LIFE CYCLE ANALYSIS OF TRANSPORTATION FUEL PATHWAYS

Prepared For:

IEA Advanced Motor Fuels
Annex 40

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EXECUTIVE SUMMARY

With the 2007 announcement of California's Low Carbon Fuel Standard (LCFS), the first major fuel carbon intensity regulation in the world, life cycle analysis (LCA) shifted from being a tool used for research to one used for regulation. Shortly after, a number of other jurisdictions began to follow California's lead: the European Union's (E.U.) Renewable Energy and Fuel Quality Directives; British Columbia's LCFS; the revised U.S. Renewable Fuels Standard (RFS2); numerous north-eastern U.S. states planning an LCFS; and various other jurisdictions announcing carbon intensity based regulations of some sort.

Since these initial regulations were announced, the role of LCA in both policy and regulation has increased dramatically. Despite this, LCA is still far from being widely understood, even among those who are affected by these developments. Further compounding what is already a complex subject is the fact that LCA does not follow a standardized procedure. Though an ISO standard exists for LCA (under ISO 14000 Environmental Management Standards), it only provides general guidelines, so different models and methodologies are used in different jurisdictions to perform the analyses which form the foundations of these regulations.

The International Energy Agency Implementing Agreement on Advanced Motor Fuels (IEA-AMF) has recently discussed the need to further its involvement in life cycle analysis (LCA) of various technological options for transportation fuels and technologies. The IEA-AMF believes it can play a role in integrating and disseminating fact based information on LCA as it relates to various transportation technology pathways. Members of the AMF have been exposed to some examples of the results of assessments of GHG emissions from LCA models in the past. However, while LCA modeling could be a useful tool for AMF members, its limitations and strengths need to be properly understood and explained.

The purpose of this work is to improve the understanding of the concept of life cycle analysis of transportation fuels and some of its pertinent issues among non-technical people, senior managers, and policy makers. This work should provide some guidance to nations considering LCA-based policies and to people who are affected by existing policies or those being developed.

As there are numerous potential analysis tools and methodologies available to evaluate the environmental performance of products over their life cycle, there have been a lot of difficulties associated with assessing results from different studies on the life cycle performance of transportation fuels. Each different modeling tool tends to give different results, even when the same fuel is modelled. This causes much confusion for policy makers, trade officials, and even scientists involved in the modelling. Naturally, the question of which result is correct is often raised. The question that should be asked, however, is not which result is correct, but instead "why are the results different?". It is possible that a number of models modelling the same fuel in different countries can give

different results and all still be correct based on the data available. This project has focused on putting LCA modelling into context, while highlighting the importance of understanding modelling methods, using a three-tiered approach:

1. Provide a general overview of Life Cycle Analysis principles (ISO methodologies, multiple approaches, etc.).
2. Characterize Transportation Fuels LCA specific sensitivities (such as scope and system boundaries, data sources, geo-physical differences, etc.).
3. Where appropriate and feasible put sensitivities into context using specific examples.

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 analyses:

- 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, 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.

LCA has been applied in evaluating the relative environmental performance of alternative transportation fuels including various hydrogen production options for use in fuel cell vehicles, the use of electricity in vehicles, and alternative biofuel options, with the primary aim of informing industry, government, Environmental Non-governmental Organizations (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.

When LCA is used to make environmental claims disclosed to the public about the performance of a product or service system as compared to alternatives (a "comparative assertion"), the ISO 14044 standard requires that a more rigorous process be followed in preparing the LCA. Some additional requirements for "comparative assertions" include:

- **Data Quality** - A high quality of data must be used in a LCA for comparative assertions. This includes addressing the following data elements:
    - time-related coverage (comparable time effects: duration, diurnal, seasonal, etc.);
    - geographical coverage (comparable geography: weather, terrain, systems, etc.);
    - technology coverage (comparable technical effects: product life cycle systems);
    - data precision (e.g. number of decimal places);
    - completeness (similar product system "reach", scope of life cycle stages);
    - data representativeness (does modeled data truly reflect actual performance?); and
    - methodology consistency and reproducibility (standard measurement tests, etc.).

- **Peer Review** - The LCA must be peer reviewed by an expert panel in accordance with the "critical review process" as outlined in ISO 14040. A review by a single internal expert or external expert is not permitted for a "comparative assertion".

- **Impact Assessment** - An impact assessment is required that uses category indicators that are sufficiently comprehensive, internationally accepted, scientifically and technically valid, and environmentally relevant. Weighting must not be used.

- **Comparable Systems** - The LCA comparison must be performed on systems using the same functional unit and equivalent methodological considerations, such as performance, system boundaries, data quality, allocation procedures, decision rules on evaluating inputs and outputs, and impact assessment. Any differences between systems regarding these parameters must be identified.

This list of requirements for a rigorous LCA provides insight into the primary drivers of why different studies can arrive at different results. The primary drivers include:

1. The data relates to different time periods. All systems change over time, either due to technological learning, or changing environmental

conditions. Data from two different time periods, while being correct in both cases, can be different.

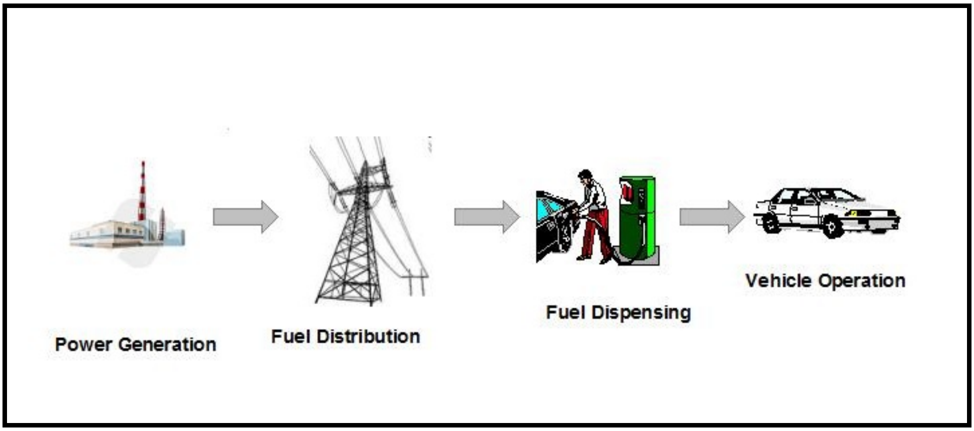
2. The same activity can be performed differently into two different regions. This can be due to different technologies being employed or different environmental conditions. Again, two different data sets can have significant differences while both being correct.
3. It can sometimes be difficult to obtain the data required to undertake an LCA. The required information may not be in the public domain, or it may be secondary data (information that has been published by a party different from the party that collected the data). This data may have been processed (averaged, units changed, etc.) and some of the original conditions pertaining to the data are no longer reported. Sometimes secondary data is collected from two sources (e.g., one reporting total emissions and another reporting production) in order to develop emission factors (emissions per unit of production). Issues can arise if the two sources have different boundaries.
4. Data might not always be truly representative of normal conditions. It might just represent the performance when a production system is operating and exclude the emissions during start-up and/or shut down. Alternatively it could include a period that had unusual production problems. This additional' clarifying information is not always presented with the data.
5. Finally, there are some cases where different methodologies are used. For example, the allocation of emissions to the multiple products that can be produced in the same system can have a significant impact on the results.

