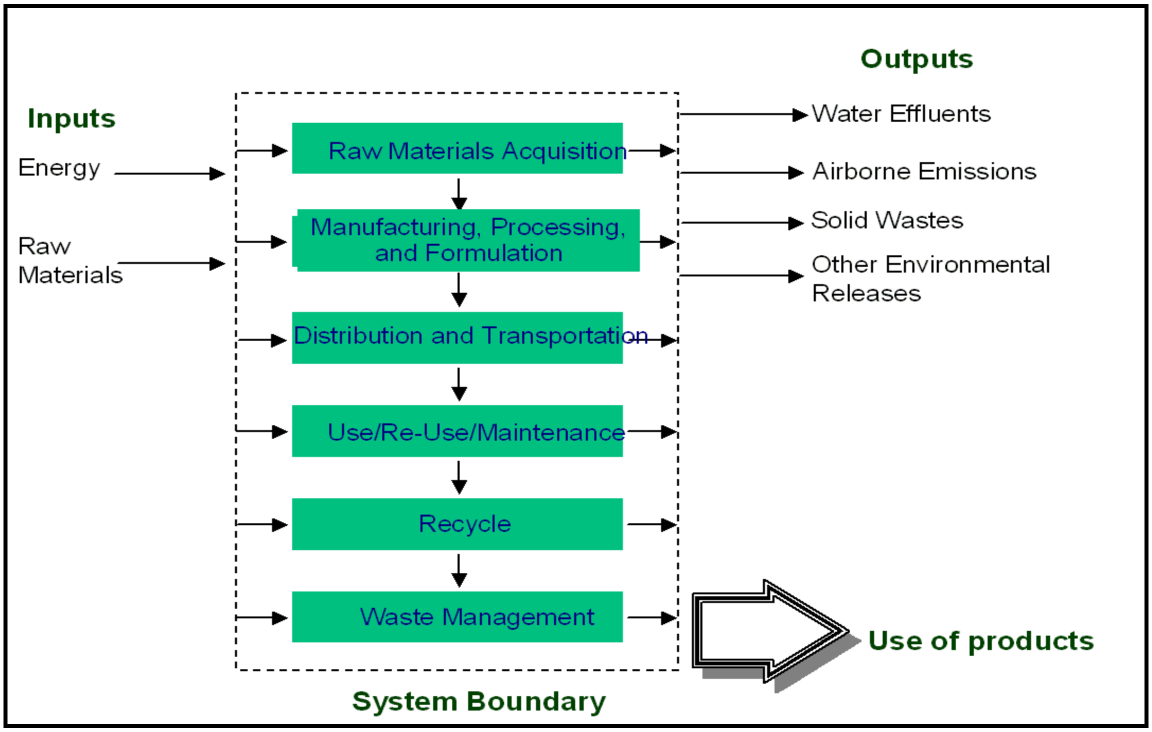
Life cycle assessment is a "cradle-to-grave" (or “well to wheels”) approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product selection.

Specifically, LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- **Compiling** an inventory of relevant energy and material inputs and environmental releases;
- **Evaluating** the potential environmental impacts associated with identified inputs and releases;
- **Interpreting** the results to help make more informed decisions.

The term "life cycle" refers to the major activities in the course of the product's life span from its manufacture, use, maintenance, and final disposal; including the raw material acquisition required to manufacture the product. The following figure illustrates the typical life cycle stages that can be considered in an LCA and the quantified inputs and outputs.

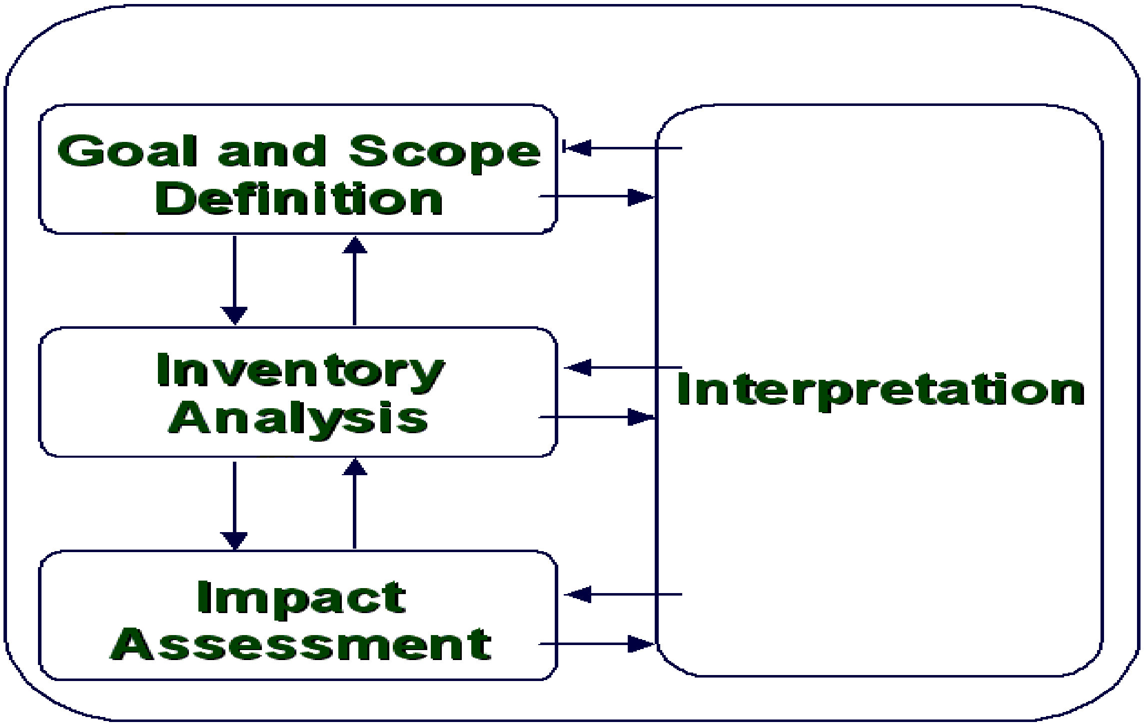
Figure 2-1 Life Cycle Stages



The LCA process is a systematic, iterative, phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in the following figure:

1. *Goal Definition and Scoping* - Define and describe the product, process or activity. Establish the context in which the assessment is to be made, and identify the boundaries and environmental effects to be reviewed for the assessment.
2. *Inventory Analysis* - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, wastewater discharge).
3. *Impact Assessment* - Assess the human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
4. *Interpretation* - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

Figure 2-2 Phases of a LCA



2.1 ISO LIFE-CYCLE ASSESSMENT STANDARDS

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

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

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

- Phase 1 - Goal and Scope Definition;
- Phase 2 - Inventory Analysis;

- Phase 3 - Impact Assessment; and
- Phase 4 - Interpretation

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

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

2.2 OVERVIEW OF CURRENT USES OF LIFE CYCLE ASSESSMENT

To date LCA has been applied in evaluating the relative environmental performance of alternative biofuel options with the primary aim of informing industry, government, Environmental Non-governmental Organization (ENGO) and consumer decision-making. Studies have been completed by LCA practitioners in consulting firms, academia, ENGOs, industry, and government. The quality of the studies has varied but over the last decade, on average, study quality has improved due to method development, data availability and higher client expectations.

A few examples of uses of biofuels' LCAs by various decision makers include the following.

- Industry: Through an examination of the results of a LCA of their biofuel production process, a producer may determine where in the process or supply chain an improvement could be made to lower their resource use or environmental discharges. The saying, "what is measured can be managed" is key. Quantifying the resource use/environmental discharges associated with the full life cycle of a biofuel allows industry to move forward toward managing these impacts.
- Government: As will be discussed in more detail below, LCAs of biofuels have been utilized for determining preferred biofuel pathways (feedstock/fuel production) for receiving government funding under biofuels' expansion programs.
- ENGOs: These organizations have utilized LCAs of biofuels to support their positions in calling for increased attention to broad sustainability issues in expansion of biofuel production.
- Consumers: Results of biofuels' LCAs have been presented by various organizations and utilized indirectly in advertising campaigns with the hope of influencing consumer choice with respect to fuel and vehicle options (e.g., purchase of a flexible fuel vehicle so as to have the potential to utilize a high level ethanol/gasoline (E85) blend).

2.2.1 Role of LCA in Public Policies/Regulations

Life cycle assessment's role in public policy development to date has been focused on informing public policy positions of industry (e.g., General Motors' decision to support ethanol) and government. In a limited set of cases, LCA has had a more direct role. For example, under the US Renewable Fuel Standard resulting from the Energy Policy Act of 2005, some renewable fuels (e.g., those from selected lignocellulosic feedstocks) that were expected to have lower life cycle environmental impacts through a weighting system that "rewarded" such pathways. This and other similar programs, however, have not required detailed LCA. Generally, although LCA has informed public policy positions it has not been the **basis** of public policies, in particular, those that have binding targets directly related to the application of the LCA method.

This appears to be changing. Over the past few years there have been several announcements related to incorporating life cycle-based standards directly into climate change regulations for transportation fuels. These regulatory initiatives include those covering all transportation fuels in a particular jurisdiction, as well as the more numerous initiatives, which are focused on biofuels. One of the most prominent initiatives is California's Low Carbon Fuel Standard (LCFS), which will consider all light-duty transportation fuels sold into State (State of CA 2007). The United Kingdom's Renewable Transportation Fuel Obligation Programme (RTFO), the German Biofuels Ordinance, the European Union Fuels Directive, and the U.S. Energy Independence and Security Act of 2007 all focus on biofuels. In Canada and the U.S., other federal, state and provincial governments have declared interest in adopting similar low carbon fuel standards (e.g., British Columbia, Ontario, Minnesota, Massachusetts). The programs are currently under development but they will require that the life cycle GHG emissions associated with the production of relevant biofuels (and in some cases, other fuels) be quantified. They will be the first regulations that will be based on systematic LCA.

The California LCFS and the UK RTFO, two of the more prominent initiatives, are described briefly. On January 18, 2007, the State of California, through Executive Order S-1-07, announced the intent to regulate a reduction of least 10% by 2020 in the life cycle carbon intensity of transportation fuels sold in the State (State of CA 2007). Enforcement of the standard will begin in 2010 while it will be fully in effect in 2020. It will complement other policies related to vehicle and transportation system improvements. Under the LCFS fuel providers (e.g., refineries, blenders, and importers) will be required to ensure that the mix of fuels they sell into the California market meets, on average, a declining carbon intensity which is expected to be based on estimates of carbon dioxide equivalent per energy unit of fuel on a life cycle basis, adjusted for vehicle efficiency (Farrell and Sperling 2007). As noted above, the California regulation applies to all fuels sold into the market, not just biofuels. This is in contrast to the UK RTFO, which is focused exclusively on biofuels (UK DOT 2006). The RTFO will, from April 2008, place an obligation on fuel suppliers to ensure that a certain percentage of their aggregate sales are made up of biofuels. The effect of this will be to require 5% of all UK fuel to come from a renewable source by 2010. The RTFO, like the LCFS, has reporting requirements and methodologies for calculating life cycle GHG emissions but as well includes social and environmental sustainability aspects, although these latter criteria will not be used in the issuing of compliance certificates until the feasibility, accuracy, and efficiency of the reporting structure are determined (UK DOT 2006).

A life cycle basis is important for informing environmental regulation because there can be very different and significant impacts in various parts of the supply chain associated with biofuel production. However, whether these regulations can achieve their intended objectives will depend upon development and application of a robust LCA framework for biofuels and successful implementation of the policy.

2.2.2 LCA Challenges for Biofuels

Numerous LCAs for bioethanol and other biofuels have been published (reviews include Fleming et al. 2006, Larson 2006, and Cheminfo 2008). Most studies have followed ISO standards (ISO 2006) but a wide range of results has often been reported for the same fuel pathway, sometimes even when holding temporal and spatial considerations constant. The ranges in results may, in some cases, be attributed to actual differences in the systems being modelled but are also due to differences in method interpretation, assumptions and data issues.

Key issues in biofuels' LCAs have been differing boundaries being adopted in studies (i.e., what activities are included/excluded from the study), differences in data being collected and utilized, and disparities in the treatment of co-products. In addition, LCAs, more generally (not solely limited to those of biofuels) have often included limited or no analysis of uncertainty and validation of model results. Boundaries in prior LCAs have often differed due to resource constraints. Data requirements in LCA are significant. Studies have not always used up to date data or data that reflect the inputs in the relevant process under study (i.e., utilization of electricity generation data for another jurisdiction rather than the one under study). There are also gaps in scientific knowledge surrounding key variables. For example, these include implications of land use change, N_2O emissions related to feedstock production, and nutrient depletion and erosion due to agricultural residue removal. Utilization of different co-product methods, and in some studies, ignoring co-products entirely, has had major impact on results of LCA studies (Kim and Dale 2002, Larson 2006, Farrell et al. 2006).

Life cycle assessment is a useful tool for comparing on a functional unit basis, the relative environmental performance (based on a specific set of metrics) of different feedstock/fuel pathways. However, LCA should be utilized along with other information in the decision making process regarding biofuel policy development. Decision-makers should be aware of both the strengths and limitations of LCA.

2.3 GHGENIUS

LCA work involves the collection and utilization of large amounts of data and thus is ideally suited to the use of computer models to assist with the inventorying and analysis of the data. In North America, two models are widely used for the analysis of transportation fuels:

- GREET. A model developed by Argonne National Laboratory in the United States, and
- GHGenius. A model developed by Natural Resources Canada, which has data for both Canada and the United States. This model also has much greater flexibility for modelling different types of crude oil production and many more types of alternative fuels.

Many other LCA models have been developed by governments, universities and the private sector. While all of these models have some small differences in the scope and system boundaries, and may have different emission factors for different regions of the world they would all provide similar results to those developed here, especially when looking at the relative changes over time.

The GHGenius model is used for this work. The model has been developed for Natural Resources Canada over the past eight years by S&T Squared Consultants Inc. It is based on the 1998 version of Dr. Mark Delucchi's Life Cycle Emissions Model (LEM). GHGenius is capable of analyzing the emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels.

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

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

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

GHGenius can predict emissions for past, present and future years through to 2050 using historical data or correlations for changes in energy and process parameters with time that are stored in the model. The fuel cycle segments considered in the model are as follows:

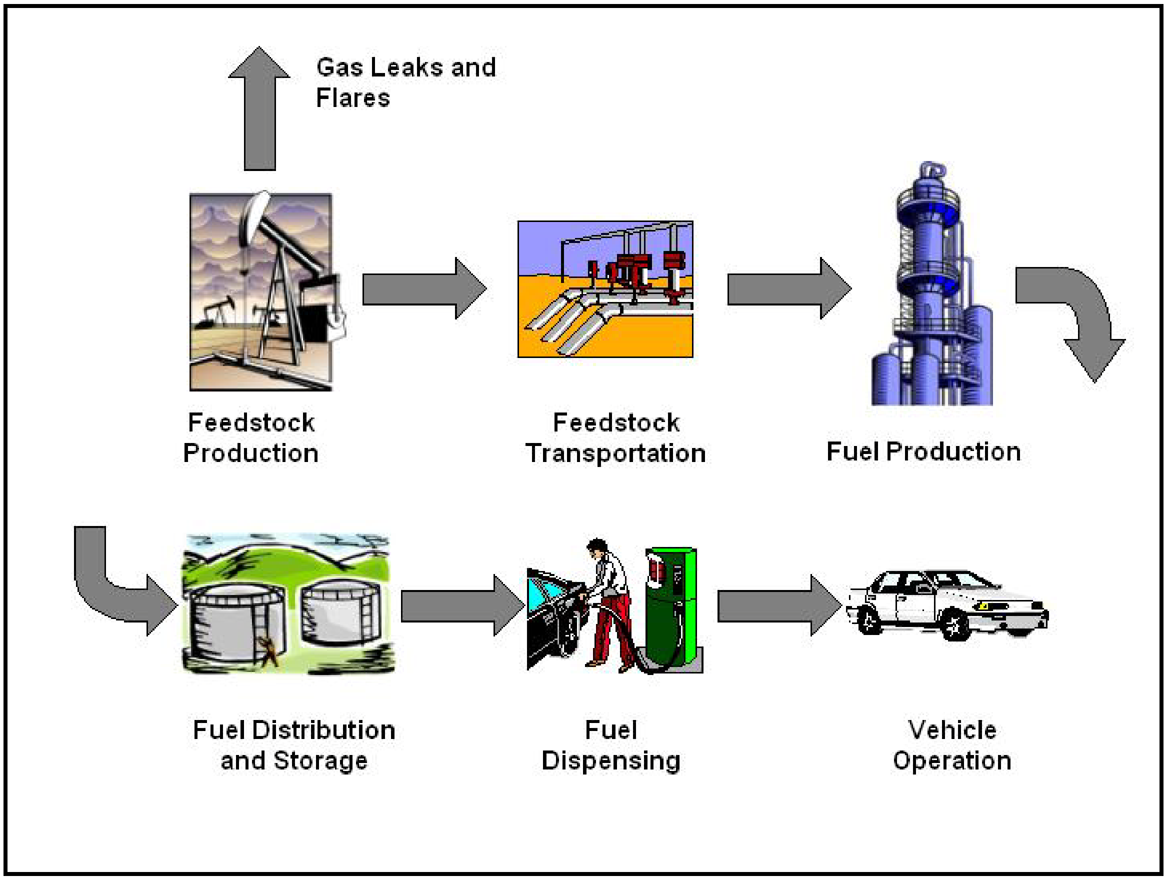
- Vehicle Operation
  Emissions associated with the use of the fuel in the vehicle. Includes all greenhouse gases.
- Fuel Dispensing at the Retail Level
  Emissions associated with the transfer of the fuel at a service station from storage into the vehicles. Includes electricity for pumping, fugitive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

to the fuel refining plant. Import/export, transport distances and the modes of transport are considered.

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

The stages of the “wells to wheels” lifecycle of traditional fossil fuels captured by GHGenius are shown in the following figure.

Figure 2-3 GHGenius Life Cycle Stages



2.4 STRENGTHS AND WEAKNESSES OF LIFE CYCLE ANALYSES

Life cycle assessment is a useful tool for comparing on a functional unit basis, the ***relative*** environmental performance (based on a specific set of metrics) of different feedstock/fuel pathways. However, LCA should be utilized along with other information in the decision making regarding transportation fuels policy. Decision-makers should be aware of both the strengths and limitations of LCA. In order to more completely understand the implications on the environment (and economy) of fuel production (e.g., scale of production issues, impacts on ecosystem and human health) LCA results should be augmented with those of other modeling systems, economic and market analyses or perhaps, integrated modeling systems could be developed in the future as well as decision makers' good judgment.

Due to the complexity of the systems being modelled, no LCA model can yet perfectly model transportation fuels. GHGenius does have a number of features that make it ideal for undertaking this kind of work, such as a full accounting of land use changes, sensitivity solvers, and the ability to project emissions changes over time.