These issues are investigated for the transportation fuel systems that have been analyzed and their impacts are highlighted for each of the studied systems.

Electric Vehicles

The findings on electric vehicles were presented first because in many respects they are the simplest to understand and relate to. It is generally understood that electricity is generated by different means, some of which are "cleaner" than others. In a system where all of the emissions are found in the fuel production stage (power generation), the performance is entirely dependent on how that power is produced. The total system is relatively simple as shown below.

Figure ES- 1 Electric Vehicle System Boundaries



The following figure shows that there is a very large variation in how power production is practiced from country to country and even from region to region in a single country. This variation in how power is generated is the single most important issue in the electric vehicle life cycle. In general, other issues such as system boundaries, temporal issues, and EV performance, while important, all have less impact on the life cycle results[1].

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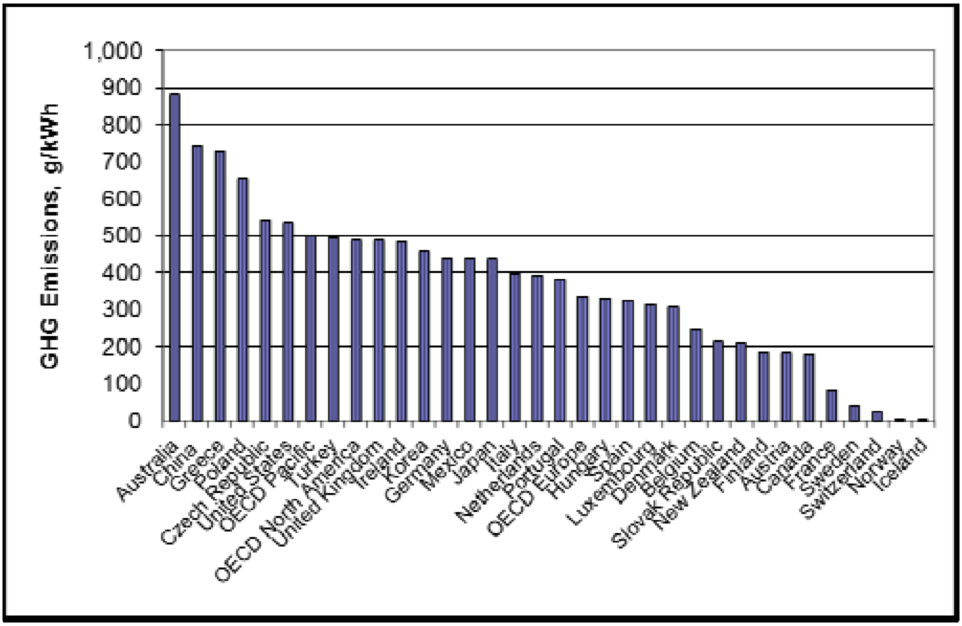
[1] There can be important issues in system boundaries for electricity generation, e.g. the influence of methane emissions from flooding large forested areas for hydroelectric dams, or the direct and indirect land use emissions of biomass harvested for electricity generation.

Figure ES- 2 Regional Carbon Intensity of Power Production

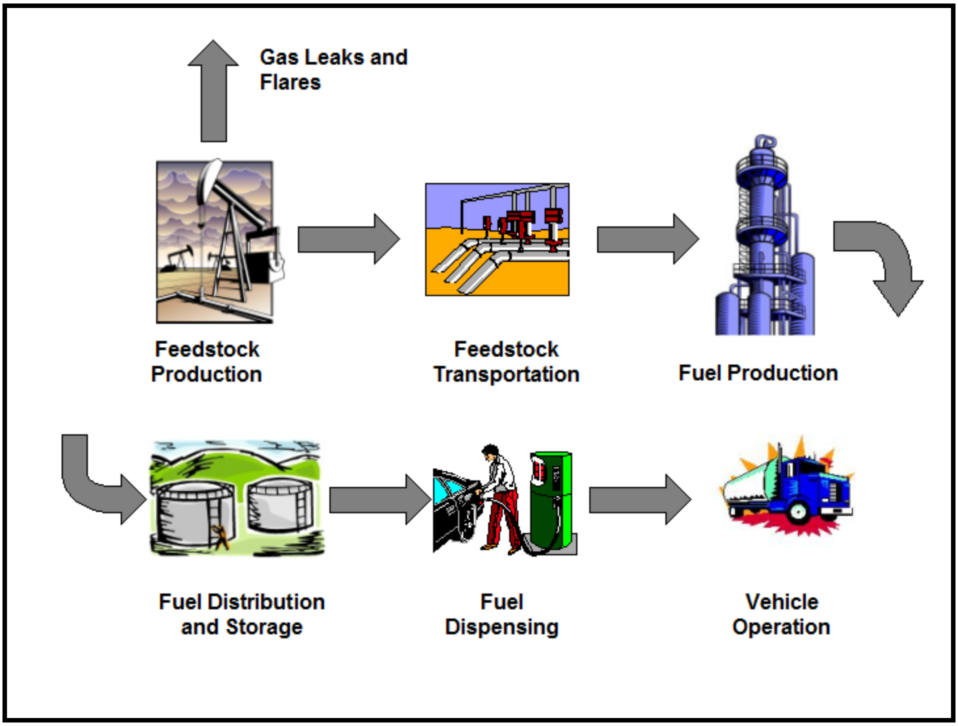


The implication of this finding goes beyond the analysis of electric vehicles, as electricity is an important input parameter for almost every other fuel and vehicle system. One should therefore expect to get different results for the same production pathway when it is practised in different regions just from the difference in the carbon intensity of the electric power. Of course, the carbon intensity of other inputs could also vary by region, either reinforcing the variation in electric power or countering the effect.

Petroleum Fuels

The petroleum fuels, gasoline and diesel fuel, are the dominant transportation fuels in the world today. Many of the regulations that are looking at reducing the carbon intensity of the transportation sector are focussed on these two fuels, yet many of the models described in the previous section only focus on biofuels and other alternatives and do not have pathways for the reference fuels. These two fuels are also important for the alternative fuels since they are the reference fuels that all others are measured against. The system for fossil fuels is shown in the following figure. It is more complex than the electric power system.

Figure ES- 3 Life Cycle Stages for Fossil Fuels



Even though fossil fuels have been used in the transportation sector for over one hundred years, there are significant uncertainties with respect to the system boundaries of many analyses, the data quality and completeness, and the way that the emissions are allocated between the products produced by refineries. The key conclusions from this review are:

1. Not all analyses include the emissions associated with exploration and drilling for oil.
2. The quality of data on the emissions associated with oil production is poor and may underestimate GHG emissions.
3. These emissions appear to be increasing with time and models that do not account for this will underestimate emissions.
4. There are significant regional differences in the emissions associated with crude oil production.
5. Refining emissions should be easier to estimate but even the primary data for energy use has some uncertainty associated with it due to the difficulty in measuring the quantities of refinery fuel gas and coke burned. Different data sources can report different results, even for the same process and country.

6. The allocation of refining emissions to specific products is a complex issue and there may not be a single correct approach.
7. Refining emissions can vary with the quality of the crude oil processed and systems that analyze the emissions of crude oil production and refining independently will not produce accurate results.
8. The specifications of the final product can influence life cycle emissions.

Natural Gas

Like electricity, natural gas can be considered a vehicle fuel as well as a major input into other production systems. It is therefore an important pathway in LCA modelling systems. Natural gas production is widely distributed throughout the world, even more so than crude oil production.

Natural gas is an important transportation fuel in many parts of the world. It has an inherent advantage over other hydrocarbon fuels in that it produces less CO_2 per unit of fuel energy than all other hydrocarbons. There can be significant differences in natural gas production and utilization pathways in different parts of the world, so that differences in reported emissions between studies may be a function of real system differences rather than differences in LCA methodology.

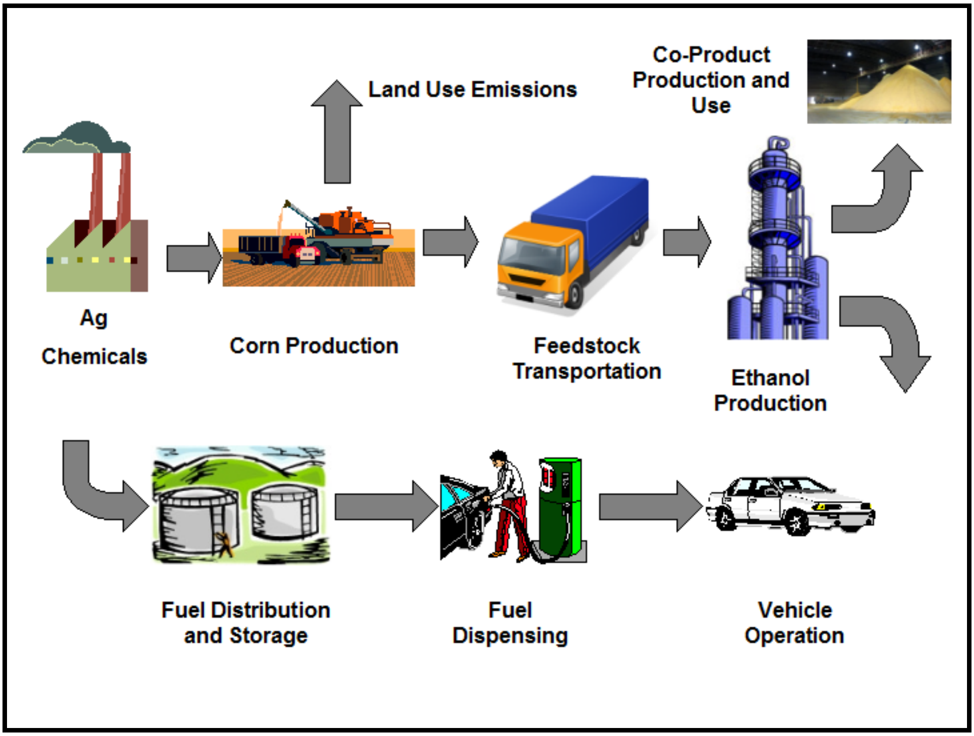
There is, however, potential for significant differences in LCA methodology:

1. Not all analyses include the emissions associated with exploration and drilling for natural gas.
2. The quality of data on emissions associated with gas production is poor, particularly with respect to leaks, and may underestimate the GHG emissions.
3. There can be significant regional differences in the emissions associated with gas production.
4. Different LCA practitioners may use different GWPs or different time horizons.
5. The energy requirements for gas compression are very dependent on local conditions and this can influence the life cycle results.
6. The conversion of gas energy to work in the vehicle is a function of engine design and this can vary widely.

Ethanol

Ethanol is the largest volume biofuel used in the transportation sector today. It is made primarily from corn (maize) and sugar cane. A number of other feedstocks are used including sugar beets, wheat, rye, barley, cassava and other starch bearing crops. A large number of process developers are working on developing technologies that could produce ethanol from lignocellulosic materials rather than from sugar or starch crops. The basic corn to ethanol life cycle is shown in the following figure. The life cycle for other cereals to ethanol is similar.

Figure ES- 4 Corn Ethanol Life Cycle



The ethanol life cycle is one of the most studied fuel life cycles and one with the largest variation in results. There are a number of reasons for this variation, some are modelling related, but others represent actual differences in the production systems.

There are two new stages in the figure above compared to the fuel systems discussed previously, fertilizer manufacture and land use emissions. Both of these stages contribute to the large variation in results for biofuel LCAs.