This work also has limitations. The focus of this work has been to look at the changes in performance of a single system over time. It is not to produce the definitive LCA for corn ethanol and thus aspects of the system are simplified or held constant over time in order to better focus on the issue being considered. For example, the use of natural gas has been chosen as the fuel for the ethanol plant since it currently supplies the energy for over 80% of the North America ethanol plants. Some plants use coal and others use biomass. The GHG emissions for these other plants can be very different from the plants shown in this analysis. Another controversial issue with grain ethanol plants is the subject of indirect land use emissions. There is no accepted methodology, nor verified results for these emissions at this time. Since the interest here is more on the changes in the ***relative*** emissions performance over time any potential indirect effects have not be quantified.

Notwithstanding these limitations, the results of the work are very informative and raise issues for policy makers that have not been thoroughly investigated before.

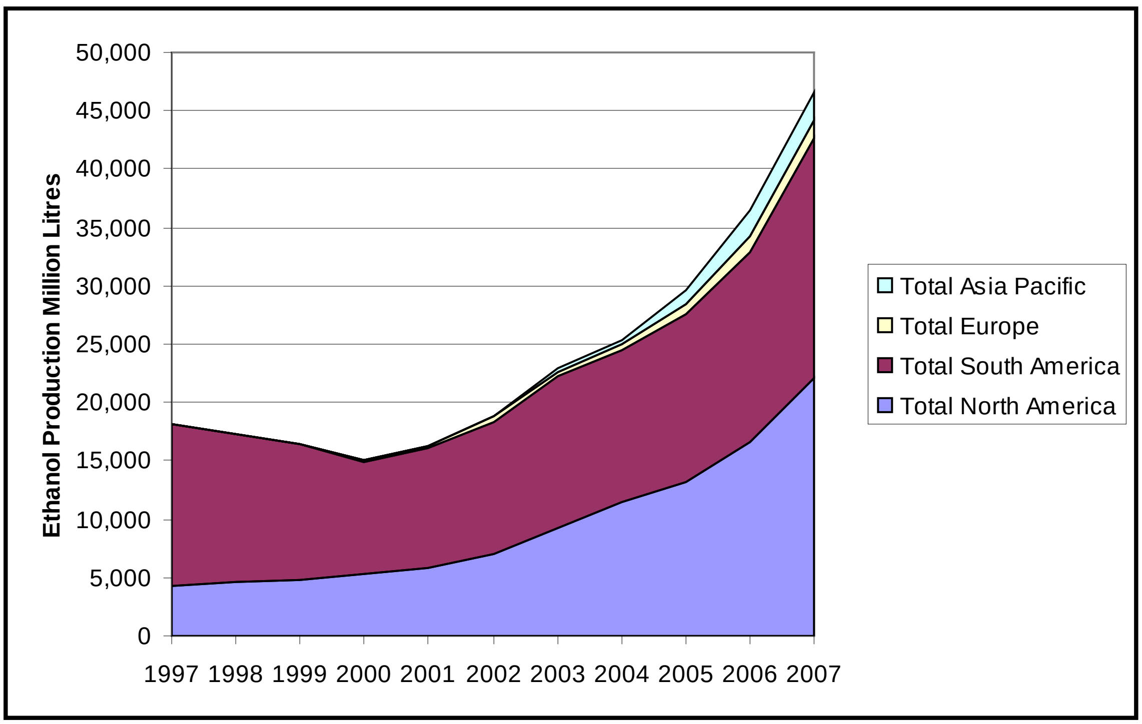
3. Starch Ethanol Facilities

Fuel ethanol is a high octane, oxygenated fuel component manufactured primarily through the fermentation of sugar. The sugar is usually derived from sugar producing crops, the hydrolysis of starch from grains, or through the hydrolysis of lignocellulosic materials such as straw, grass and wood. The later approach is not yet widely practiced but is the focus of much development effort.

Ethanol has been used as a motor fuel since the early 1900's. In 1908, Henry Ford designed his Model T to run on ethanol. Ethanol gasoline blends were used in parts of the United States prior to the Second World War but through the 1950's and 1960's there was no ethanol used in gasoline in North America. In 1975, the Brazilian Government launched their Proalcool program, and in 1979, the US Congress established the US federal ethanol program to stimulate the rural economy and reduce the dependence on imported oil. These two efforts have led to the development of very significant fuel ethanol industries in Brazilian (using sugar cane) and in the United States (using primarily corn). Fuel ethanol production has since expanded to a number of developed and developing economies around the world.

There are now over 45 billion litres of fuel ethanol used in gasoline in the world each year (BP, 2008). Production is dominated by the US and Brazil as shown in the following figure.

Figure 3-1 World Ethanol Production



In North America and Europe, fuel ethanol is currently produced mostly from starch containing crops such as corn, wheat and milo. Several plants use a waste sugar stream from another industrial plant such as a sulphite pulp mill, a brewery, cheese factories, potato processors and other food processing plants. The dominant feedstock is corn.

3.1 LIFE CYCLE BOUNDARIES

System boundaries are an important aspect of life cycle assessment. They should be as complete as possible and consistent between the reference system and the system under study. Ideally, an LCA includes all four stages of a product or process life cycle: raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management.

- Raw Materials Acquisition

  The life cycle of a product begins with the removal of raw materials and energy sources from the earth. For instance, the harvesting of trees or the mining of non-renewable materials would be considered raw materials acquisition. Transportation of these materials from the point of acquisition to the point of processing is also included in this stage.

- Manufacturing

  During the manufacturing stage, raw materials are transformed into a product or package. The product or package is then delivered to the consumer. The manufacturing stage consists of three steps: materials manufacture, product fabrication, and filling/packaging/distribution.

  - Materials Manufacture

    The materials manufacture step involves the activities that convert raw materials into a form that can be used to fabricate a finished product.

  - Product Fabrication

    The product fabrication step takes the manufactured material and processes it into a product that is ready to be filled or packaged.

  - Filling/Packaging/Distribution

    This step finalizes the products and prepares them for shipment. It includes all of the manufacturing and transportation activities that are necessary to fill, package, and distribute a finished product. Products are transported either to retail outlets or directly to the consumer. This stage accounts for the environmental effects caused by the mode of transportation, such as trucking and shipping.

- Use/Reuse/Maintenance

  This stage involves the consumer's actual use, reuse, and maintenance of the product. Once the product is distributed to the consumer, all activities associated with the useful life of the product are included in this stage. This includes energy demands and environmental wastes from both product storage and consumption. The product or material may need to be reconditioned, repaired or serviced so that it will maintain its performance. When the consumer no longer needs the product, the product will be recycled or disposed.

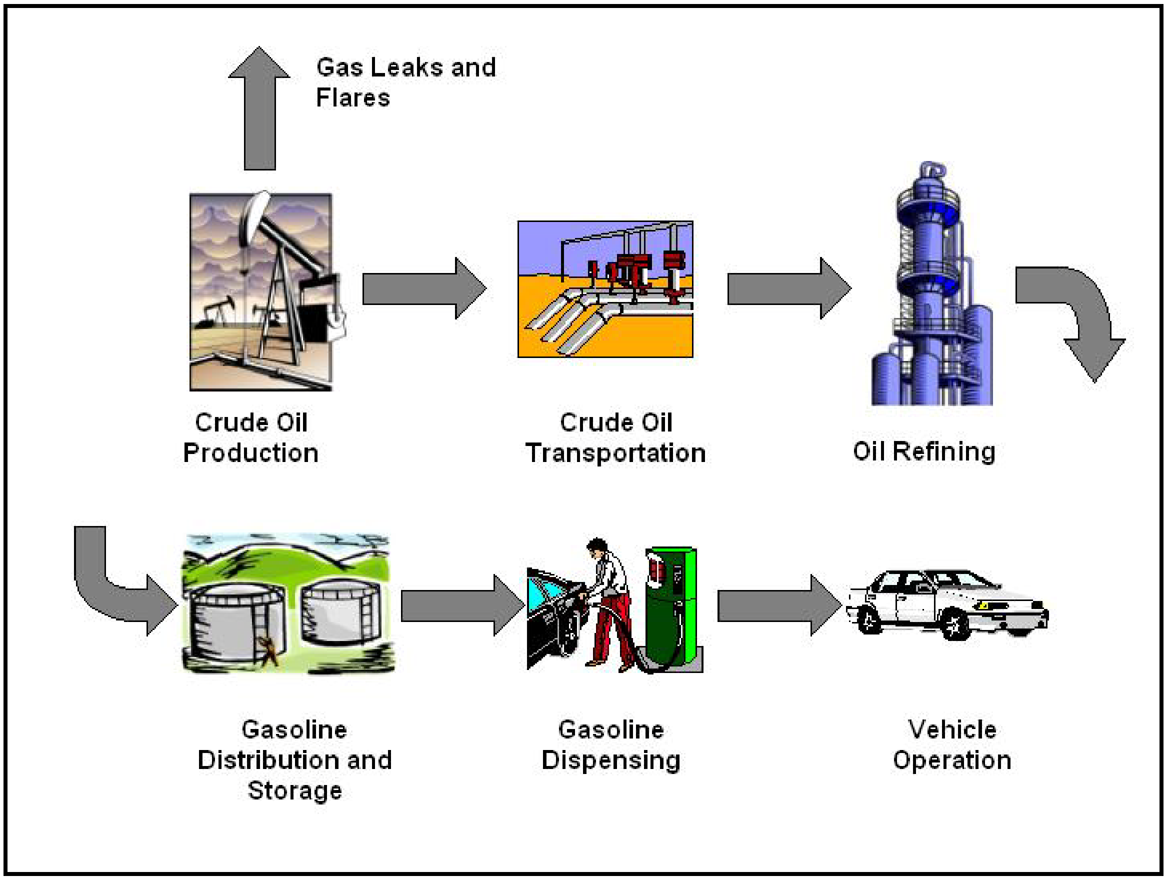
  - Recycle/Waste Management

    The recycle/waste management stage includes the energy requirements and environmental wastes associated with recycling and disposition of the product or material.

3.1.1 Reference System

The reference system for fuel ethanol is the production and use of gasoline refined from crude oil. In GHGenius, this includes all steps of the process as shown earlier and in the following figure.

Figure 3-2 Gasoline Life Cycle Stages



The emissions associated with the construction of the refinery are not included in the system boundary but the emissions associated with the manufacture of transportation systems such as pipelines, trucks, trains, and vessels are included in the analyses.

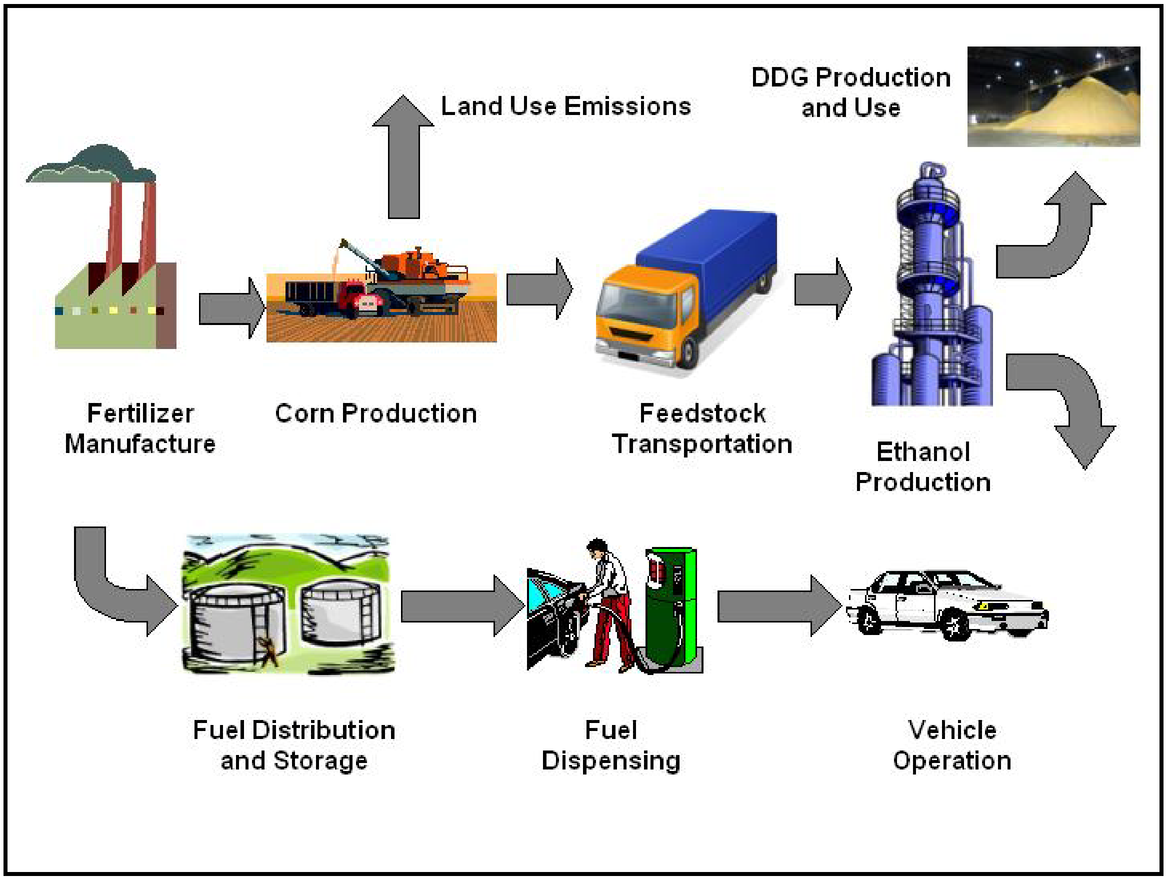
GHGenius has data for three regions of Canada, three regions of the United States, Mexico and India. For each region, there can be differences in the source of crude oil, the refining efficiency, the electric power mix and differences in agriculture practices and emission factors. For this work, the model has been set to Central Canada. The quality of the Canadian data in the model is slightly better than that for the US in most areas. Central Canada is the corn producing region in Canada and the crude oil slate is a mixture of Canadian oil (including some oil sands derived synthetic oil) and imported oil.

3.1.2 Ethanol System

The ethanol system is conceptually similar to gasoline but it is more complex. The emissions associated with the manufacture of fertilizer, emissions arising from the application of the fertilizer and other land use changes are additional emission sources included. The production of distillers' grains is a co-product from the system. An emissions credit for distillers' grain is calculated based on the emissions associated with the displacement of other feed sources. As with the gasoline system emissions associated with the construction of the ethanol plant are not included but the emissions associated with the manufacture of the transportation systems are included.

Neither the gasoline reference system nor the ethanol system considers energy or emissions associated with the human activity required to undertake each of the activities.

Figure 3-3 Ethanol Lifecycle Stages



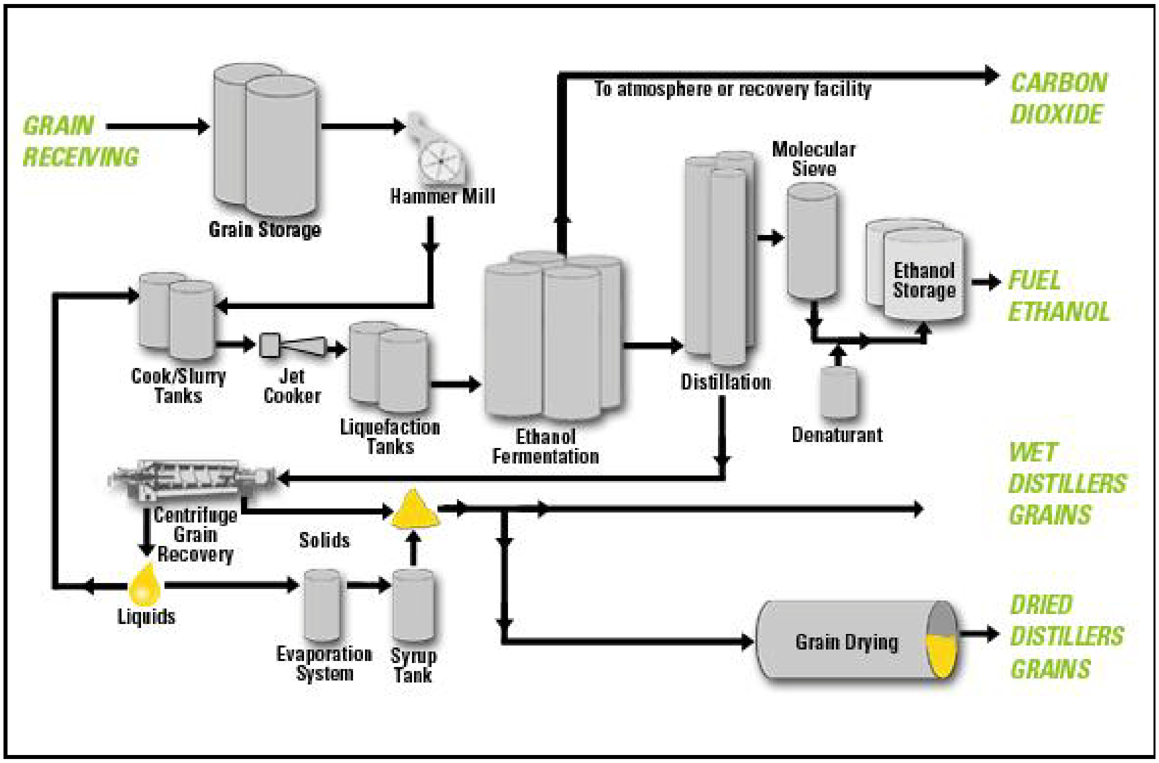
As with the gasoline reference system the emissions associated with the construction of the ethanol plant are not included in the analysis. As noted previously any indirect land use emissions associated with increased feedstock production have been excluded from this analysis.

3.2 ETHANOL PRODUCTION PROCESS

The basic process involves the enzymatic hydrolysis of starch to sugars and the fermentation of the sugars to ethanol via yeast. The weak ethanol solution known as beer is then distilled and dried to produce anhydrous ethanol, which is suitable for blending with gasoline. There are a number of process variations that are employed such as dry or wet milling, batch or continuous fermentation, etc.

Most new ethanol plants being considered are dry mill ethanol plants. The basic process flow for one of these plants is shown in the following figure. Thermal energy is added to the system in the cooking, distillation, evaporation, and drying stages. Thermal energy is removed from the system prior to fermentation, during fermentation, after distillation, after co-product drying. Processes that optimize this addition and removal of energy can lower the need for the net energy into the system.