A large number of factors have been identified that can cause variation in the calculated life cycle emissions for the production of ethanol. It is generally accepted that the emissions will be different for different feedstocks but the impact of other regional, temporal, allocation, and process issues are less well understood and accepted. The key findings from this review are:

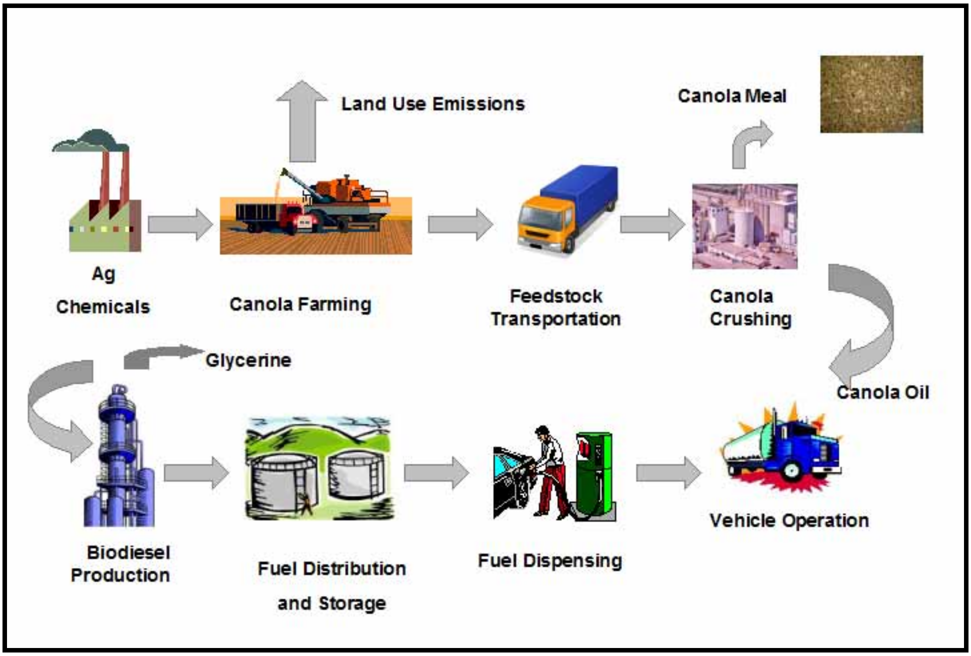
1. For important inputs like nitrogen fertilizer, there can be large variations in GHG emissions by type of nitrogen fertilizer and, for a given type, there are regional differences in plant efficiencies.

2. There are a wide range of emission factors used to determine N_2O emissions from the application of nitrogen fertilizers. Some variation is expected due to climate and soil conditions, but there are also variations in the methodologies used by various governments to develop their National GHG Inventories.
3. Biomass feedstock practices are changing rapidly, resulting in increased yields and reduced fertilizer requirements for most feedstocks.
4. There is significant variation in the yields achieved for the same feedstock in one region to another, even just considering the top producing regions of the world.
5. In some regions soil carbon is increasing as a result of changing management practices and not all models and studies account for this emission sink. In others, soil carbon is decreasing due to changing land management and is an emission source.
6. Ethanol plant technology has improved considerably over the past several decades; high quality, current data are required to accurately assess the emissions from these plants.
7. The method used to allocate feedstock and plant emissions can have a significant impact on the reported emission results. Not all models or studies consider the ISO guidelines for undertaking LCA work.
8. The carbon intensity of the electric power consumed by ethanol plants, and the process fuel used, have a large impact on the life cycle results. These can be expected to vary from one region to another.

Biodiesel

Biodiesel is the second largest volume biofuel currently being used in the world today. The largest producers and markets are found in Europe. There are many different feedstocks that can be used to make biodiesel but the three largest ones are soybeans, rapeseed/canola, and palm. The basic biodiesel life cycle is shown in the following figure, in which canola is used as an example.

Figure ES- 5 Canola Biodiesel Life Cycle



Biodiesel LCAs have all of the same issues with respect to agricultural inputs and land use emissions as do ethanol systems.

A large number of factors have been identified that can cause variation in the calculated life cycle emissions for the production of biodiesel. It is generally accepted that emissions will be different for different feedstocks, but the impact of other regional, temporal, allocation, and process issues are less well understood and accepted. Many of the issues are the same as those identified for ethanol. The key findings from this review are:

1. For important inputs like nitrogen fertilizer, there can be large variations in GHG emissions by type of nitrogen fertilizer and, for a given type, there are regional differences in plant efficiencies.
2. There are a wide range of emission factors used to determine N_2O emissions from the application of nitrogen fertilizers. Some variation is expected due to climate and soil conditions but there are also variations in the methodologies used by various governments to develop their National GHG Inventories.
3. Biomass feedstock practices are changing rapidly, with increased yields and reduced fertilizer requirements being significant for most feedstocks.

4. There is significant variation in the yields achieved for the same feedstock from one region to another, even just considering the top producing regions of the world.
5. In some regions soil carbon is increasing as a result of changing management practices and not all models and studies account for this emission sink. In others, soil carbon is decreasing due to changing land management and is an emission source.
6. The method used to allocate feedstock and plant emissions can have a significant impact on the reported emission results. Not all models or studies consider the ISO guidelines for undertaking LCA work.
7. When allocation by mass or energy is used, it is still important to include emission impacts arising from the use of co-products. Many studies do not consider this.

Indirect Effects

In the past several years the issue of the indirect impacts of expanded biofuel production has received considerable attention by the policy and academic communities. A significant number of modelling projects have been undertaken to try to quantify the land use change impacts and the resulting GHG emissions from the changes.

There are significant issues with the quality of modelling efforts, a fact acknowledged by many of the modellers. Some of the major uncertainties are:

1. Determining an accurate inventory of cropland throughout the world. Most models don't include cropland that is temporarily idle in their calculations.
2. Determining which kind of land is converted is a problem for many models. Most do not include the cost of land conversion and thus overestimate the conversion of forest land to cropland.
3. Most models have difficulty dealing with co-products. They try to determine the effect of co-products on land requirements just through the price of the products, since the models are not capable of doing this based on the functional value of the co-products (i.e. their protein or energy contents).
4. There are indirect impacts for biofuels that are not calculated in many of the models. Some of these could reduce the ILUC impact.
5. There are indirect effects of other fuels. Some estimates for fossil fuels have been in the same range as some of the biofuel estimates.