Figure 3-4 Ethanol Process Flow Schematic



3.3 Current Industry Performance

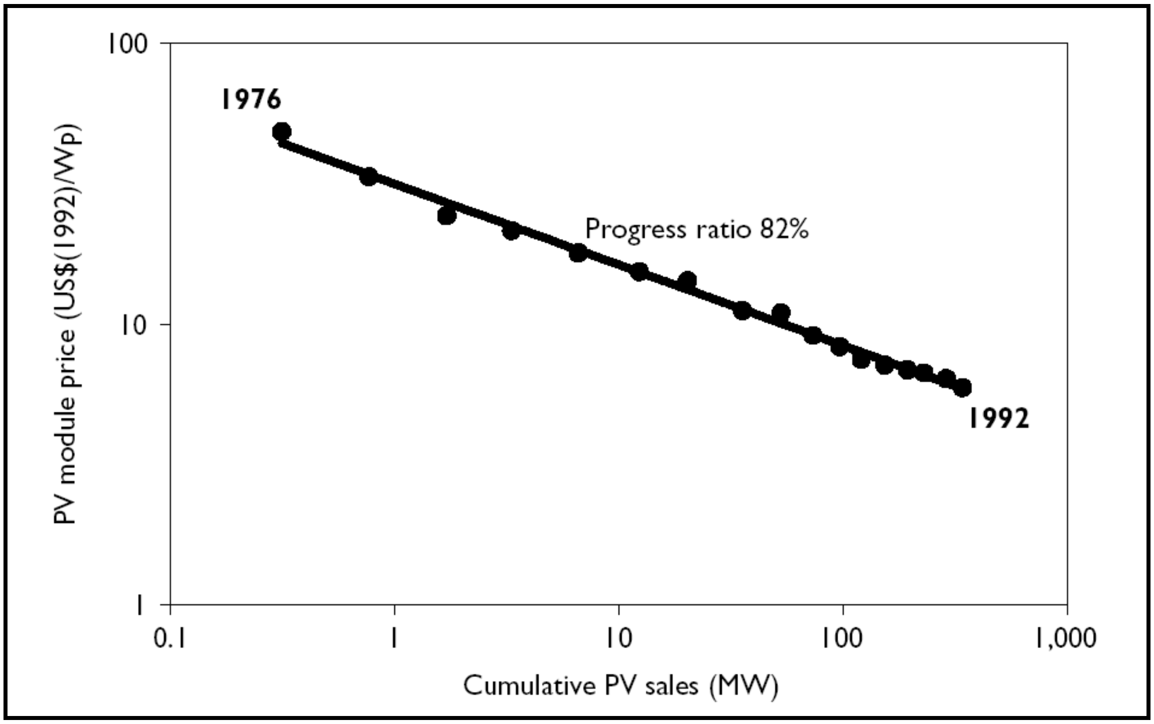
One of the challenges of collecting data for any LCA work is that the data should ideally be all collected in the same time period, otherwise comparison between systems can be skewed simply because the comparison is made between two products produced in different time periods.

For some of the systems involved in the ethanol lifecycle we have a significant body of knowledge concerning the input data and how it has changed over time but for other aspects, the data quality is not as good.

All technologies have a tendency to improve their performance over time. There is overwhelming empirical evidence that deploying new technologies in *competitive markets* leads to *technology learning*, in which the cost of using a new technology falls and its technical performance improves as sales and operational experience accumulate. Experience and learning curves, which summarize the paths of falling technology costs and improving technical performance respectively, provide a robust and simple tool for analysing technology learning.

The shape of the curves indicates that improvements follow a simple power law. This implies that relative improvements in price and technical performance remain the same over each doubling of cumulative sales or operational experience. As an example, the following figure shows that the prices of photovoltaic modules declined by more than 20 percent as each doubling of sales occurred during the period between 1976 and 1992 (IEA, 2000). Furthermore, the relationship remains the same over three orders of magnitude of sales.

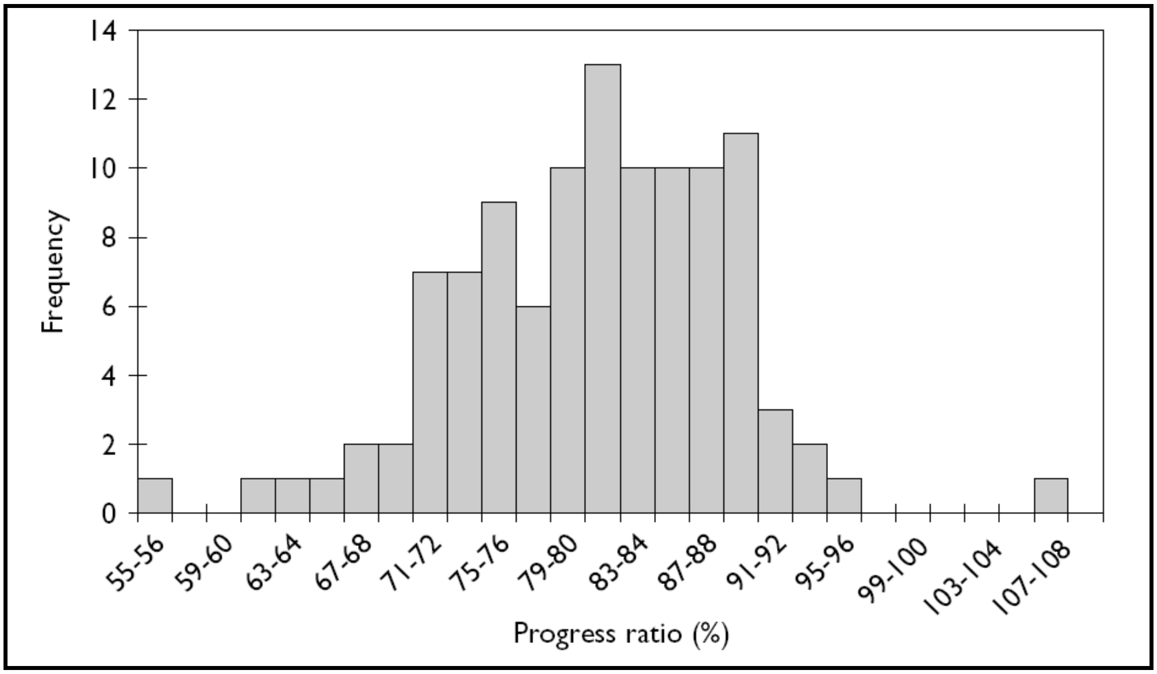
Figure 3-5 Photovoltaic Experience Curve



The straight line captures a very important feature of the experience curve. Anywhere along the line, an increase by a fixed percentage of the cumulative production gives a consistent percentage reduction in price. This means that for technologies having the same progress ratio, the same absolute increase in installed capacity will yield a greater cost decrease for young technologies (i.e., they learn faster) than old technologies. This also means that the same absolute increase in cumulative production will have more a dramatic effect at the beginning of a technology's deployment than it will later on. For well-established technology, such as oil refineries using conventional technology, the volume required to double cumulative sales may be of the order of 100 million bbls/day, so the experience effect will hardly be noticeable in stable markets.

There is a significant amount of information on experience curves in the literature for many different technologies. The following figure shows the distribution of Progress Ratios for 108 case studies for a range of different products in the manufacturing sector (IEA, 2000). The average value of the progress ratio over these case studies was 82%. The consistency of the Progress Ratios over so many different technologies and products means that the approach can be used confidently, with some care, as a policy analysis tool for a range of technologies.

Figure 3-6 Distribution of Progress Ratios for 108 Case Studies in the Manufacturing Sector



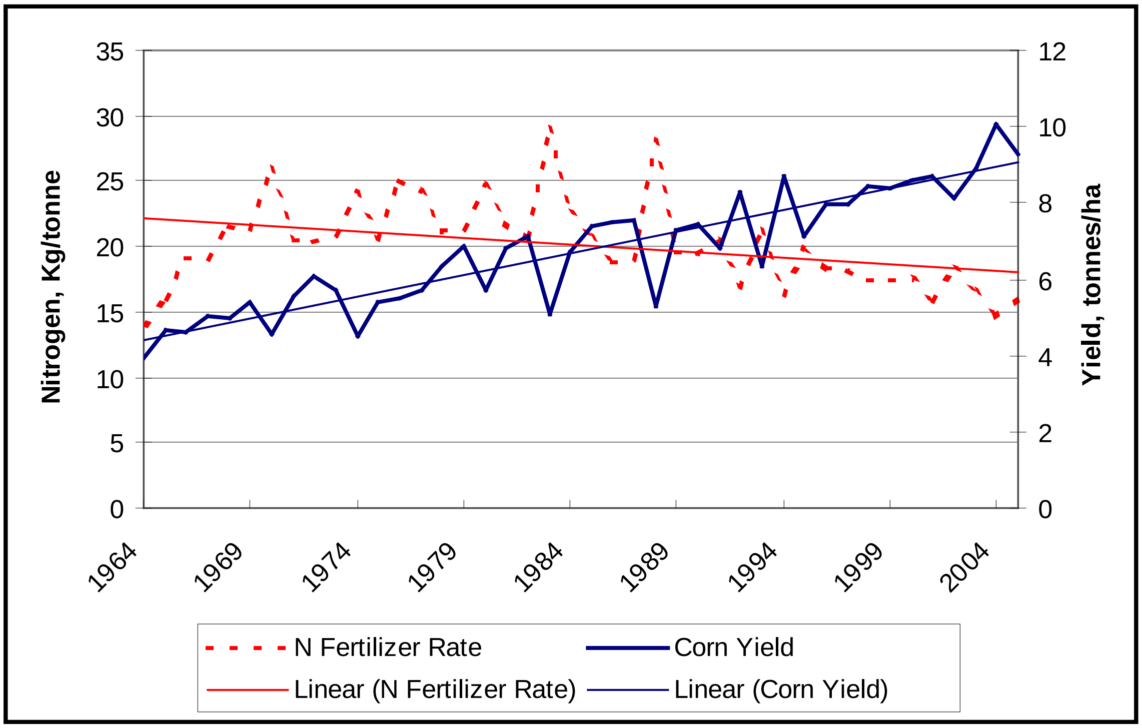
The learning curve approach can be applied not only to the costs of a technology but also to specific issues such as the energy requirements for a process.

An excellent discussion of the application of the learning experience to the US Ethanol industry has been documented by Hettinga (2007). This source of information focussed on costs and energy use and the data can be supplemented with other data sources to develop a picture on not only what the current inputs are for the corn ethanol process but also how they developed to this point. The key inputs are discussed in more detail below.

3.3.1 Feedstock Production

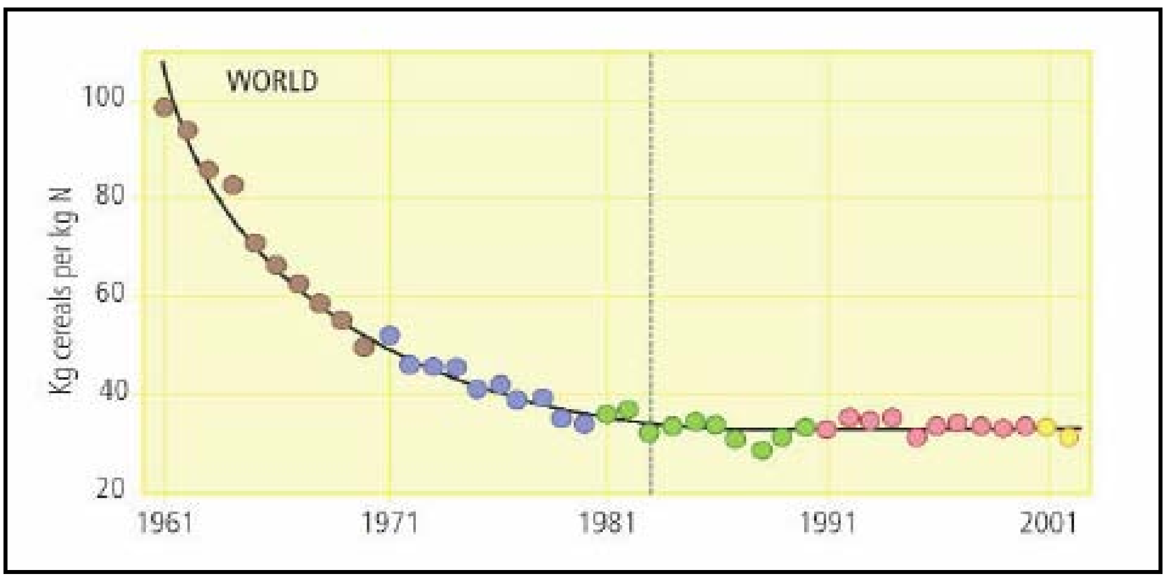
The production of the corn feedstock has evolved continuously over the past 50 years. Corn production has become significantly more productive and efficient because of new varieties, better agricultural management practices and other factors. The following figure shows how the yield has increased and the nitrogen fertilizer requirement has decreased on a per unit of corn produced basis (USDA data). The yield has increased by 0.113 tonnes/ha/year and the nitrogen requirement has decreased at the rate of 0.10 kg N/tonne/year based on a 50-year trend. There is no evidence that these trends are slowing.

Figure 3-7 Changes in Corn Productivity



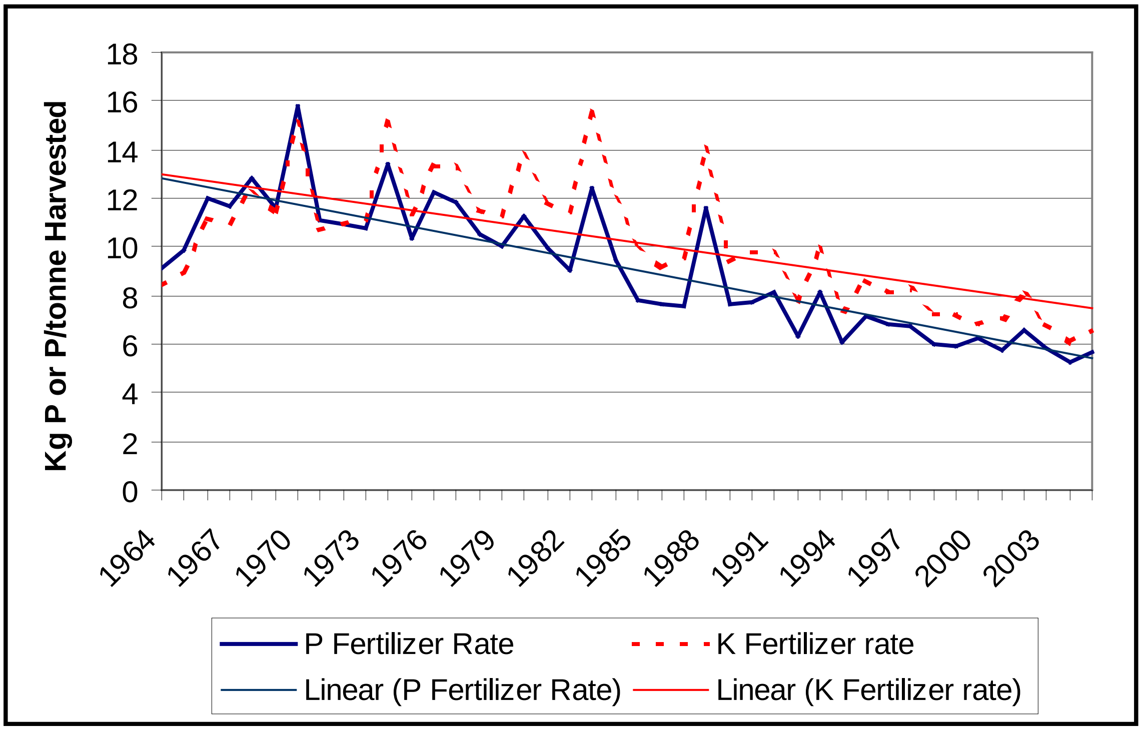
This trend to improved nitrogen efficiency is happening not only in North America but also in most countries in the world as shown in the following figure (IFA, 2007).

Figure 3-8 World Nitrogen Utilization



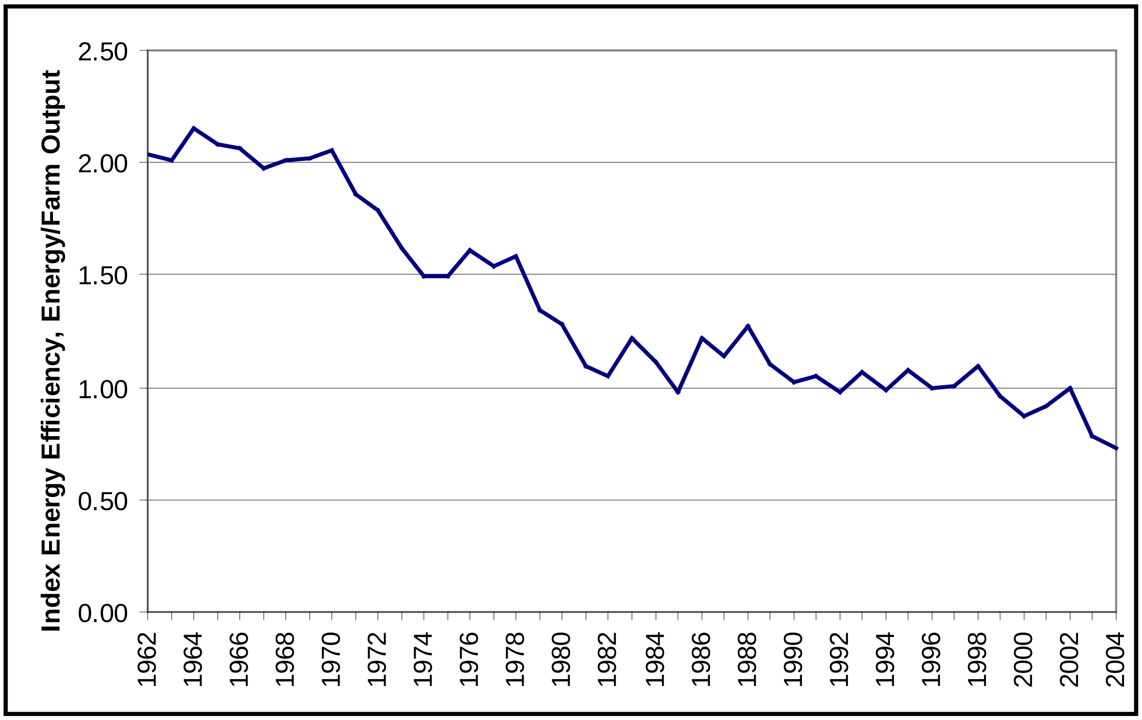
Similar trends are evident in the rates of phosphorus and potassium fertilizers. The application of phosphorus fertilizer has been declining at a rate of 0.18 kg P/tonne/year and the rate of decline of potassium has been 0.13 kg/tonne/year.