In the following table the main issues for the analyses of the different pathways have been ranked on a scale of 1-5, with 1 being not significant and 5 being very significant. A low ranking in the table does not imply that the GHG emissions implications for the pathway are insignificant, but that there is less difficulty in determining the issues such as system boundaries of electricity production for example. The issue of indirect effects are excluded from the rankings.

Table ES- 1 Comparison of Issues in Various Fuel Systems

	System Boundaries	Data Temporal Issues	Regional Practices	Data Availability	Representative Data	Methodology
Electricity	1	1	5	2	2	2
Crude Oil Production	3	5	5	4	4	2
Gasoline and Diesel Fuel Refining	1	3	3	3	3	4
Natural Gas	3	3	3	4	4	4
Biofuel Feedstock Production	2	4	5	4	4	4
Ethanol Production	1	4	3	3	3	5
Biodiesel Production	1	4	3	3	4	5

It is apparent from the table that different fuel pathways have different sensitivities to the important issues. The simpler pathways, such as electricity, are driven by one important issue, i.e. the type of electricity production system in that specific region. Other pathways, like biofuels, can have a number of important issues that influence the results.

Advice to Policy Makers

While the concept of employing LCA to evaluate fuel options is simple and straightforward, the act of putting the concept into practice is complex and fraught with issues.

Policy makers need to understand the limitations inherent in carrying out LCA work for transportation fuel systems. For many systems, even those that have been employed for a 100 years, there is a lack of sound data on the performance of those systems.

Comparisons between systems should ideally be made using the same tool, so that differences caused by system boundaries, allocation processes, and temporal issues can be minimized (although probably not eliminated). Comparing the results for fuel pathway 1 from tool A to those of fuel system 2 from tool B introduces significant uncertainty into the results. There is also the question of the scale of system changes. LCA will give more reliable estimates when it is used to examine small changes in transportation fuel pathways than when used to estimate large scale changes that replace current pathways with completely new pathways.

Some LCA tools have been developed recently primarily for regulatory purposes. These tools may deviate from ISO principles in order to facilitate simplicity and ease of use. In a regulatory environment, simplicity and ease of use are worthy objectives and in most cases there is nothing inherently wrong with this approach, particularly for assessing relative performance. However, the results of these tools should not be confused with, or compared to, the results that are obtained from a more complex and rigorous ISO compliant LCA.

It should be reiterated that an LCA will not determine which product is the most cost effective or works best. No LCA can identify optima in the manner of, say, a linear program. This would still be true even if all inputs were specified with complete accuracy and precision because no result would yield a simultaneous optimum for all outputs.

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1. INTRODUCTION

With the 2007 announcement of California's Low Carbon Fuel Standard (LCFS), the first major fuel carbon intensity regulation in the world, life cycle analysis (LCA) shifted from being a tool used for research to one used for regulation. Shortly after, a number of other jurisdictions began to follow California's lead: the European Union's (E.U.) Renewable Energy and Fuel Quality Directives; British Columbia's LCFS; the revised U.S. Renewable Fuels Standard (RFS2); numerous north-eastern U.S. states planning an LCFS; and various other jurisdictions announcing carbon intensity based regulations, either as a qualifying criteria or as a means to reduce carbon intensity.

Since these initial regulations were announced, the role of LCA in both policy and regulation has increased dramatically. Despite this, LCA is still far from being widely understood, even among those who are affected by these developments. Further compounding what is already a complex subject is the fact that LCA does not follow a standardized procedure. Though an ISO standard exists for LCA (under ISO 14000 Environmental Management Standards), it only provides general guidelines; so different models and methodologies are used in different jurisdictions to perform the analyses which form the foundations of these regulations.

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

The International Energy Agency Implementing Agreement on Advanced Motor Fuels (IEA-AMF) has recently discussed the need to further its involvement in life cycle analysis (LCA) of various technological options for transportation fuels and technologies. The IEA-AMF believes it can play a role in integrating and disseminating fact based information on LCA as it relates to various transportation technology pathways. As the AMF works encompasses all alternative fuels as well as advanced petroleum-based fuels, and focuses on the entire spectrum of fuels from feedstock, through fuel processing, distribution, and, finally, end use in vehicles, it is at the centre of the work of many other IEA Implementing Agreements (IAs). For example, although the Bioenergy Implementing Agreement looks at the production pathways for biofuels, AMF will look into issues associated with the distribution and end use of those fuels. Additionally, although the bulk of the work often is related to on-road transportation, AMF deals with all modes of transport, including Marine, Rail, Air and other off-road applications. As such, members of the AMF have been exposed to some examples of the results of assessments of GHG emissions from LCA models in the past. However, while LCA modeling could be a useful tool for AMF members, its limitations and strengths need to be properly understood and explained. This project is intended to provide, as far as possible in non-technical language, a better understanding of LCA models and their appropriate uses.

1.1 STRUCTURE OF THE REPORT

The purpose of this work is to improve the understanding of the concept of life cycle analysis of transportation fuels and some of its pertinent issues among non-technical people, senior managers, and policy makers. This work should provide some guidance to nations considering LCA-based policies and to people who are affected by existing or in-development policies.

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1. Provide a general overview of Life Cycle Analysis principles (ISO methodologies, multiple approaches, etc.).
2. Characterize Transportation Fuels LCA specific sensitivities (such as scope and system boundaries, data sources, geo-physical differences, etc.).
3. Where appropriate and feasible put sensitivities into context using specific examples.

Chapter 2 of the report provides some background information on Life Cycle Analysis with a description of some of the International Standards Organization’s standards and principles. A short overview of the current uses of LCA is provided.

Chapter 3 provides additional information on LCAs including the limitations of LCAs, and issues with the data that is used in the inventory analysis stage of an LCA.

Chapter 4 provides a listing and short description of some of the LCA models that are used today for the analysis of transportation fuels and some information on some of the important LCA databases.

Chapter 5 to 9 deal with the issues related to the LCA of specific transportation fuels. Chapters are provided for electricity, the fossil fuels gasoline and diesel fuel, natural gas, ethanol and biodiesel.

Chapter 10 addresses indirect emissions in general and indirect land use change in particular.

Chapter 11 includes short sections on the use of LCA in specific countries that contributed to this work.

Chapter 12 summarizes some final findings and conclusions

2. LIFE CYCLE ANALYSIS

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.

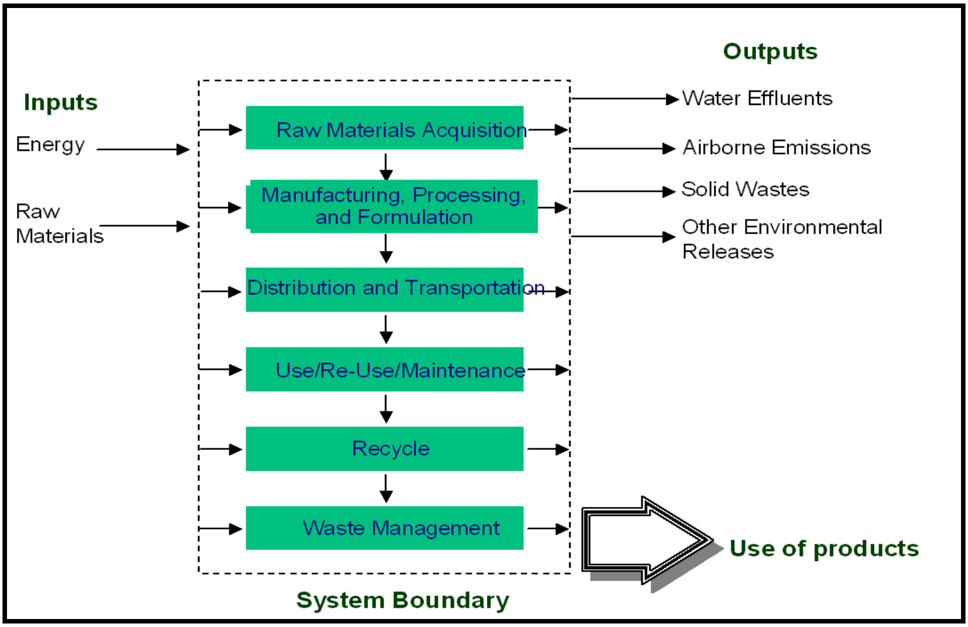
Life cycle assessment is a "cradle-to-grave" (or “well to wheels”) approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages 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:

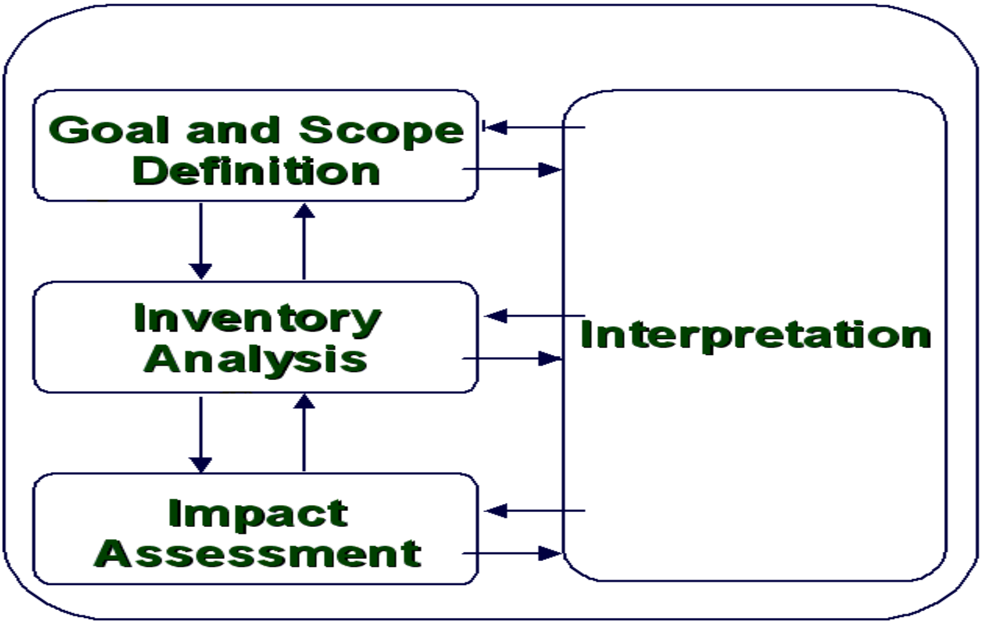
Goal Definition and Scoping - Define and describe the product, process or activity. Establish the context in which the assessment is to be made, and identify the boundaries and environmental effects to be reviewed for the assessment.

1. *Inventory Analysis* - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, wastewater discharge).

2. *Impact Assessment* - Assess the human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

3. *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



Life cycle assessment can be one part of a sustainability assessment but sustainability assessments generally also consider social and economic considerations. Life cycle analyses are generally quantitative, producing numerical results that can be compared between systems. Sustainability assessment can have some quantitative aspects but often are also qualitative in nature. Both have roles to play in policy development and in regulatory schemes, although the use of sustainability assessment tools in regulatory schemes is still mostly voluntary. There are concerns about the legality of some aspects of sustainability assessments under international trade rules.

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.

2.1.1 ISO 14040

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

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

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

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

2.1.2 ISO 14067 Carbon Footprint

This ISO standard is under development at the committee stage with a draft document that has received one round of comments. This standard will focus on the unique requirements of doing an LCA with a specific focus of GHG emissions.

The draft acknowledges that climate change arising from anthropogenic activity has been identified as one of the greatest challenges facing countries, governments, business and human beings with major implications for both human and natural systems. In response, international, regional, national and local initiatives are being developed and implemented to limit greenhouse gas (GHG) concentrations in the Earth’s atmosphere. Such GHG initiatives rely on the assessment, monitoring, reporting and verification of GHG emissions and/or removals.

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

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

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

2.1.3 ISO 13065 Bioenergy Sustainability

Increase in the production and use of bioenergy has a potential role in reducing greenhouse gas emissions, promoting energy security and fostering economic growth. This ISO standard is designed to achieve those objectives in a sustainable way.