Figure 3-9 P and K Fertilizer Rates



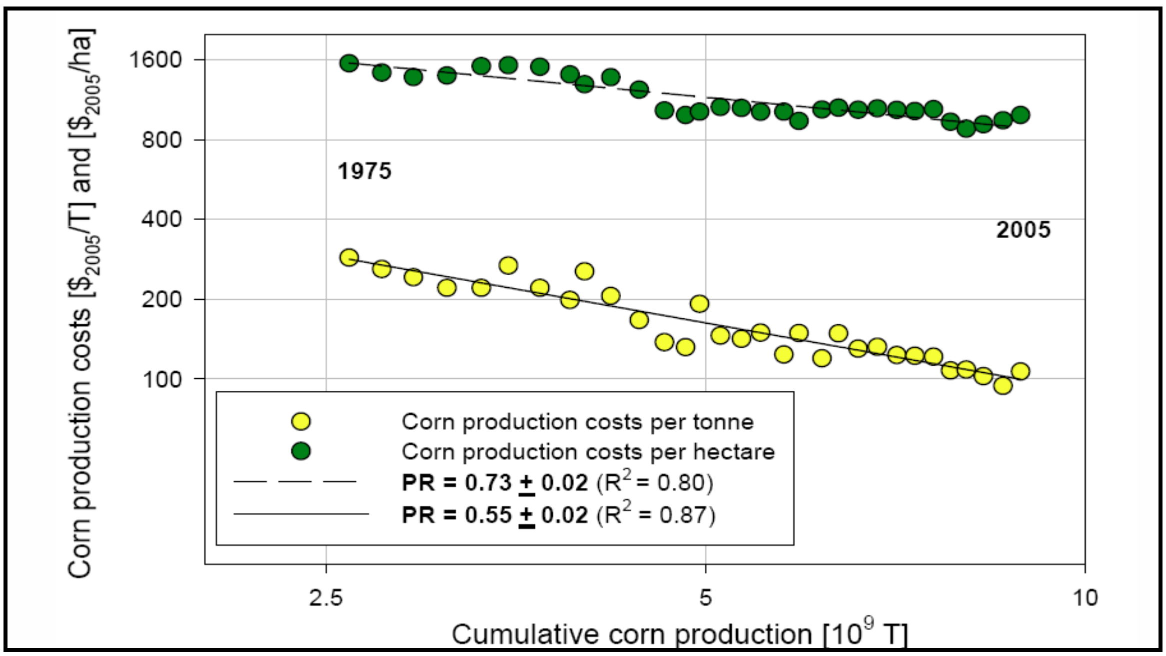
Data on fuel consumed per unit of production and per year are not surveyed on a regular basis, but the following figure shows the energy intensity index over 40 years for US agriculture and it shows similar trends to the fertilizer requirements. Most of the energy requirements for production are related to the land area and not to the production volume so energy per unit of output tends to decrease as yield increases. In addition, there have been improvements in farm machinery efficiencies, and a trend to greater adoption of no-till management practices that also reduce the energy required per unit of agricultural production.

Figure 3-10 Agriculture Energy Efficiency Index - US

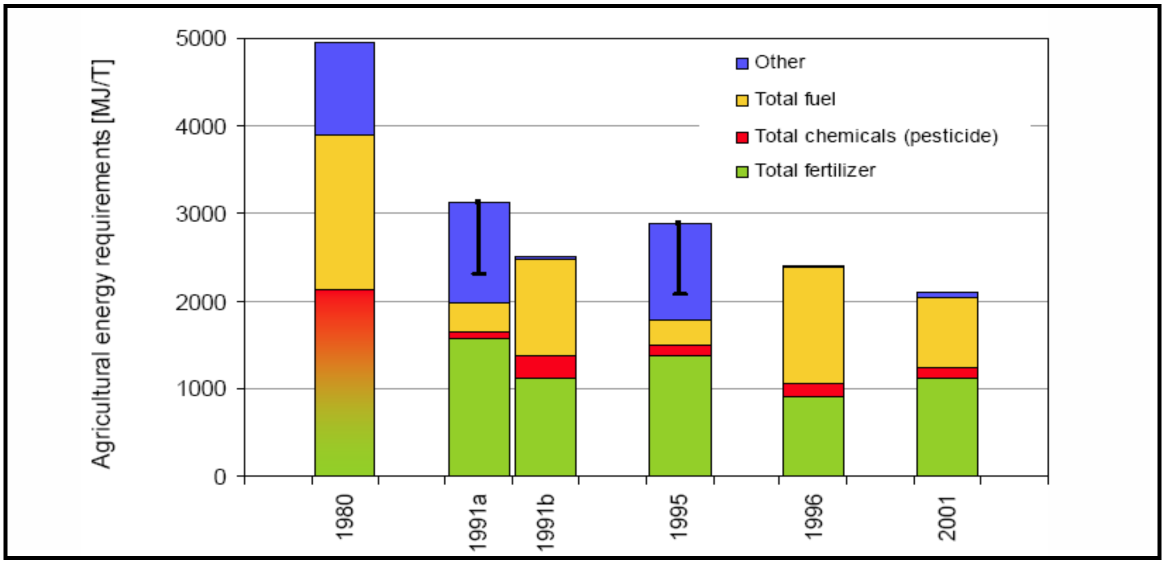


Hettinga found that corn production costs followed the expected experience curve, both on a per hectare basis and on a per tonne of production basis as shown in the following figure.

Figure 3-11 Corn Production Experience Curve



Hettinga found that data on the actual energy expenditure for corn production was more difficult to obtain but information from surveys undertaken over many years found that a trend to lower energy use was apparent as shown in the following figure. When the surveys are only undertaken every five years, the results become quite dependent on the yield in the surveyed year.

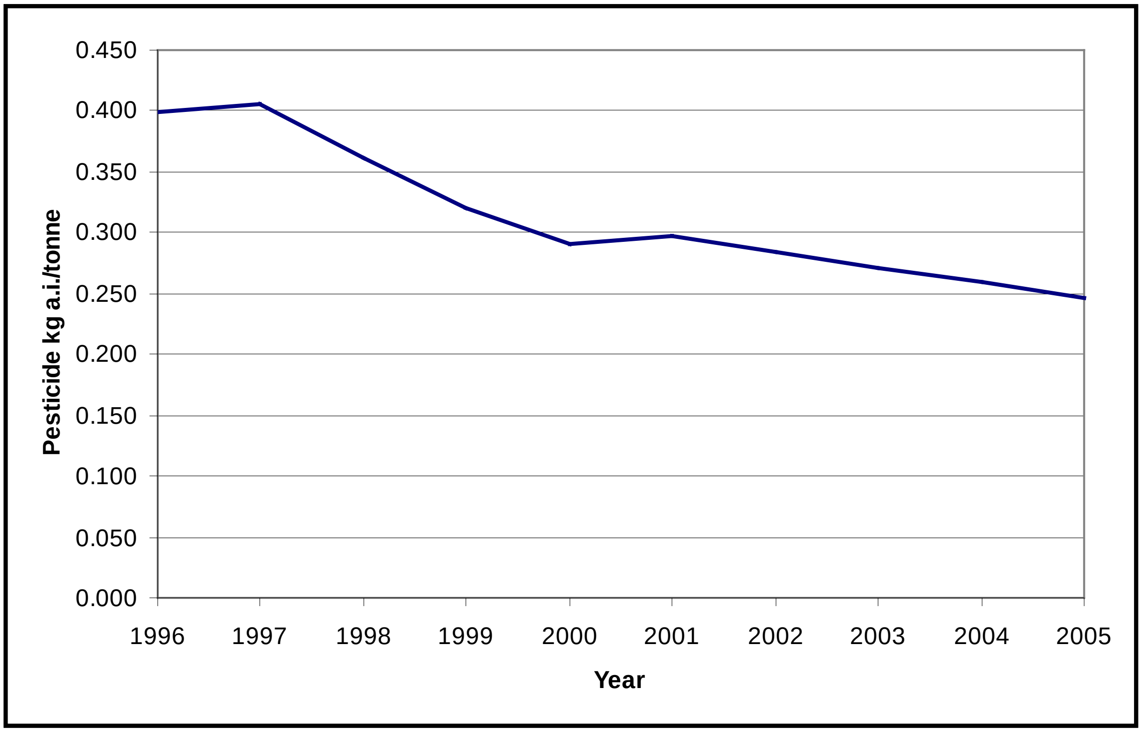


It is clear that the fertilizer requirements and direct energy use required for corn ethanol is declining, as one would expect, based on experience curve theory. This has at least two significant implications for LCA work:

1. All data used for modelling should come from the same time period if the overall results are to have any real significance, and
2. The results should be qualified as indicative of a specific period and that there is an underlying trend to the data.

It is also known that pesticide chemical usage is also dropping with time in spite of a trend to increased adoption of no till agriculture which generally increases chemical usage while reducing fuel use and soil disturbances. A complete, long term, consistent data set was not identified but the following figure shows the shorter term trend in the reduction of active ingredient (a.i.) applied.

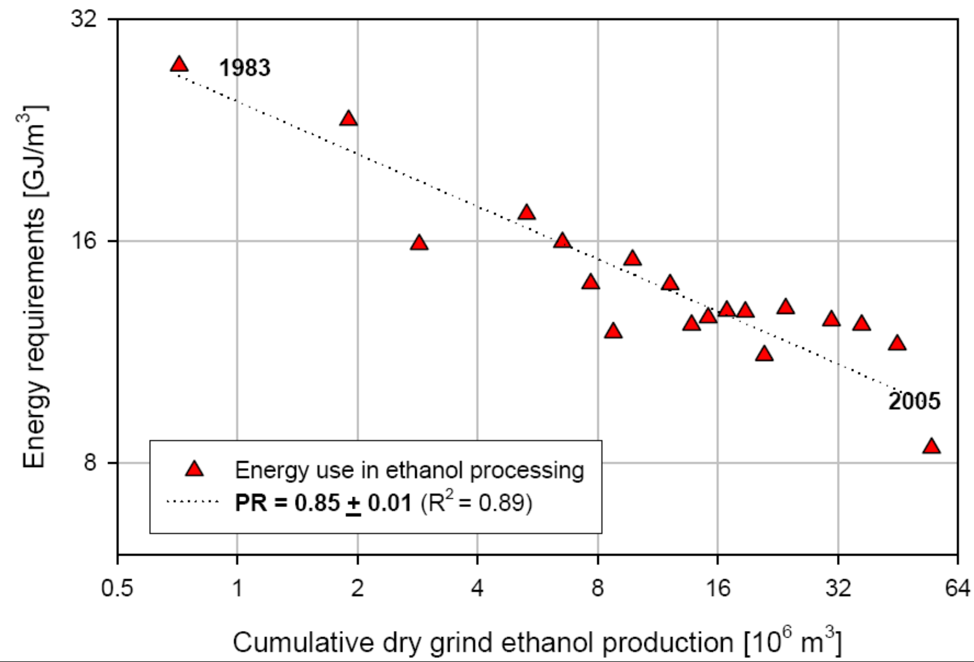
Figure 3-12 Pesticide Application Rates



3.3.2 Ethanol Production

Energy efficiency at ethanol plants has increased steadily over time as shown in the following figure (Hettinga, 2007). Between 1983 and 2005 the energy requirements for producing ethanol in a dry mill plant decreased by 63%. The data shows that for every doubling of production the energy requirements were reduced by 16%. As was found for the corn production information, the calculated lifecycle GHG emissions of ethanol from various studies will therefore be strongly dependent on when the input data for the ethanol plant was gathered.

Figure 3-13 Ethanol Plant Historical Energy Consumption



The performance demonstrated by the ethanol industry in reducing the energy costs is fully consistent with all of the experience curve knowledge gained in other industries and in fact is the expected performance, given our understanding of how industries develop.

One of the most recent survey on ethanol energy use undertaken in the United States (Wu, 2008) indicated that natural gas fired dry mills in 2007 used only 7.7 GJ of natural gas/m^3 per litre of ethanol produced, with a range from 4.5 to 10.3 GJ/m^3. The large range is a function of the amount of co-product sold wet vs. dry. Coal fired dry mills used 8.14 GJ of coal (or coal and natural gas) per litre of ethanol produced. While no similar survey has been undertaken in Canada yet, there is no reason to believe that the Canadian industry is any less efficient than the US industry.

Another ethanol benchmarking survey (Christianson, 2008) reported the energy consumption and ethanol yield for each year between 2004 and 2007. The number of plants participating in this survey increased from 14 in 2004 to 33 in 2007. All plants except one in 2007 used natural gas as the source of thermal energy. The data from that survey is shown in the following table.

Table 3-1 Energy Use US Ethanol Plants

	Natural Gas Use	Electric Power use
	MJ/litre	kWh/Litre
2004	8.8	0.205
2005	8.4	0.195
2006	7.8	0.185
2007	7.6	0.180

Both surveys are consistent and suggest that energy use in 2005 was 8.4 MJ/litre of natural gas and 0.195 kWh/litre for electricity. Approximately 50% of the thermal energy is used as steam in multiple locations in the production process and 50% is used as heat in the co-product drying stage. The co-product drying is thus the single largest energy consumer in the plant and an area that has some potential for reducing energy consumption in the future.

3.3.3 Co-products

Corn ethanol production utilizes only the starch from the kernel and all of the fibre, protein, and minerals remain unutilized in the process. This material is concentrated and dried (or has some moisture removed) in the production process. It becomes distillers' grains and is used mostly for animal feed. It supplies both energy and protein to livestock rations and thus has the potential to displace both corn and soybean meal from a livestock ration.

There continues to be a large amount of research undertaken on the nutritional properties of DDG in animal diets (http://www.ddgs.umn.edu/). The subject is very complex as it is difficult to control all of the variables to determine the impact of a single commodity change and one is dealing with different animals that can respond differently under similar circumstances. Much of the information in the literature is based on calculated relative values based on the composition of different feedstocks and not on actual feed trials. There is enough information in the literature to also know that the displacement ratios are not linear, that is the ratios are probably higher at low inclusion rates in the diets and move lower as the inclusion rates increase.

The relative values of corn DDG were published by Linn et al in 1996 based on the published nutritional compositions form the US NRC. These relative values were one kilogram of DDG replace 0.531 kg of corn plus 0.514 kg of soybean meal. These factors are based on balancing the energy content and the crude protein levels of the feed. The quality of DDG has generally improved since the NRC established their nutritional composition and other factors such as by-pass protein levels are known to be important for certain classes of animals. These additional factors are not factored into the above equation.

Recent work on the energy content of wet distillers grains by Birkelo et al is informative as it allows displacement ratios to be calculated for corn DG for dairy rations and it contains information on the impact of the corn DG on the methane production rate of the dairy animals. The displacement ratios found in this work were that one kg of DG replaced 0.56 kg of corn plus 0.60 kg of soybean meal plus 0.12 kg of corn silage plus 0.07 kg of hay. Using displacement ratios for corn silage, this can be further reduced to 0.68 kg of corn plus 0.60 kg of soybean meal plus 0.07 kg of hay. The milk production in both diets was the same.

In GHGenius, the displacement ratios for corn DDG are 0.68 for corn and 0.60 for soybean meal.

3.3.3.1 Avoided Methane Emissions

The impact of nutritional supplements on the methane production from ruminants has become well established. For example, the FAO reports that:

> *The efficiency of digestion in the rumen requires a diet that contains essential nutrients for the fermentative microorganisms. When the available feed lacks these nutrients digestion will be less efficient, lowering productivity and raising methane emissions per unit product. Strategic supplementation of missing nutrients can greatly improve the efficiency of digestion without requiring a change in the basic*

diet. The use of molasses/urea multi-nutrient blocks (MNBs) is a proven and cost effective diet supplementation strategy.

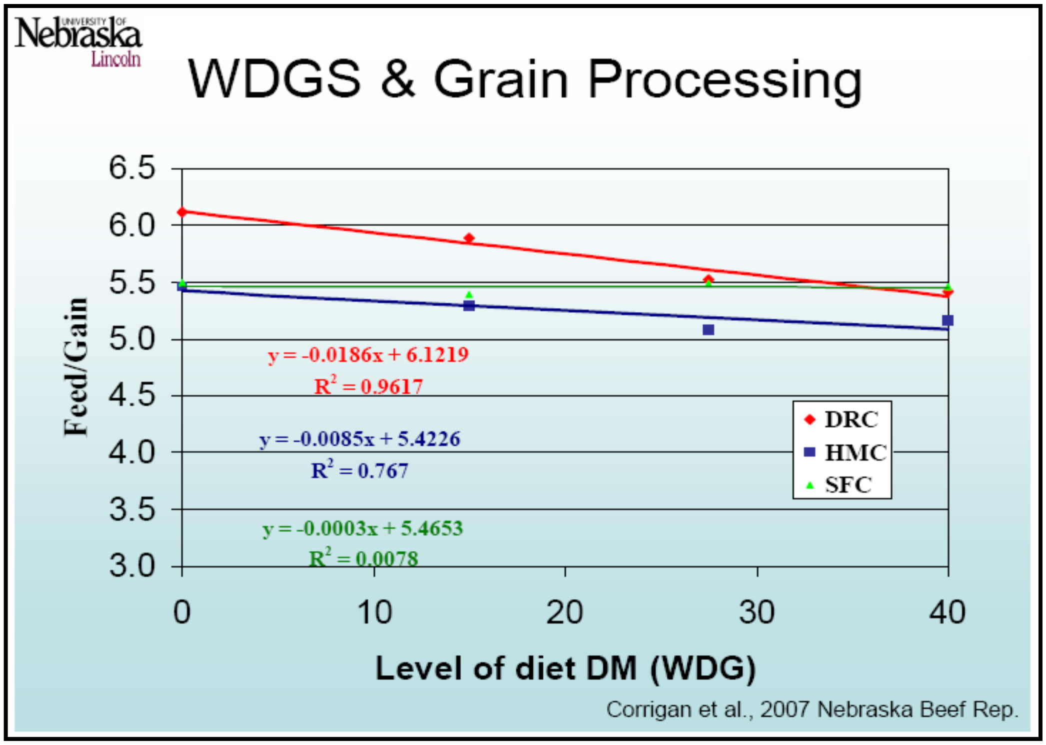
For grazing animals and those fed low quality diets, the primary limitation on efficient digestion is the concentration of ammonia in the rumen. It has been accepted that the optimum level of ammonia in the rumen is 50-60 mg/l. However, more recent studies have shown that digestibility is maximized above 80 mg/l, and feed intake increases at levels up to 200 mg/l (Perdok et al., 1988). Supplying ammonia can therefore greatly increase digestive efficiency and utilization of available energy.

Ammonia can be supplied by urea, chicken manure, or soluble protein that degrades in the rumen. Urea is broken down in the rumen to form ammonia, and adding urea to the diet has been the most effective method of boosting rumen ammonia levels demonstrated to date. Chicken manure, which has a high uric acid content, has been used in some regions, where available. While protein in the feed can provide rumen ammonia, sources of protein are often scarce, and where possible should be processed and used as a bypass protein in conjunctions with the MNBs.