Different types of biomass are used for the production of bioenergy in a significant number of countries and by a variety of economic operations of different sizes. Virtually every country in the world produces and consumes some form of bioenergy. The characteristics therefore are very heterogeneous, and the production processes depend on several aspects, such as geographic location, climatic conditions, level of development, and technological issues. The purpose of this standard is to provide a flexible, practical framework for considering the environmental, social, and economic aspects of bioenergy that could be used for the production, supply chain, and application of bioenergy.

This standard will provide a harmonized approach on sustainability criteria rather than providing threshold values. It takes into account the work of other relevant ISO standards, published and under development. As part of the development of this standard an inventory was carried out of other sustainability initiatives. This standard aims to promote the sustainable production and use of bioenergy while facilitating trade.

The target date for the establishment of this standard is 2015.

2.2 ISO Principles

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

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

2.2.1 Life Cycle Perspective

LCA considers the entire life cycle stages of a product or service, including: extraction and acquisition of all relevant raw materials, energy inputs and outputs, material production and manufacturing, use or delivery, end-of-life treatment, and disposal or recovery. This systematic overview of the product “system” provides perspective on the potential differences in environmental burden between life cycle stages or individual processes.

2.2.2 Environmental Focus

The primary focus of a LCA is on the environmental aspects and impacts of a product system. Environmental aspects are elements of an activity, product, or service that cause or can cause an environmental impact through interaction with the environment. Some examples of environmental aspects are: air emissions, water consumption, releases to water, land contamination, and use of natural resources. Economic and social aspects are typically outside the scope of an LCA, although it is possible to model some of these elements. Other tools may be combined with LCA for more extensive analysis.

2.2.3 Relative Approach and Functional Unit

LCA is a relative analytical approach, which is structured on the basis of a functional unit of product or service. The functional unit defines what is being studied and the life cycle inventory (LCI) is developed relative to one functional unit. An example of a functional unit is a light-duty gasoline vehicle driving an average kilometre (with other details of time, geography, trip characteristics, and potential fuels added). All subsequent analyses are then developed relative to that functional unit since all inputs and outputs in the LCI and, consequently, the LCA profile, are related to the functional unit.

An LCA does not attempt to develop an absolute inventory of environmental aspects (e.g. air emissions inventory) integrated over an organizational unit, such as a nation, region, sector, or technology group.

2.2.4 Iterative Approach

LCA is an iterative analytical approach. The individual phases of an LCA (Goal and Scope Definition; Inventory Analysis; Impact Assessment; and Interpretation) are all influenced by, and use the results from, the other phases. The iterative approach within and between phases contributes to a more comprehensive analysis and higher quality results.

2.2.5 Transparency

The value of an LCA depends on the degree of transparency provided in the analysis (for example: the system description, data sources, assumptions and key decisions). The principle of transparency allows users to understand the inherent uncertainty in the analysis and properly interpret the results.

2.2.6 Comprehensiveness

A well-designed LCA considers all stages of the product system (the “reach”) and all attributes or aspects of the natural environment, human health, and resources. Tradeoffs between alternative product system stages and between environmental aspects in different media (soil, air, and water) can be identified and assessed.

2.2.7 Priority of Scientific Approach

It is preferable to make decisions from an LCA analysis based on technical or science reasoning, rather than from social or economic sciences. Where scientific approaches cannot be established, consensual international agreement (e.g. international conventions) can be used. The power of the technical or scientific approach lies in the proper attribution of facts to sources and the potential reproducibility of these facts under scientific conditions. While the scientific approach is typically more objective than economic or social values, it does not preclude the use of economic or social values for informing LCA decisions.

2.3 OVERVIEW OF CURRENT USES OF LIFE CYCLE ASSESSMENT IN THE TRANSPORTATION SECTOR

To date LCA has been applied in evaluating the relative environmental performance of alternative transportation fuel options, with the primary aim of informing industry, government, Environmental Non-governmental Organizations (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 been varied but on average over the last decade, study quality has improved due to improved method development, data availability and higher client expectations.

Some examples of the use 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, their environmental discharges, or to turn a waste product into a revenue stream. 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 or in establishing eligibility of fuels in meeting regulated volume targets or GHG performance levels.
- 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 potentially increase the use of high level blends of ethanol/gasoline (E85)).

2.3.1 Role of LCA in Public Policies/Regulations

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

In recent years this solution appears to be changing. 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 more numerous initiatives that are focused on biofuels. One of the most prominent initiatives is California’s Low Carbon Fuel Standard (LCFS), which will cover 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 here. On January 18, 2007, the State of California, through Executive Order S-1-07, announced the intent to regulate a reduction of at 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, and it will be fully in effect by 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). Beginning in April 2008, the RTFO places an obligation on fuel suppliers to ensure that a certain percentage of their aggregate sales are made up of biofuels. The effect of this is to require 5% of all UK fuel to come from a renewable source by 2010. The RTFO, like the LCFS, had reporting requirements and methodologies for calculating life cycle GHG emissions but in addition includes social and environmental sustainability aspects, although the 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). The RTFO is in the process of being changed so that it is fully compliant and aligned with the EI Renewable Energy Directive.

The application of life cycle analyses in a regulatory framework is not without its challenges. The work underway in the EU, the UK, Germany, and the Netherlands to develop LCA criteria for regulatory purposes differs significantly from more scientific LCA work. Good regulations are generally simple regulations, so regulatory LCA work has been moving away from some of the principles of ISO LCA work in order to simplify the process. These systems are adopting default values that are deliberately conservative for many of the data inputs so that biofuel producers do not have to invest in tracking and documenting the inputs through the life cycle if they choose not to. In other cases, some of these systems are developing co-product allocation systems that are simple and are designed to try to ensure that there are no opportunities for making poor decisions that would provide good results for one particular indicator (GHG emissions) at the expense of another indicator (for example, land use). While they serve regulators' needs, these allocation schemes are not necessarily considered the most sound from an ISO perspective.

These simplified regulatory LCA frameworks, while providing the advantage of being simple and possibly less expensive to utilize, will not produce the same results as well done, more scientific LCAs. This will undoubtedly create some confusion for all stakeholders but more importantly may result in missed opportunities to implement some attractive environmental solutions.

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 the development and application of a robust LCA framework for biofuels and the successful implementation of the policy.