In addition to ammonia, there are numerous nutrients that must be present in the diet to support the microbe population in the rumen. The most common nutrients required are sulphur and phosphorus, although this will vary greatly by region.

Distillers Grains are high in protein and in particular, by-pass protein that degrades in the rumen. Numerous studies have also shown that the inclusion of DG in the rations improves feed efficiency and thus can be expected to result in lower methane emissions. The results from a recent publication are shown below. It can be seen that for dry rolled corn (DRC) and hammermilled corn (HMC) the amount of feed consumed by the animal to add a unit of weight to the animal decreased as the quantity of DG included in the ration increased. Interesting no similar correlation was found for steam flaked corn (SFC). In North America SFC is used in cattle feeding regions where corn costs are high as this treatment reduces feed costs as can be seen in the figure.

Figure 3-14 Impact of DG Use on Feed Efficiency



This figure also supports the previously discussed displacement ratio where one kg of DDG displaces more than one kg of feed from the ration.

The exact methane emission rates from beef and dairy cattle are difficult to determine with certainty. The Canadian national inventory uses emission factors of 118 kg of methane/head per year (320 gm/head/day) for diary cattle and 72 kg/head/year (198 gm/head/day) for beef cattle. Agriculture and Agri-Food Canada (Beauchemin, 2005) recently measured emission rates of between 9.2 and 24.6 grams/kg of dry matter intake for feedlot fed cattle depending on the phase that the animal was in (backgrounding vs. finishing). The dry matter intake was 8.3 kg/day during the finishing phase and 7.6 to 10.2 kg/day during the backgrounding phase. The methane emissions were therefore between 76 and 250 gm/head/day.

Jarosz and Johnson reported on the feed energy values and methane emission rates of cattle fed distillers and brewers' grains and corn gluten feed. They found that steers fed distillers grains produced up to 40% less methane than steers fed corn gluten feed. They found the results for brewers' grains and distillers gain somewhat unexpected and speculated that the high fat content of these grains may have played a role in the results.

Birkelo's work described above found that the methane emissions from the diary cattle were reduced by 14% on the corn DG diet compared to the soybean meal diet. In this trial, all of the feeds contained similar levels of protein.

We can calculate a methane emission reduction factor based on the emission rate for dairy cattle of 320 gm/head/day and a reduction in emissions of 14% when 30% of the diet is corn DG and the dry matter intake is 20 kg/day. In this case, each kg of DG reduces methane emissions by 7.4 grams methane. This should be a conservative approach since in the diary test both the control diet and the distiller's grain diets had adequate protein. Larger reductions in methane emissions could be expected to occur in diets that were deficient in protein.

The second change is the inclusion of a methane reduction credit for the use of DDG. To be conservative a value of 3.7 grams methane/kg will be used. This is one half of that found in the dairy study but the impact on the beef cattle may not be as great. There is some evidence that the impact could be up to five times larger than this in some cases.

3.3.4 Land Use Emissions

A significant portion of the GHG emissions in the ethanol lifecycle arises from the category of land use emissions. These emissions include N_2O emissions from the application of nitrogen fertilizer, changes in soil carbon from the cultivation of the soil, and above and below ground biomass changes associated with changing the type of land used for feedstock production. Each of these categories can produce a wide range of results depending on specific conditions. The assumptions used for this project are summarized below ((S&T)^2, 2008).

The direct N_2O emission factor is 1.47% of the total nitrogen applied (fertilizer, manure and crop residues). This factor can also be impacted by the amount of no till agriculture practiced. This is the IPCC Tier 2 factor for the corn growing region of Canada. The indirect N_2O emissions are calculated for both nitrogen volatilization and nitrogen leaching.

The IPCC approach to quantifying changes to soil carbon, is based on the premise that changes in soil carbon stocks over a certain period occur following changes in soil management that influence the rates of either carbon additions to, or carbon losses from, the soil. If no change in management practices has occurred, the carbon stocks are assumed to be at equilibrium, and hence the change in carbon stocks is deemed to be zero.

Soil carbon changes can result from changing the use of the land, for example forest land or grassland converted to cropland. It can also result when cropland remains cropland by a change in the mixture of cropland type, for example changes in perennial crops or annual crops, from changes in tillage practices, and from changes in the area of summerfallow. All of these can influence the biomass pathways in the model.

Within the LCA community, carbon changes have been classified recently as either direct or indirect land use impacts. Direct impacts would be those such as changes in tillage practices, and the indirect impacts would result from a change from forest to cropland (for most biomass types) or cropland to forest land for woody biomass feedstocks. The indirect effects are therefore related to the requirement of bringing new land into production to meet the feedstock requirements. As noted earlier the boundary conditions of GHGenius have been set to exclude the indirect effects but the model does have the capacity for dealing with both types of soil carbon changes. The indirect issues are briefly discussed below.

The fundamental issue that must be addressed is where does the feedstock for the biofuel pathways come from. There are a number of possibilities depending on the feedstock and the pathway.

1. The co-products of the fuel production process may displace other biomass sources.
2. The yield of the crop on existing land may be increased through changes in management practices.
3. There may be new land brought into production.
4. The feedstock may be a waste product, such as cereal straws, or wood residues from other manufacturing operations.

Most of the focus in the recent literature has been on the third option and because the potential implications are large, there has been the suggestion that development should focus on feedstocks falling into the fourth category.

What has been missing in the discussion on indirect land use has been a quantification of the role of co-products in replacing some of the feedstock diverted to biofuel use. Corn and to a lesser degree wheat are used as livestock feed. In the case of corn, this is the dominant use throughout the world. When corn is used to produce ethanol, it also produces distillers dried grains, which is also used for animal feed. The use of corn for ethanol thus both removes and adds product to the animal feed supply pool. The net impact is what would drive the need for new land.

In GHGenius, the DDG is assumed to displace corn and soybean meal in feed rations. It is well established that it also improves feed efficiency in the animals and one kg of DDG effective displace more than one kg of other feed as shown earlier in Figure 3-14.

As noted earlier, the displacement ratios in GHGenius for corn DDG are one kg of DDG displaces 0.68 kg of corn and 0.60 kg of soybeans. The DDG production rate is variable with time, but for 2005 the value is 0.30 kg per kg of corn. Thus from one tonne of corn there will be 395 to 400 litres of ethanol plus 0.204 tonnes of corn and 0.180 tonnes of soybean meal displaced. These can be converted into area with the conversion rates and yields in the model and for 2005 one hectare of corn land yields 3,500 litres of ethanol and effectively 0.201 ha of corn and 1.016 ha of soybean land. The co-products essentially displace the same (or more) land as was required to produce the corn and no new land is required to produce ethanol and feed as was required to produce feed, just a shift in the crop variety planted. These relationships have been programmed into the displace acres for corn (row 301, sheet W) in the model so they will change as yields change or as displacement ratios change.

For this work, it is assumed that the corn is produced on land that has been in crop production for some time and thus the direct emissions are just a result of changes in management practices. Indirect land use emissions for corn ethanol are outside of the boundary conditions for this modelling but as noted above may not be as large as some have suggested.

3.4 Data for Modelling

Given the influence of time on the performance of the key variables of the ethanol lifecycle and the forward looking nature of this work it is beneficial to consider how the emissions profile may have changed in the past ten years as well as how in might change in the next ten years. Data for the year 1995 and 2005 are used to calculate the energy and carbon balance for fuel ethanol. The key input parameters for modelling are summarized in the following table. A small increase in soil carbon is projected because of the increase in no till management practices. It is assumed that all of the fertilizer is synthetic fertilizer (no manure).

Table 3-2 Modelling Input Data

	1995	2005
Corn Production		
Corn yield, tonnes/ha	7.80	8.94
Nitrogen applied, kg/tonne	19.1	18.1
Phosphorus applied, kg/tonne	7.4	5.6
Potassium applied, kg/tonne	8.9	7.6
Pesticides, kg a.i./tonne	0.40	0.25
Direct energy, litres diesel/tonne	21.5	18.8
No till, % acres	0	35
Soil carbon change, kg C/ha/year	0	0.0235
Ethanol Plant		
Natural gas, MJ/litre ethanol	11.0	8.4
Electricity, kWh/litre	0.31	0.20

Within GHGenius, many of the other industrial inputs can change over time either due to the experience gained or to fundamental shifts in the industrial infrastructure. Power production emissions intensity can change due to new power plants being added to the system, the types of crude oil processed can change due to resource availability, etc. These types of changes can also influence the energy balance and GHG emissions but for this work, no attempt has been made to hold these other factors constant, they will change with the year modelled. Their influence is small compared to the changes in the corn ethanol production cycle and can be positive or negative depending on the factor.

3.5 HISTORICAL ENERGY AND CARBON BALANCES

The total and fossil energy balance for corn ethanol for the two years modelled is summarized in the following tables. The first table shows the total energy balance and the second the fossil energy balance, where renewable energy inputs are not included. In both cases, the energy balance for gasoline is shown.

Table 3-3 Total Energy Balance Comparison – Gasoline and Ethanol

Fuel	Gasoline		Ethanol	
Feedstock	Crude Oil		Corn	
	1995	2005	1995	2005
	Joules consumed/joule delivered			
Fuel dispensing	0.0024	0.0024	0.0037	0.0038
Fuel distribution, storage	0.0065	0.0066	0.0147	0.0150
Fuel production	0.1510	0.1745	0.6402	0.5208
Feedstock transmission	0.0128	0.0124	0.0127	0.0130
Feedstock recovery	0.0916	0.1067	0.1061	0.0950
Ag. Chemical manufacture	0.0000	0.0000	0.1295	0.1144
Co-product credits	-0.0008	-0.0011	-0.0616	-0.0572
Total	**0.2634**	**0.3015**	**0.8452**	**0.7048**
Net Energy Ratio (J delivered/J consumed)	**3.7961**	**3.3171**	**1.1831**	**1.4189**

The fossil energy balance is shown in the following table.

Table 3-4 Fossil Energy Balance Comparison– Gasoline and Ethanol

Fuel	Gasoline		Ethanol	
Feedstock	Crude Oil		Corn	
	1995	2005	1995	2005
	Joules consumed/joule delivered			
Fuel dispensing	0.0005	0.0006	0.0009	0.0010
Fuel distribution, storage	0.0049	0.0051	0.0140	0.0143
Fuel production	0.1414	0.1638	0.5638	0.4578
Feedstock transmission	0.0101	0.0099	0.0125	0.0128
Feedstock recovery	0.0795	0.0950	0.1046	0.0938
Ag. Chemical manufacture	0.0000	0.0000	0.1221	0.1083
Co-product credits	-0.0007	-0.0010	-0.0531	-0.0493
Total	**0.2358**	**0.2734**	**0.7648**	**0.6387**
Net Energy Ratio (J delivered/J consumed)	**4.2410**	**3.6575**	**1.3076**	**1.5657**

There has been a significant improvement in the energy balance of corn ethanol production over the 10 year period studied because of the improvements made in both corn production and ethanol production. Due to changes in the sulphur content of gasoline and changes in the types of crude oil processed (more oil sands crude oil) the gasoline energy balance has deteriorated over this 10 year period.

The GHG emissions for gasoline and ethanol are shown in the following table. The emissions are presented on energy unit basis.

Table 3-5 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline		Ethanol	
Feedstock	Crude Oil		Corn	
Year	1995	2005	1995	2005
	g CO_2 eq/GJ (HHV)			
Fuel dispensing	118	115	185	181
Fuel distribution and storage	656	553	1,107	1,109
Fuel production	11,181	12,495	35,012	28,294
Feedstock transmission	1,084	994	1,004	1,009
Feedstock recovery	7,257	7,759	12,012	10,550
Land-use changes, cultivation	8	10	21,827	20,987
Fertilizer manufacture	0	0	8,261	7,033
Gas leaks and flares	3,486	2,238	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-65	-92	-18,490	-17,934
Sub-Total	23,725	24,072	60,919	51,229
Combustion emissions	62,917	63,676	3,058	2,237
Grand Total	86,642	87,748	63,977	53,466
% Reduction GHG Ethanol vs. gasoline			26.2	39.0

The GHG emissions for gasoline have increased over the time period, primarily due to the reduction in fuel sulphur and the changing crude oil mix. The GHG emissions for ethanol have dropped significantly through this same time period due to improvements in corn production and ethanol manufacturing.

The GHG emissions metric of g CO_2 eq/GJ often used as a basis of comparison although it assumes that there are no differences in combustion efficiency, which has been shown to be not the case with ethanol blended gasoline. In GHGenius, it is assumed that an E10 blend achieves a 1% better thermal efficiency than gasoline. The best data available from controlled tests indicated that the combustion efficiency improvement is from 1 to 2.5% better (Hochhauser, et al., 1993, Ragazzi et al., 1999). The GHG emissions on a g CO_2 eq/km basis that includes the combustion efficiency factor are shown in the following table.

Table 3-6 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline		E10	
Feedstock	Crude Oil		Corn	
Year	1995	2005	1995	2005
	g CO_2 eq/km			
Vehicle operation	210.1	211.6	206.2	209.4
C in end-use fuel from CO_2 in air	0.0	0.0	-13.5	-14.0
Net Vehicle Operation	210.1	211.6	192.6	195.4
Fuel dispensing	0.4	0.4	0.4	0.4
Fuel storage and distribution	2.2	1.8	2.2	1.9
Fuel production	37.3	41.5	46.4	44.8
Feedstock transport	3.6	3.3	3.6	3.3
Feedstock and fertilizer production	24.3	25.8	27.0	27.8
Land use changes and cultivation	0.0	0.0	5.1	4.9
CH_4 and CO_2 leaks and flares	11.6	7.4	10.7	6.8
Emissions displaced by co-products	-0.2	-0.3	-4.5	-4.4
Sub total (fuelcycle)	289.3	291.6	283.5	280.8
% Changes (fuelcycle)			-2.0	-3.7
GHG Reductions g CO_2 eq/litre of ethanol			840	1,100

4. OPPORTUNITY FOR PERFORMANCE IMPROVEMENTS

In the previous section, it was shown that the energy balance and GHG emissions of fuel ethanol have improved as experience was gained with both corn production and ethanol manufacturing. This improvement should have been expected given our understanding of learning and technology development but given that there is significant debate in the literature concerning the environmental benefits of 1st generation ethanol the learning experience perspective would appear to have been overlooked by many who have studied the issue. It is apparent that a potential reason for the different results that have been presented could be that data was selected from different time periods leading to different results.

It should be noted that the improvement in energy balance and GHG emissions are indirect benefits associated with reducing the costs of production. There is currently no direct financial benefit from a better energy balance or GHG emission metric only the indirect benefit of lower production costs, although that may change in the future as governments consider regulations and financial instruments directed exclusively towards reducing GHG emissions.

Public policy should be based not on what has happened in the past but on what should happen in the future. After all, one of the primary objectives of public policy is change the public's behaviour. Projecting the future can be difficult but the experience curves, long term data trends, an understanding of the drivers behind the trends, and some knowledge of emerging technologies can all be useful tools when developing the future scenarios.

The year 2015 has been chosen for the future scenario to model, as that will provide an equal time interval to the one chosen for the historical view.

4.1 FEEDSTOCK PRODUCTION

Between 40 and 45% of the ethanol lifecycle emissions arise from the feedstock production (net of co-product credits) and the remainder is from the ethanol production process based on the 2005 results. Within the feedstock production portion, the GHG emissions are split about equally between emissions associated with land use and emissions associated with fertilizer production and cultivation. The co-product credits are about equal to either the land use emissions or the fertilizer and cultivation related emissions.

The emissions associated with corn production are expected to continue to decrease based on a continuation of the historical trends. In most cases, there are sound reasons for the continuation of the trends and these are discussed below.

4.1.1 Yield

Over forty years of corn yield data was shown earlier. The best trend line fit for this data was a linear increase followed closely by an exponential curve. The data does suggest that the rate of increase appears to be accelerating as new technologies in plant breeding are utilized. The 40 year linear trend shows a 0.113 tonne/year yield increase, the 15 year trend shows a 0.162 tonne/year increase, the 10 year trend is 0.198 tonnes/year and the five year slop shows a 0.242 tonne/year increase.

The leading seed companies in North America are all projecting significant increases in corn yield over the next 15 to 30 years. Monsanto (2008) have pledged to double the yields of corn, soybeans and cotton between 2000 and 2030 in their major markets. It should be noted that many corn producers already achieve corn yields above 12.55 tonnes/ha in some US states. The National Corn Growers Association (2008) reported that the highest yield reported in their 2008 corn crowing contest was 22.6 tonnes/ha and that the average of the 24 winners in eight categories averaged over 19 tonnes/ha.

A conservative yield projection for 2015 would be 10.08 tonnes per hectare (160 bushel/acre) based on the 40 year trend and a more aggressive projection based on the five year trend would be 11.4 tonne/hectare (180 bu/acre). We will model 11.40 tonne/hectare (180 bushels/acre).

4.1.2 Fertilizer Requirements

A continuation of the existing trend would see the amount of nitrogen reduced to 17.1 kg/tonne of corn. Note that the nitrogen taken up by the corn kernels themselves is on the order of 12 to 13 kg N/tonne of corn so there is significant room to accelerate the trend towards lower nitrogen application. The use of nitrogen fertilizers contributes to GHG emissions in two ways, the production of synthetic fertilizers releases significant quantities of CO_2 into the atmosphere during manufacturing and a small portion of the nitrogen that is applied is transformed to N_2O in the soil and is emitted to the atmosphere. There can therefore be a double benefit from reducing the amount of nitrogen applied to the soil.

Kuo (2008) identified a number of options for reducing N_2O emissions from Agriculture. These fell into two categories, improving nitrogen utilization and inhibition of N_2O formation. The later approach is discussed below. Some of the options for improving nitrogen utilization identified include:

- Soil testing to optimize nitrogen application rate – More nitrogen is usually applied to soil than is needed because of the concern of production lost by under-fertilizing. Soil nitrogen testing can be used to help growers adjust nitrogen application rates to match site-specific conditions and have more efficient use of fertilizers. This is being adopted today.
- Controlled released fertilizers – These are intended to release nutrients at a rate that corresponds with nutrient demand of growing crops. Typically, there is a physical barrier (e.g., a polymer coating) that decreases the rate of nutrient release into the soil.
- Changes in the timing and/or frequency of fertilizer application – The use of fertilizer will be more efficient when the fertilizer application coincides with the period of rapid plant uptake. Several applications of small amounts (split applications) during the growing season would be a more effective means of supply nitrogen for plan growth and the N_2O emission loss should be smaller. There may be increased fuel use required to implement this approach.
- Matching fertilizer nitrogen type to season and general weather pattern – Nitrate-based fertilizer is less stable in soil than the ammonia-based fertilizer. When leaching potential is high, ammonia-based fertilizer should be used.
- Substitute manure for chemical fertilizer – If commercial fertilizers are replaced with livestock manure, N_2O emission from chemical fertilizers can be reduced without increasing emissions from manure (since they will likely occur anyways without the benefit of soil fertilization. Early application and immediate incorporation of manure into soil would reduce the direct N_2O emissions and ammonia volatilization.

- Cover crops – Winter or fallow cover crops can prevent the build-up of residual soil nitrogen, catching nitrogen that would otherwise be emitted as N_2O or leached.
- Improvement of fertilizer spreading – With better spreader maintenance, more uniform spreading can be achieved to increase efficiency and avoid over-application or under application.
- Optimization of fertilizer distribution geometry can also prevent losses into ditches. Fertilizer banding can increase efficiency of nitrogen use, reduce volatilization up to 35%, and increase yield up to 15%. Use of precision farming technologies such as yield mapping, global positioning system, and automatic sensing allows crop performance and output to be measured in different areas of a specific field and has potential in reducing nitrogen application and the N_2O emissions.

The high cost of nitrogen fertilizer should help to accelerate the trend towards better utilization as long as the options don’t reduce the crop yield.

The best curve fit for the phosphorus application data suggests an exponential decay curve. Extrapolation of this curve would suggest that the P fertilizer rate could decline to 4.8 kg/tonne in 2015. Some of the same techniques that are applied for reducing nitrogen losses can increase phosphorus and potassium efficiencies.

The best curve fit for the potash application data also suggests an exponential decay curve. Extrapolation of this curve would suggest that the K fertilizer rate could decline to 6.5 kg/tonne in 2015.

Pesticide application rates are expected to continue to decline. It is forecast that the rate in 2015 will be 0.20 kg a.i./tonne of corn.

4.1.3 Direct Fuel Use

Direct fuel use is expected to continue to decline as crop yields increase. Fuel use is mostly a function of the number of passes of the equipment and is therefore closely related to the area and much less to the mass of the crop produced. The trend to larger equipment, increased no till or reduced till management systems, and more efficient engines all support the trend. It is expected that the direct fuel use will decrease to 13.0 litres/tonne of corn, just slightly below the impact projected by the yield increase alone.

4.1.4 N_2O Emission Factors

Several agricultural activities increase mineral nitrogen availability in soils for nitrification and denitrification and ultimately increase the amount of N_2O emissions. Although most of the N_2O emissions from agricultural activities are from soils, the emission flux of N_2O per unit surface area of soil is small and varies greatly across time and space. The flux rate depends significantly on soil type, climate conditions, and soil management practices. There are two types of strategies and related technological options that are applicable to emission reduction of N_2O from agricultural soils. The first type, described above, uses measures that improve efficiencies in nitrogen utilization, and the second type inhibits the formation of nitrous oxide.

It should be noted that there are overlaps in these two types. For example, the use of the nitrification inhibitor and change in irrigation practices are also measures for improving nitrogen fertilizer efficiencies in the field.

With regards to inhibition of N_2O formation to reduce its emission from agricultural soil, there are many technological options and practices mentioned in the literature; but few have detailed discussion and information. Below are a list and a brief description of the technological options and practices found from the literature search (Kuo):

- Nitrification inhibitors – Nitrogen applied must be nitrified to nitrate before it is available for denitrification. Nitrification inhibitors delay the transformation of ammonium to nitrate. They can reduce the loss of nitrogen and permit crop production at constant or improved yields at given fertilizer application rates.
- Urease inhibitors – Urease inhibitors delay the transformation of urea to ammonium to help matching the timing of nitrogen supply with crop demand.
- Alternative tillage systems – Some studies suggested that N_2O emissions could decline as a result of reduced nitrogen application rates following a shift to no till agriculture. This reduction appears to be a function of soil and climate conditions and is less effective in regions with higher moisture levels, such as those required for good corn yields. Conversion from conventional tillage to no till will cause fewer disturbances to soils and more crop residual is retained.
- Changes in irrigation practices – Because soil-water content is an important factor in volatilization as well as nitrification/denitrification, irrigation practices can have an important impact on N_2O emissions from agriculture. However, the appropriate use of irrigation water is site-, crop-, soil-, and temperature-specific, therefore this option may not be easy for practical application.
- Improving drainage and avoiding soil compaction – Improving drainage and preventing soil compaction can reduce N_2O emissions.

These options are probably less likely to be implemented that those that improve nitrogen utilization and the impact of changes in the N_2O emission factor will not be considered here.

4.1.5 Soil Carbon

Soil carbon can change when management practices change. There is an increasing trend towards the use of minimum or no till management. It is expected that this trend will continue with 70% of the growers using no till practices by 2015. This is expected to result in an increase in soil carbon of 0.047 tonnes C/ha/year.

The modelling data for corn production in 2015 is shown in the following table and compared to the data for 1995 and 2005.

Table 4-1 Modelling Input Data – Corn Production 2015

	1995	2005	2015
Corn Production			
Corn yield, tonnes/ha	7.80	8.94	11.4
Nitrogen applied, kg/tonne	19.1	18.1	17.1
Phosphorus applied, kg/tonne	7.4	5.6	4.8
Potassium applied, kg/tonne	8.9	7.6	6.5
Pesticides, kg a.i./tonne	0.40	0.25	0.20
Direct energy, litres diesel/tonne	21.5	18.8	13.0
No till, % acres	0	35	70
Soil carbon change, kg C/ha/year	0	0.0235	0.047

4.2 PRODUCTION FACILITIES

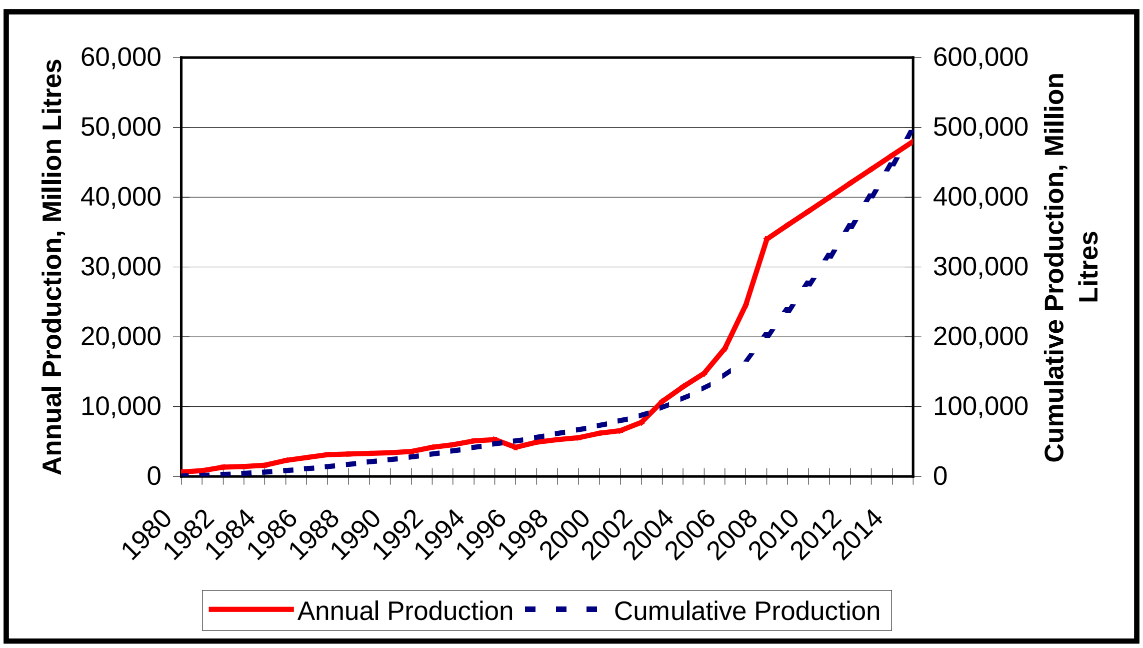
While the basic configuration of the ethanol plant has not changed significantly since the modern industry was established in the late 1970's there have been many small improvements that have been made to the process that have significantly improved energy use at the facilities. Enzymes and yeasts are now much more effective and have allowed ethanol yields to increase, higher concentrations of ethanol can be fermented resulting in less water use, and a much better integration of heat use and heat recovery in the plants.

Some new approaches to the process are beginning to be incorporated into some plants such as fractionation of the grain prior to the process, new drying technologies that capture some of the latent heat of vapourization in the DG dryer stacks, alternative fuels used to supply the energy requirements, and the capture of the CO_2 from the fermenters not for use in the food industry but for sequestration underground. All of these emerging concepts are investigated below to determine their impact on the energy balance and carbon footprint of future plants.

4.2.1 Energy Use

The ethanol production in the United States has been increasing rapidly in recent years as shown in the following figure. The rapid increase is expected to slow down once the current construction boom is completed in late 2008 or early 2009. Nevertheless, the cumulative ethanol production is expected to increase by almost a factor of four (two doublings of cumulative ethanol produced) between 2005 and 2015, from 125 billion litres to a total of 496 billion litres by the end of 2105.

Figure 4-1 Historical US Ethanol Production



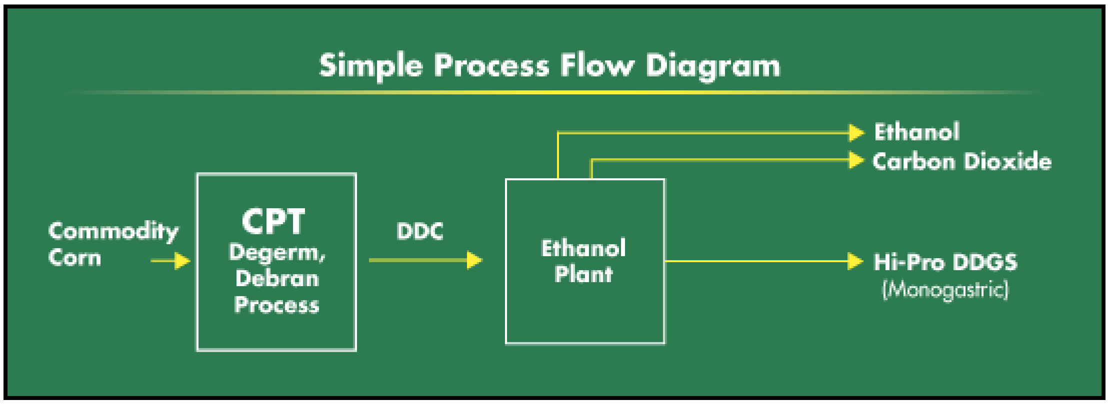
From the shape of the experience curve shown earlier (Figure 3-13), this could see the energy use at a corn ethanol plant reduced by a further 30% from the level of 2005. This would result in natural gas use of 5.9 MJ/litre and electricity use of 0.14 kWh/litre.

While one of the attractive features of experience curves is that the future can be predicted without knowing exactly how to get there it is also worthwhile to investigate some of the likely paths to see how close the existing knowledge could get towards the goal. It was shown earlier that a survey of some plants in 2007 found that the average gas use was 8.4 MJ/litre with a range of 4.3 to 10.3 MJ/litre, and the power use was 0.20 kWh/litre with a range from 0 to 0.41 kWh/litre. At least some plants are already exceeding the average expected performance of the industry in 2015.

4.2.1.1 Fractionation

A number of corn ethanol plants have installed a feedstock fractionation process ahead of the traditional ethanol plant. The concept is shown in the following figure.

Figure 4-2 Fractionation Pre-Treatment Process



Variations of the process are offered by many of the traditional ethanol plant developers as well as grain processing development companies such as:

- Poet, BFRAC™ Process
- Delta-T/Ocrim
- Renessen (JV of Monsanto and Cargill)
- FWS
- Frazier-Barnes
- ICM/LifeLine Foods
- Cereal Process Technologies

The technology could be applied with some variation to any cereal grain. In the case of corn, the system generally fractionates the corn into at least three streams, corn germ, corn bran, and the endosperm. The endosperm is utilized in an existing dry-grind ethanol plant instead of whole corn. The germ and bran co-products could be further processed into corn oil, de-oiled corn germ and processed bran products or they could be combined with the distillers' grains that are produced from the ethanol plant.

The various process developers claim that the ethanol plant could realize some or all of the following benefits with the addition of the a fractionation process:

- A Substantial Increase in the Number and Value of the Co-Products Produced
    - Corn Oil

- De-oiled Corn Germ
- Corn Bran Products
- Hi-Protein DDGS
- Ultra-High Protein DDG

• Reduction in Plant Energy Requirements

The thermal energy requirements for the ethanol plant will be reduced by 15% to 20%. Most of this reduction comes from the reduction in the volume of DDGS that requires drying. The volume of low value DDGS will be reduced by nearly 50% since fewer unfermentables are processed through the ethanol plant. Although there will be a substantial reduction in electrical consumption, this reduction will be partially offset by additional electrical requirements for the corn fractionation process.

A proprietary ethanol process model has been utilized to quantify the energy benefits of grain fractionation. The model was first set up to conditions that provided the 8.4 MJ/litre of process natural gas that the industry was averaging in 2005. Then the starch content of the grain was increased from 72% to 80% (removing the bran and germ from the kernel increases the starch content of the remainder). The energy requirements were reduced to 6.8 MJ/litre after optimization of the fermentation process with the lower solids content. This produces a 19% reduction in natural gas requirements.

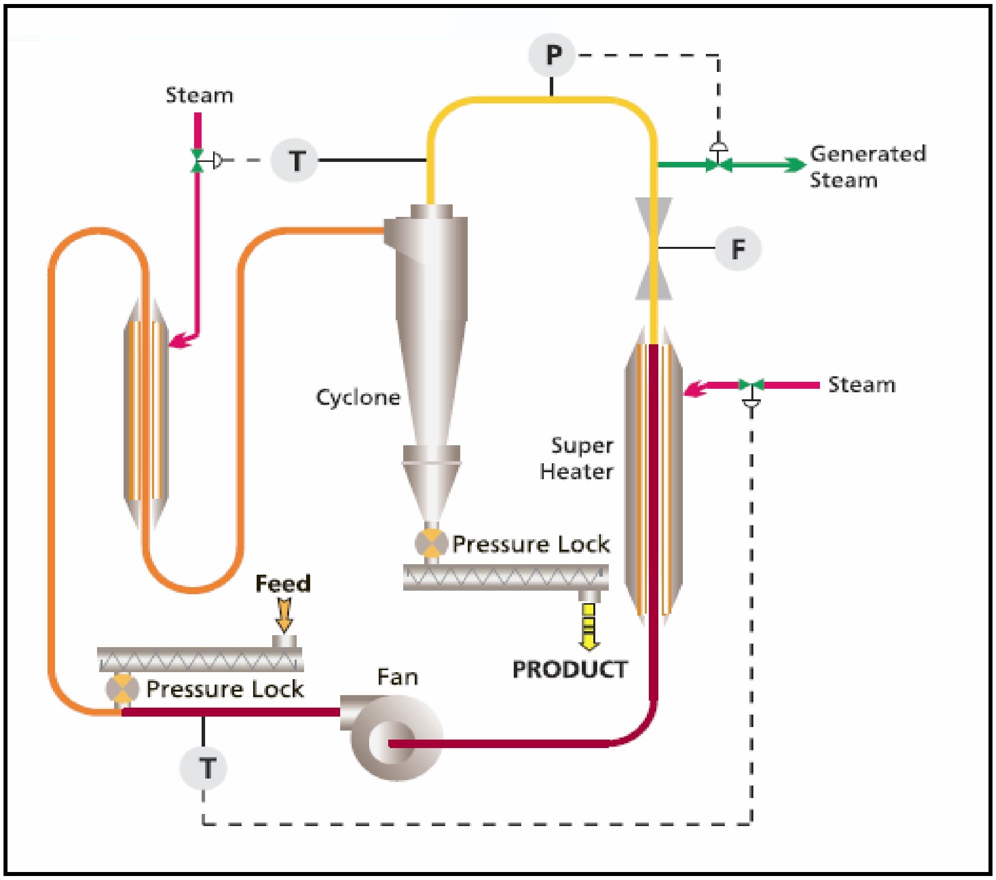
4.2.1.2 Dryer Energy Recovery

Another energy integration project that has recently been installed at several plants is the recovery of the latent heat of vapourization from the distillers' grain dryer stack. The drying of the distillers' grains can account for 30 to 50% of the energy requirements of a corn ethanol plant. Typically, 4 to 4.5 MJ/litre of ethanol are used in the dryer when the plant is equipped with an effective evaporation system. Of this energy, the heat of vaporization of the water represents 65 to 70% of the energy; the remainder is the energy required to heat the water to the boiling point and the energy required to heat the air and solids in the dryer system.

These drying systems are able to capture the heat of vaporization as low pressure steam that can be used in other parts of the ethanol plant. Typically, about 80% of the available energy can be recovered for useful purposes. This can reduce the overall energy requirement by about 2.5 MJ/litre of ethanol produced.

These dryers employ a closed loop superheated steam to transport and dry the product. Another advantage is that they can use any energy source since the material is heated indirectly. The systems generate excess steam at a pressure of 1-5 bar. This steam can be reused either directly or after a re-boiler generating clean steam. The concept is shown in the following figure.

Figure 4-3 Super Heated Steam Dryer



4.2.1.3 Other Opportunities

There will be other opportunities for energy reduction resulting from the improvement in enzymes and yeast systems, better energy integration and other approaches. Some enzyme supplies, for example, have products which function at much lower temperatures and can reduce or eliminate some of the energy used in the cooking systems.

Some of these systems can be combined. We have run our process model with fractionation and super heated steam drying. The thermal energy requirements were reduced to 5.9 MJ/litre. This is close to the experience curve projection without considering other small incremental increases that are likely.

For the 2015 case we will model the energy requirements based on the experience curve projections as shown in the following table.

Table 4-2 Ethanol Plant Modelling Data - 2015

Ethanol Plant	1995	2005	2015
Natural gas, MJ/litre ethanol	11.0	8.4	5.9
Electricity, kWh/litre	0.31	0.20	0.14

4.3 Future Energy and Carbon Balances

The results of the modelling for energy balances and GHG emissions are presented below. The gasoline energy balance is projected to continue to decline as more synthetic crude oil is incorporated into the refining slate. The ethanol energy balance continues to improve as efficiency gains are made both with feedstock production and ethanol manufacturing. Note that the value of the co-product credit also declines as efficiencies are realized with corn and soybean production. This illustrates the dynamic nature of the GHGenius model.

Table 4-3 Total Energy Balance Comparison – Gasoline and Ethanol

Fuel	Gasoline		Ethanol		
Feedstock	Crude Oil		Corn		
	1995	2015	1995	2005	2015
	Joules consumed/joule delivered				
Fuel dispensing	0.0024	0.0023	0.0037	0.0038	0.0036
Fuel distribution, storage	0.0065	0.0067	0.0147	0.0150	0.0154
Fuel production	0.1510	0.1716	0.6402	0.5208	0.3650
Feedstock transmission	0.0128	0.0119	0.0127	0.0130	0.0135
Feedstock recovery	0.0916	0.1299	0.1061	0.0950	0.0681
Ag. Chemical manufacture	0.0000	0.0000	0.1295	0.1144	0.1035
Co-product credits	-0.0008	-0.0016	-0.0616	-0.0572	-0.0500
Total	**0.2634**	**0.3208**	**0.8452**	**0.7048**	**0.5192**
Net Energy Ratio (J delivered/J consumed)	**3.7961**	**3.1174**	**1.1831**	**1.4189**	**1.9262**

The fossil energy balance is shown in the following table. Similar trends are evident to the total energy balance since most of the fuels used in these two scenarios are fossil fuels.

Table 4-4 Fossil Energy Balance Comparison– Gasoline and Ethanol

Fuel	Gasoline		Ethanol		
Feedstock	Crude Oil		Corn		
	1995	2015	1995	2005	2015
	Joules consumed/joule delivered				
Fuel dispensing	0.0005	0.0006	0.0009	0.0010	0.0009
Fuel distribution, storage	0.0049	0.0052	0.0140	0.0143	0.0148
Fuel production	0.1414	0.1612	0.5638	0.4578	0.3204
Feedstock transmission	0.0101	0.0096	0.0125	0.0128	0.0133
Feedstock recovery	0.0795	0.1184	0.1046	0.0938	0.0672
Ag. Chemical manufacture	0.0000	0.0000	0.1221	0.1083	0.0981
Co-product credits	-0.0007	-0.0014	-0.0531	-0.0493	-0.0424
Total	**0.2358**	**0.2935**	**0.7648**	**0.6387**	**0.4723**
Net Energy Ratio (J delivered/J consumed)	**4.2410**	**3.4072**	**1.3076**	**1.5657**	**2.1175**

The GHG emissions for gasoline and ethanol are shown in the following table. The emissions are presented on energy unit basis. For gasoline, the increase in energy use is mostly offset by the efforts to reduce fugitive emissions from operating wells. This has been the focus of significant efforts in Canada and other crude oil producing countries in recent years. The GHG emissions savings from ethanol production and use have more than doubled between 1995 and the projected level in 2015. This indicates the danger of making policy decision based on historical data without taking into account learning experiences and the potential gains that can be expected as industries develop. The GHG emissions reductions in 2015 from corn ethanol would qualify as advanced biofuels under proposed US regulations.

Table 4-5 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline		Ethanol		
Feedstock	Crude Oil		Corn		
Year	1995	2015	1995	2005	2015
	g CO_2 eq/GJ (HHV)				
Fuel dispensing	118	90	185	181	142
Fuel distribution and storage	656	507	1,107	1,109	1,124
Fuel production	11,181	12,162	35,012	28,294	19,085
Feedstock transmission	1,084	903	1,004	1,009	1,031
Feedstock recovery	7,257	8,724	12,012	10,550	7,348
Land-use changes, cultivation	8	15	21,827	20,987	20,369
Fertilizer manufacture	0	0	8,261	7,033	6,215
Gas leaks and flares	3,486	1,688	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0
Emissions displaced	-65	-137	-18,490	-17,934	-17,219
Sub-Total	23,725	23,951	60,919	51,229	38,095
Combustion emissions	62,917	64,813	3,058	2,237	1,973
Grand Total	86,642	88,764	63,977	53,466	40,068
% Reduction			26.2	39.0	54.9

When the ethanol is blended with gasoline and the emissions reported on a distance-travelled basis then the lifecycle emissions benefits improve as shown in the following table.

Table 4-6 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline		E10		
Feedstock	Crude Oil		Corn		
Year	1995	2015	1995	2005	2015
	g CO_2 eq/km				
Vehicle operation	210.1	210.2	206.2	209.4	208.0
C in end-use fuel from CO_2 in air	0.0	0.0	-13.5	-14.0	-14.0
Net Vehicle Operation	210.1	210.2	192.6	195.4	194.0
Fuel dispensing	0.4	0.3	0.4	0.4	0.3
Fuel storage and distribution	2.2	1.7	2.2	1.9	1.8
Fuel production	37.3	40.2	46.4	44.8	41.4
Feedstock transport	3.6	3.0	3.6	3.3	3.0
Feedstock and fertilizer production	24.3	28.9	27.0	27.8	29.7
Land use changes and cultivation	0.0	0.0	5.1	4.9	4.7
CH_4 and CO_2 leaks and flares	11.6	5.6	10.7	6.8	5.1
Emissions displaced by co-products	-0.2	-0.5	-4.5	-4.4	-4.4
Sub total (fuelcycle)	289.3	289.4	283.5	280.8	275.7
% Changes (fuelcycle)			-2.0	-3.7	-4.7
GHG Reductions g CO_2 eq/litre of ethanol			840	1,100	1,413

4.3.1 Types of Energy Used

The type of energy used in ethanol plants can have a small impact on the total energy balance but a large impact on the fossil energy balance and the GHG emissions if some fossil energy is replaced by bioenergy such as corn stover, wood residues, land fill gas, etc. All of these alternative energy sources are being used or considered in some ethanol plants. Bioenergy is also used to supply the energy needs of most sugar cane ethanol plants. The Brazilian sugar cane industry makes claims of their good overall energy balance compared to corn ethanol but they are really comparing the fossil energy balance between the two systems as the total energy balance, when the combusted bagasse is included, is on average no different than the US corn ethanol industry.

A future case has been modelled where the natural gas requirements are replaced by corn stover. The nutrients in the corn stover are replaced by additional fertilizer. No change is made to the soil carbon estimates, as the removal of some corn stover should be easily accomplished without impacting soil carbon.

The total and fossil energy results are shown in the following table. The total energy balances is slightly worse when using the corn stover as extra energy is required for transportation, fertilizer and the boiler efficiency is usually lower with biomass than it is with natural gas. The fossil energy balance is considerably better when the natural gas is replaced by bioenergy.

Table 4-7 Energy Balance Comparison – By Ethanol Plant Energy Source

Fuel	Ethanol		Ethanol	
Feedstock	Corn		Corn	
	Total Energy		Fossil Energy	
Year	2015	2015	2015	2015
Fuel Source	NG	Stover	NG	Stover
	Joules consumed/joule delivered			
Fuel dispensing	0.0036	0.0036	0.0009	0.0009
Fuel distribution, storage	0.0154	0.0154	0.0148	0.0148
Fuel production	0.3650	0.3691	0.3204	0.0517
Feedstock transmission	0.0135	0.0156	0.0133	0.0154
Feedstock recovery	0.0681	0.0906	0.0672	0.0894
Ag. Chemical manufacture	0.1035	0.1035	0.0981	0.0981
Co-product credits	-0.0500	-0.0500	-0.0424	-0.0424
Total	**0.5192**	**0.5479**	**0.4723**	**0.2278**
Net Energy Ratio (J delivered/J consumed)	**1.9262**	**1.8251**	**2.1175**	**4.3892**

The GHG emissions for the bioenergy case are compared to the fossil energy case and gasoline in the following table. The GHG emissions benefit has increased to almost 68% compared to gasoline.

Table 4-8 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline	Ethanol	
Feedstock	Crude Oil	Corn	
Year	2015	2015	2015
Process fuel		NG	Corn Stover
	g CO_2 eq/GJ (HHV)		
Fuel dispensing	90	142	142
Fuel distribution and storage	507	1,124	1,124
Fuel production	12,162	19,085	5,815
Feedstock transmission	903	1,031	1,193
Feedstock recovery	8,724	7,348	9,776
Land-use changes, cultivation	15	20,369	20,329
Fertilizer manufacture	0	6,215	6,215
Gas leaks and flares	1,688	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-137	-17,219	-17,211
Sub-Total	23,951	38,095	27,382
Combustion emissions	64,813	1,973	1,973
Grand Total	88,764	40,068	29,355
% Reduction		54.9	66.9

The GHG emission results when distance driven is used as the functional unit are shown in the following table. The emissions reductions have increased to 1.685 kg CO_2 eq/litre of ethanol produced and consumed.

Table 4-9 Comparison of GHG Emissions - Gasoline and Ethanol

Fuel	Gasoline	E10	
Feedstock	Crude Oil	Corn	
Year	2015	2015	2015
Process Fuel		NG	Corn Stover
	g CO_2 eq/km		
Vehicle operation	210.2	208.0	208.0
C in end-use fuel from CO_2 in air	0.0	-14.0	-14.0
Net Vehicle Operation	210.2	194.0	194.0
Fuel dispensing	0.3	0.3	0.3
Fuel storage and distribution	1.7	1.8	1.8
Fuel production	40.2	41.4	38.4
Feedstock transport	3.0	3.0	3.0
Feedstock and fertilizer production	28.9	29.7	30.2
Land use changes and cultivation	0.0	4.7	4.7
CH_4 and CO_2 leaks and flares	5.6	5.1	5.1
Emissions displaced by co-products	-0.5	-4.4	-4.4
Sub total (fuelcycle)	289.4	275.7	273.2
% Changes (fuelcycle)		-4.7	-5.6
GHG Reductions g CO_2 eq/litre of ethanol		1,413	1,665

4.3.2 Co-product Applications

The co-products from ethanol production can be significant sources of emissions credits as the mass of the distillers grains is about the same as the mass of the ethanol produced by the process. The co-products are high in protein and energy and traditionally have been used almost exclusively as a component of livestock feed. There are alternative uses being considered such as the use as a natural fertilizer, the feedstock for an energy system (direct combustion or anaerobic digestions), ingredients in plastics, and other uses. It is highly likely than animal feed will remain the predominant use for the product over the ten year period considered in this forecast.

For all protein meals, GHGenius undertakes a two step process to calculate the GHG emissions offset by their use. The first step is a system expansion between soybean production and crushing and canola (rapeseed) production and crushing. This step assumes that equivalent products (soy oil and canola oil, and soybean meal and canola meal (after protein correction)) have the same environmental burden. The model then solves two simultaneous equations with two unknowns and determines how the energy use and emissions are allocated between oil and soybean meal. The other protein meals in the model are valued based on their displacement ratios to soybean meal. No assumptions are required by the user as to how to allocate the emissions between the two products from the production process are required.

In the following sections, two aspects of co-products are considered and their impact on the energy balance and GHG emissions evaluated. The first is the area of animal nutrition and the second is the utilization of the CO_2 from the fermentation process.

4.3.2.1 *Animal Nutrition*

GHG emissions from the enteric fermentation in livestock represent about 30% of agriculture's GHG emissions and 4% of the world's total GHG emissions (UNFCCC, 2008). Kuo (2008) reported on the various approaches to reducing these emissions and assigned them to one of six categories;

- Improvements to animal husbandry/livestock reduction
- Improved feed conversion efficiency
- Improving animal productivity through the use of growth hormones
- Improving genetic characteristics
- Improving nutrition through strategic supplementation
- Improving reproduction

Two of these categories related to the actual feeding of the livestock, improving feed conversion and strategic supplementation. The opportunities that he summarized to improved feed conversion and where distillers grains can play a role include;

- Improved level of feed intake – An increase in level of feed intake can change the volatile fatty acid (VFA) content in the rumen and less acetate and more propionate is formed resulting in lower methane production and emissions.
- Replacing roughage with concentrates – Roughage contains a high level of structural carbohydrates (fibres). Replacing part of the roughage in the animal diet with concentrates can improve propionate generation and reduce methane production and emissions.
- Changing composition of concentrates – Adding unsaturated fatty acid and/or lipids (high fat diet) to the animal diet can increase the formation of propionate and reduce methane production and emissions.

Thus, it is clear that the observed improvement in feed efficiency when distillers' grains are included in the rations have a sound basis in science. Not all livestock operations that feed distillers grains properly formulate their rations for the complete impact that distillers grains can have on the ration and the animal's performance. Some other models also utilize higher displacement ratios than does GHGenius. The impact of higher displacement ratios will be investigated below.

With respect to improved nutrition through strategic supplementation some of the options identified by Kou that are relevant to distillers grains include;

- Molasses/urea blocks – Many nutrients must be present in the diet to support the rumen microbial population; ammonia concentration in rumen is often the primary limitation on efficient digestion. Urea added to the diet has been the most effective method of boosting ammonia levels in the rumen. The molasses/urea block is easy to use and methane emission reductions per unit product can be as high as 40%.
- Molasses/urea blocks with bypass protein – Animals capable of higher yields and faster growth-rates need a greater supply of amino acids. Providing supplements of molasses/urea blocks with by-pass proteins, which can escape degradation in the rumen and are digested in the lower gut, can greatly increase milk yield and weight-gain of animals on straw/forage.

- Targeted mineral/protein supplement – Protein and specific minerals may be deficient seasonally or throughout the year. Supplements targeted to these deficiencies can improve productivity and reduce methane emissions.

Distillers' grains have high levels of by-pass protein and often contain some urea that is added in the ethanol fermentation process.

GHGenius does calculate an emissions benefit from reduced methane emissions from the use of distillers' grains but the default emission factor is quite low compared to some of the values reported in the literature.

In the following tables the impact of two changes are investigated. In the first two cases, the displacement rations for corn and soybean meal are each increased by 50% compared to the default values. The second case shows the impact on increasing the default methane reduction factor in GHGenius by 100%; this may still be a conservative value. The energy balance impact is shown in the following table. There can be small benefits to the energy balance from improving the utilization of distillers' grains. There is no energy balance impact from reducing methane emissions.

Table 4-10 Energy Balance Comparison – Co-product Impact

Fuel	Ethanol			
Feedstock	Corn			
	Total Energy Balance			
Year	2015	2015	2015	2015
Fuel Source	NG	NG	NG	NG
	Base	Higher corn displacement	Higher SBM[1] displacement	Both higher
	Joules consumed/joule delivered			
Fuel dispensing	0.0036	0.0036	0.0036	0.0036
Fuel distribution, storage	0.0154	0.0154	0.0154	0.0154
Fuel production	0.3650	0.3650	0.3650	0.3650
Feedstock transmission	0.0135	0.0135	0.0135	0.0135
Feedstock recovery	0.0681	0.0681	0.0681	0.0681
Ag. Chemical manufacture	0.1035	0.1035	0.1035	0.1035
Co-product credits	-0.0500	-0.0685	-0.0564	-0.0750
Total	**0.5192**	**0.5006**	**0.5127**	**0.4941**
Net Energy Ratio (J delivered/J consumed)	**1.9262**	**1.9977**	**1.9505**	**2.0239**

The impact on the GHG emissions of the alternate assumptions regarding co-product displacement ratios is shown in the following table. The changes from the individual components are small and of approximately equal value but the combined effect can be quite significant. Note that the protein and energy benefits of the distillers' grains are of about equal magnitude when the changes in the corn displacement (energy) and the soybean meal (protein) are compared.

[1] SBM. Soybean Meal

Table 4-11 Comparison of GHG Emissions – Co-Product Effects

Fuel	Gasoline	Ethanol				
Feedstock	Crude Oil	Corn				
Year	2015					
Process fuel		NG				
		Base	Higher corn displace ment	Higher SBM displace ment	Both higher	High Methane Reduction
				g CO_2 eq/GJ (HHV)		
Fuel dispensing	90	142	142	142	142	142
Fuel distribution and storage	507	1,124	1,124	1,124	1,124	1,124
Fuel production	12,162	19,085	19,085	19,085	19,085	19,085
Feedstock transmission	903	1,031	1,031	1,031	1,031	1,031
Feedstock recovery	8,724	7,348	7,348	7,348	7,348	7,348
Land-use changes, cultivation	15	20,369	20,369	20,369	20,369	20,369
Fertilizer manufacture	0	6,215	6,215	6,215	6,215	6,215
Gas leaks and flares	1,688	0	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0	0
Emissions displaced	-137	-17,219	-20,782	-20,934	-24,496	-20,188
Sub-Total	23,951	38,095	34,533	34,381	30,818	35,126
Combustion emissions	64,813	1,973	1,973	1,973	1,973	1,973
Grand Total	88,764	40,068	36,506	36,254	32,791	37,099
% Reduction		54.8	58.8	59.1	63.0	58.2

4.3.2.2 Carbon Capture and Storage

There are some ethanol plants in the United States that are participating in pilot projects to capture and sequester (CCS) the carbon dioxide from the fermentation process. The Midwest Geological Sequestration Consortium is working with ADM at their Decatur, Illinois ethanol plant. The Andersons Marathon ethanol plant in Greenville, Ohio is working with the Mid-west Regional Carbon Sequestration Partnership to capture and sequester CO_2 from fermentation.

This application of carbon capture and storage technology is interesting from several perspectives. First, the CO_2 produced by fermentation is biogenic and thus capturing it and removing it from the atmosphere is a net reduction in atmospheric CO_2, not just a reduction in CO_2 emissions. Secondly, the almost pure CO_2 produced from fermentation makes the source one of the easiest to capture in terms of extra energy required to capture and compress the CO_2.

The modelling parameters used for CCS are that 0.5 GJ/tonne of CO_2 of electric power is required for compression of the gas and that 85% of the gas can be captured and stored. These are typical values often found in the literature for the technology.

GHGenius can model CCS from many different applications including the fermentation gases from an ethanol plant. The impact on the energy balance and GHG emissions profile in the year 2015 is shown in the following tables for both the natural gas and bioenergy scenarios.

Table 4-12 Energy Balance Comparison – With CCS

Fuel	Ethanol			
Feedstock	Corn			
	Total Energy Balance			
Year	2015	2015	2015	2015
Fuel Source	NG	NG	Stover	Stover
	wo CCS	w CCS	wo CCS	w CCS
	Joules consumed/joule delivered			
Fuel dispensing	0.0036	0.0036	0.0036	0.0036
Fuel distribution, storage	0.0154	0.0154	0.0154	0.0154
Fuel production	0.3650	0.3842	0.3691	0.3883
Feedstock transmission	0.0135	0.0135	0.0156	0.0156
Feedstock recovery	0.0681	0.0681	0.0906	0.0906
Ag. Chemical manufacture	0.1035	0.1035	0.1035	0.1035
Co-product credits	-0.0500	-0.0500	-0.0500	-0.0500
Total	**0.5192**	**0.5384**	**0.5479**	**0.5671**
Net Energy Ratio (J delivered/J consumed)	**1.9262**	**1.8574**	**1.8251**	**1.7633**

The impact on the GHG emissions of the incorporation of CCS on both the natural gas and corn stover fired plants is shown in the following table. The case of a biomass-fired plant with CCS in 2015 is projected to be almost free of GHG emissions.

Table 4-13 Comparison of GHG Emissions - Gasoline and Ethanol with CCS

Fuel	Gasoline	Ethanol			
Feedstock	Crude Oil	Corn			
Year	2015	2015		2015	
Process fuel		NG		Corn Stover	
		wo CCS	w CCS	wo CCS	w CCS
	g CO_2 eq/GJ (HHV)				
Fuel dispensing	90	142	142	142	142
Fuel distribution and storage	507	1,124	1,124	1,124	1,124
Fuel production	12,162	19,085	19,979	5,815	6,709
Feedstock transmission	903	1,031	1,031	1,193	1,193
Feedstock recovery	8,724	7,348	7,348	9,776	9,776
Land-use changes, cultivation	15	20,369	20,369	20,329	20,329
Fertilizer manufacture	0	6,215	6,215	6,215	6,215
Gas leaks and flares	1,688	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0
Emissions displaced	-137	-17,219	-45,719	-17,211	-45,711
Sub-Total	23,951	38,095	10,489	27,382	-223
Combustion emissions	64,813	1,973	1,973	1,973	1,973
Grand Total	88,764	40,068	12,362	29,355	1,750
% Reduction		54.8	86.0	66.9	98.0

5. DISCUSSION

This work has identified some interesting issues for the life cycle assessment of ethanol produced from corn that are not frequently identified in the discussion of the costs and benefits of biofuels. Further discussion of the results and the potential implications is presented below.

5.1 ALTERNATIVE FUNCTIONAL UNITS

The GHG results in the paper have been presented using both energy units and distance travelled as the function units. The results are slightly different for these two units since different fuels have different combustion characteristics and could be expected to provide different kilometres driven for the same energy content. Some researchers also consider different function units as part of the analysis.

One functional unit that is used is a unit of land. While this is not particularly useful for comparing a fossil fuel to a biofuel, it can be useful in comparing two biofuels. Assuming that land availability is the supply constraint, then the crop that provides the greatest GHG emissions benefit per unit of land could be the best biofuel option to pursue.

In this work, we have only considered the one crop, corn, but it is interesting to see how the performance changes over time for this one crop when the functional unit is a hectare of land. This information is presented in the following table.

Table 5-1 Alternate Functional Units

	1995	2005	2015	2015 w CCS
Corn Yield, tonnes/ha	7.8	8.94	11.4	11.4
Ethanol Yield, litres/ha	3,120	3,576	4,560	4,560
GHG Reductions				
Kg CO_2 eq/litre ethanol	0.84	1.1	1.41	2.32
Kg CO_2 eq/ha	2,621	3,934	6,430	10,579
Kg CO_2 eq/tonne corn	336	440	564	928
Percent Improvement over Base Case				
Reductions/litre		31%	68%	176%
Reductions/ha		50%	145%	304%
Reductions/tonne corn		31%	68%	176%

The rate of change in GHG emissions per unit of land is greater than the rate of change per unit of ethanol produced over the 20 year period considered. The reductions per tonne of corn and per litre of ethanol are the same because we did not consider changes in corn composition or further improvement in plant ethanol yields as part of this work, but it is likely that there will be some change in these parameters as well over time.

5.2 ALTERNATE DEVELOPMENT SCENARIOS

The scenarios developed here have all produced lower GHG emissions than the base case. There is the potential for technological development to not produce GHG emission reductions and potentially even an increase in emissions.

In the 1980s some of the first fuel ethanol plants developed were coal fired and some of those plants are still operating. Coal has traditionally been a lower cost energy source than natural gas but the capital costs of coal boilers are higher than natural gas boilers and they require more operating attention. Very large plants can make the higher investment payoff but smaller plants have found that in most cases natural gas plants have better overall economics.

One potential development is a smaller, cost effective coal boiler for ethanol plants. In the following table the GHG emissions for a coal plant are compared to those of a natural gas fired plant. The energy efficiency of the coal plant is assumed to be 5% lower than the gas plant. While coal fired ethanol plants do not produce the same level of GHG emission reductions as gas fired plants with the expected improvement in plant energy efficiency a coal fired plant in 2015 could provide larger GHG emission reductions than a 2005 gas fired plant provides.

Table 5-2 Comparison of GHG Emissions – Coal vs. Natural Gas

Fuel	Gasoline	Ethanol			
Feedstock	Crude Oil	Corn			
Year	2005	2005		2015	
Process fuel		NG	Coal	NG	Coal
	g CO_2 eq/GJ (HHV)				
Fuel dispensing	118	181	181	142	142
Fuel distribution and storage	656	1,109	1,109	1,124	1,124
Fuel production	11,181	28,294	44,696	19,085	26,573
Feedstock transmission	1,084	1,009	1,009	1,031	1,031
Feedstock recovery	7,257	10,550	10,550	7,348	7,348
Land-use changes, cultivation	8	20,987	20,987	20,369	20,369
Fertilizer manufacture	0	7,033	7,033	6,215	6,215
Gas leaks and flares	3,486	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0
Emissions displaced	-65	-17,934	-17,934	-17,219	-17,219
Sub-Total	23,725	51,229	67,631	38,095	45,583
Combustion emissions	62,917	2,237	2,237	1,973	1,973
Grand Total	86,642	53,466	69,868	40,068	47,566
% Reduction		39.0	19.4	54.9	46.4

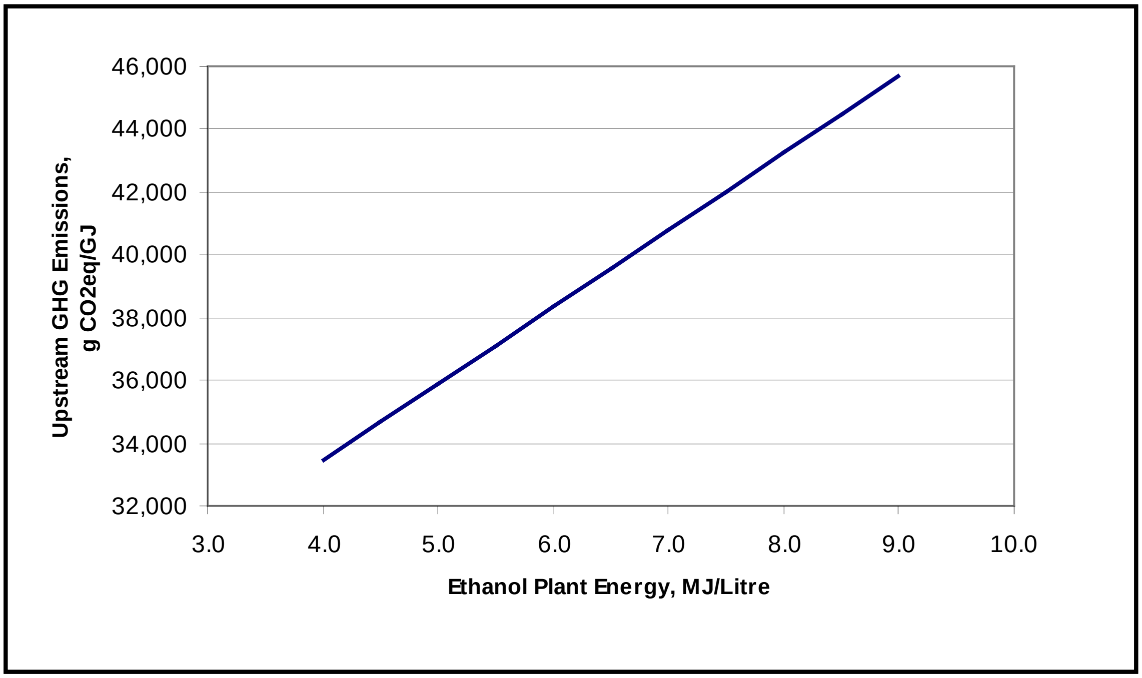
5.3 Sensitivity Analyses

Projecting the future performance of any technology is always subject to uncertainty. In order to better understand that uncertainty it is possible to undertake sensitivity analyses when one variable is uncertain or a Monte Carlo simulation when there are multiple variables that are uncertain. The results of the sensitivity of some of the key parameters are discussed below.

5.3.1 Plant Energy Requirements

The experience curve data is suggesting that there will be a further significant reduction in energy consumption in the ethanol plant by 2015. The sensitivity of the results to this forecast is shown in the following figure. The plant thermal energy requirements are varied from 4 to 9 MJ/litre of ethanol produced (2015 base value is 5.9 MJ/litre). The plant energy use is the major driver of GHG emissions as can be seen in the following figure.

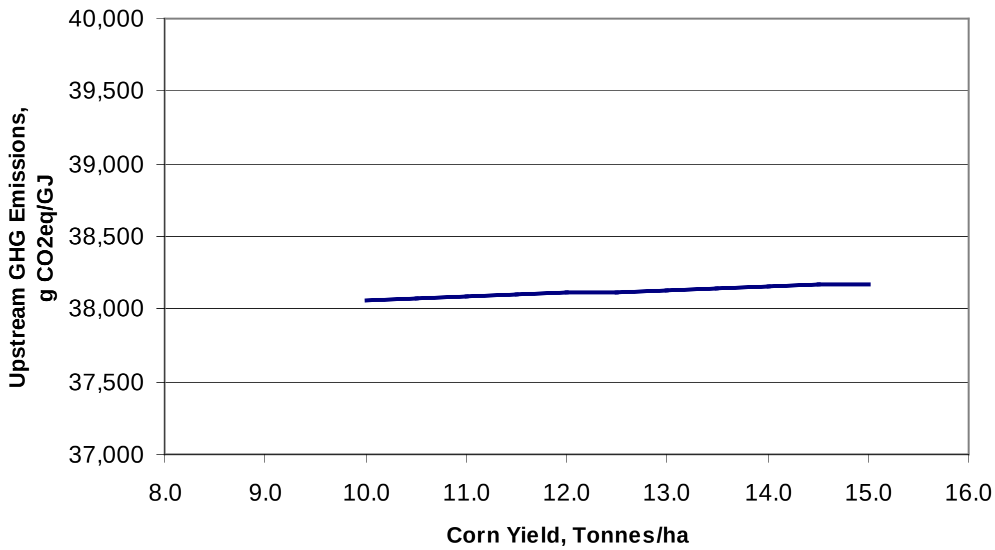
Figure 5-1 Impact of Plant Energy Use on Upstream Ethanol GHG Emissions



5.3.2 Corn Yield

The major corn seed developers are projecting an increased rate of yield increase in the near future as they apply new techniques to seed development. In the following figure, the upstream GHG emissions for the year 2015 are shown when corn yield is varied from 10 to 15 tonnes/ha (the base value is 11.4 tonnes/ha). It can be seen that yield has little impact on the overall result, as most of the inputs are a function of the production and not the area cultivated.

Figure 5-2 Impact of Corn Yield on Upstream Ethanol GHG Emissions



5.3.3 Corn Productivity

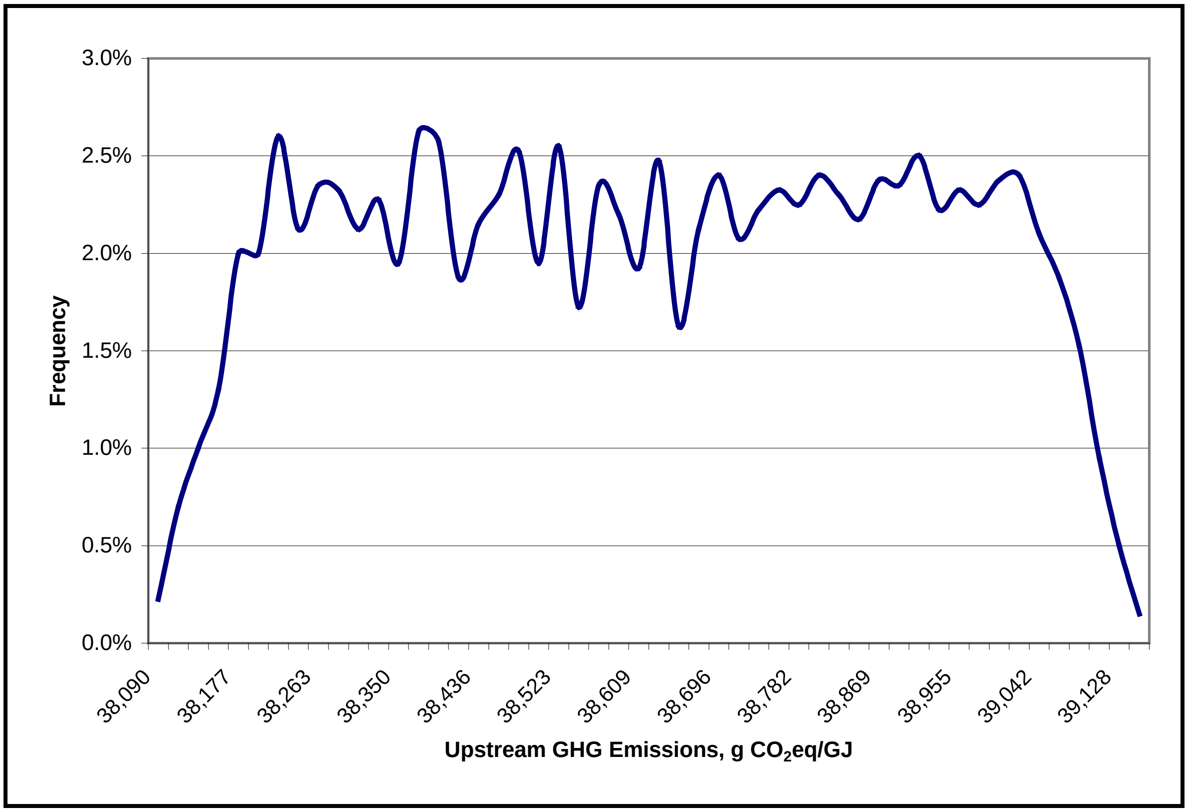
There are multiple variables that could influence the corn production related emissions. These include the yield, the fertilizer efficiency, and the energy requirements. When there are multiple variables at play, a Monte Carlo simulation can provide a better view of the uncertainty than just considering a single variable at a time. The inputs to the Monte Carlo simulation investigating the corn production input variables are summarized in the following table.

Table 5-3 Monte Carlo Simulation Variables

	Min/Mean	Max/ Std Dev	Type of Distribution
Corn Yield	11.4 tonne/ha	1.0	Normal
Nitrogen Use	17.1 kg/tonne	19.1	Uniform
Farming Energy	13.0 litres diesel/tonne	1.0	Normal
Phosphorus use	4.8 kg/tonne	6.0	Uniform
Potassium use	6.5 kg/tonne	8.0	Uniform

The distribution of the total upstream emissions for corn ethanol production from the Monte Carlo analysis is shown in the following figure. The range is relatively narrow (90% of the results are between 38,170 and 39,040 g CO_2eq/GJ of ethanol) and the distribution is obviously influenced by the variables with a uniform distribution. One of the factors influencing the narrow range is that the co-product credit also varies as the corn emissions vary and thus there is a tendency to offset changes in the emissions related to corn production with the credit for the Distillers Dried Grains.

Figure 5-3 Monte Carlo Results Lifecycle GHG Emissions vs. Corn Production Variables



5.4 Financial Implications

There can be financial issues that can accelerate or impede the rate of adoption of new technology. These are discussed below.

5.4.1 Operating Costs

If the innovation can be implemented with little or no incremental capital costs then many of those activities that reduce costs will also reduce GHG emissions. These innovations will be adopted the quickest. In many cases, the cost savings of a new product are shared between the supplier and the user. For example, seed developers may be able to increase the price of seed if the new, high cost seed also reduces the costs for the user. Similar situations can be found when new enzyme products have been introduced, prices are initially higher and then tend to decrease over time. While this is typical of the behaviour of competitive markets, it can influence the rate of adoption of new technologies and the rate at which GHG emissions can be reduced.

5.4.2 Capital Costs

Innovations that involve a capital expenditure typically take much longer to penetrate a market. This is particularly true in the case of individuals as opposed to corporations as individuals tend to have a much higher discount value applied to future cash flows and thus require very high rates of return. There is a potential role for governments to play in assisting with the capital requirements in return for a portion of the improved cash flow or an assignment of the GHG emissions benefits.

5.4.3 Value of GHG Emissions

There are few jurisdictions in the world that have implemented a true price on carbon emissions so the reduction in GHG emissions that has been achieved over time is being driven because of the accompanying reduction in operating costs and competitiveness. Pricing carbon emissions in the agricultural sector is more difficult because some of the emissions are not related to fuel combustion and taxes on fuel use are the easiest way to implement carbon pricing.

5.5 Conclusions

This work has shown that the GHG emissions related to producing ethanol from corn are not static and have shown continual improvement over time. This is one possible explanation for some of the differences reported in the literature for different LCA results for corn ethanol. The results found in this work are much more significant than just helping to explain why the results of past studies have varied. They show that the benefits of relatively immature technologies can change quite rapidly as the technologies develop and mature.

This reduction in emissions is due to the learning experience that is common to the development of many innovations. This learning experience can be expected to continue into the future as even more experience is gained with the technology. While the learning rate will be constant when measured on a logarithmic scale, it usually declines when measured against time. Nevertheless, the rapid expansion of the ethanol industry in the past few years will see the cumulative production in North America increase by a factor of four between 2005 and 2015.

This work shows that policy development based solely on historical data, without considering future developments, is a flawed approach and could lead to the rejection of some options that could eventually be very attractive options for GHG emission reductions. As governments around the world try to establish the GHG emissions benefits of various biofuels the use of methodologies such as default emission factors could lead to a significant underestimation of the benefits unless the factors are updated on a frequent basis. Furthermore, the default emission factors will only be relevant if the data used to calculate them can be verified as being from the same time period and that time period needs to be stated.

The biofuels industry will need to do a better job of benchmarking its performance than it traditionally has done if the GHG emissions benefits that it provides are to be credible. The industry will also need better visibility over the entire supply chain which will mean that biofuel producers will need much better visibility on feedstock supply than exists in many regions of the world.

While this analysis has focused on corn ethanol, it is likely that the same directional trend would be found for other feedstocks such as sugar cane, wheat, and sugar beet. All crops are likely benefiting from the improvements found in the agriculture sector, and some of the improvements in the ethanol production process (such as improved enzymes) are generic in nature and applicable to all feedstocks.

A similar analysis should be considered for biodiesel produced from rapeseed and soybeans to determine how those emissions may have changed over time and how they might be expected to change in the future.

Opportunities exist to direct technology development with appropriate policy instruments. The improvements seen to date in the biofuels industry have developed because they also reduce production costs as they reduce emissions. Governments should consider policy instruments that would accelerate the adoption of new technology in the biofuel sector so that greater GHG emissions benefits are achieved sooner than would otherwise be the case. In some cases, it may be possible to achieve GHG emission benefits for 1st generation biofuels that are similar to those that are expected from the 2nd generation processes at a lower cost and in a shorter time frame.

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