2.3.2 Application of LCA to Product Comparisons

LCA can be an effective tool within organizations to improve environmental management or to guide research activities because of its requirements for comprehensiveness and the iterative approach. However, when LCA is used to make environmental claims disclosed to the public about the performance of a product or service system as compared to alternatives (a "comparative assertion"), the ISO 14044 standard requires that a more rigorous process be followed in preparing the LCA. Some additional requirements for "comparative assertions" include:

- **Data Quality** - A high quality of data must be used in a LCA for comparative assertions. This includes addressing the following data elements:
    - time-related coverage (comparable time effects: duration, diurnal, seasonal, etc.);
    - geographical coverage (comparable geography: weather, terrain, systems, etc.);

- technology coverage (comparable technical effects: product life cycle systems);
- data precision (e.g. number of decimal places);
- completeness (similar product system "reach", scope of life cycle stages);
- data representativeness (does modeled data truly reflect actual performance?); and
- methodology consistency and reproducibility (standard measurement tests, etc.).

- **Peer Review** - The LCA must be peer reviewed by an expert panel in accordance with the "critical review process" as outlined in ISO 14040. A review by a single internal expert or external expert is not permitted for a "comparative assertion".

- **Impact Assessment** - An impact assessment is required that uses category indicators that are sufficiently comprehensive, internationally accepted, scientifically and technically valid, and environmentally relevant. Weighting must not be used.

- **Comparable Systems** - The LCA comparison must be performed on systems using the same functional unit and equivalent methodological considerations, such as performance, system boundaries, data quality, allocation procedures, decision rules on evaluating inputs and outputs, and impact assessment. Any differences between systems regarding these parameters must be identified.

2.3.3 Attributional vs. Consequential LCA

There are many different types of Life Cycle Assessments that can be utilized to determine the emissions output for any given product. These different types of LCAs can produce dramatically different results that are largely dependent on the defined system boundaries within the selected LCA mode. Two of these LCAs that can, and often will, produce very different results are the Attributional and Consequential LCAs.

Attributional LCA (ALCA) provides the user with information about the impacts of the production, consumption, and disposal of a product, without considering any indirect emissions that may occur, whereas a Consequential LCA (CLCA) models the causal relationships that originate from a decision to change the level of output and are highly dependent upon economic models that represent the relationship between demand, supply, price elasticity, and market effects of co-products. ALCA is useful for consumption based carbon accounting because it provides information on the average unit of a product. CLCA models the consequences of a change in output by considering effects both inside and outside of the life cycle of the product. The table below outlines key differences between these two systems. (Brander et. al, 2009)

Table 2-1 Comparison of Attributional and Consequential LCAs

	Attributional LCA	Consequential LCA
Question the method aims to answer	What are the total emissions from the processes and the material flows directly used in the life cycle of a product?	What is the change in total emissions as a result of a marginal change in the production (and consumption and disposal) of a product?
Application	ALCA is applicable for understanding the emissions directly associated with the life cycle of a product. ALCA is also appropriate for consumption-based emissions accounting. ALCA is not an appropriate approach for quantifying the change in total emissions resulting from policies that change the output of certain products.	CLCA is applicable for informing consumers and policy-makers on the change in total emissions from a purchasing or policy decision. CLCA is not appropriate for consumption-based emissions accounting.
System boundary	The processes and material flows directly used in the production, consumption and disposal of the product. The vehicle may be an important consideration for some fuels.	All processes and material flows, which are directly or indirectly affected by a marginal change in the output of a product (e.g. through market effects, substitution, use of constrained resources etc).
Marginal or average data	ALCA tends to use average data, e.g. the average carbon intensity of the electricity grid. Though, some models offer a choice.	CLCA tends to use marginal data e.g. the marginal carbon intensity of the electricity grid.
Market effects	ALCA does not consider the market effects of the production and consumption of the product.	CLCA considers the market effects of the production and consumption of the product.
Allocation methods	ALCA allocates emissions and process energy inputs to co-products based on either economic value, energy content, co-product energy displacement, or mass.	CLCA uses system expansion to quantify the effect of co-products on emissions.
Time-scales, means by which change is	ALCA aims to quantify the emissions attributable to a product at a given level of	CLCA aims to quantify the change in emissions, which result from a change in

promoted, and magnitude of the change	production at a given time.	production. It is necessary to specify the time-scale of the change, the means by which the change is promoted, and the magnitude of the change.
Uncertainty	ALCA has low uncertainty because the relationships between inputs and outputs are generally stoichiometric.	CLCA is nearly always highly uncertain because it relies on models that seek to represent complex socio-economic systems that include feedback loops and random elements.

2.3.3.1 Attributional LCA Approaches

From the literature there appear to be two primary means of determining the emissions that are embedded in energy production facilities: a *process-chain analysis* (PCA) and an *input/output analysis* (IOA). The PCA calculates the energy embedded in and the emission-equivalents caused by the production of materials used in the application. The IOA works with economic sectors related to the manufacturing activities. The PCA approach requires some knowledge of the materials included in the facility whereas the IOA only requires an understanding of the costs of construction and the economic structure of the country or region where the construction is occurring. Both approaches should yield similar results and they are discussed briefly in the following sections.

2.3.3.1.1 Process Chain Analysis

The PCA looks at the *materials* (steel, concrete, plastics, etc.) and converts them, considering all underlying production steps, into the corresponding amount of energy used and GHGs emitted. Shortcomings of the PCA are that the method is intrinsically incomplete (some processes cannot be expressed in an amount of material and are therefore likely to be overlooked) and that all products, made from the same basic material, are dealt with in the same way. Materials produced in different countries may also have different energy and materials flows making it sometimes difficult to extrapolate results between regions.

PCA basis is an inventory analysis using bottom-up data collection. It investigates the flow of materials and energy in each production process. Each material or energy that forms the main process is traced back through its initial extraction. It evaluates the embedded energy and the embedded emissions caused by the material production. PCA considers all individual emission points of GHG, and therefore requires careful analysis of all flow of energy and materials associated with its links of production processes. Hence, emission factors of all energy types and all materials required by all the process steps must be available. Data collection can be very time consuming and complex.

2.3.3.1.2 Input Output Analysis

The IOA divides a product into its *economic components*. Each input, which contributes to the creation of the final product, is ascribed to an economic sector (machinery, electrical, services, etc). For each sector, an average product is calculated, which is characterized by an amount of energy needed and an amount of GHG emitted. The advantage of the IOA is that each input can easily be expressed in an economic value. The main shortcoming of the IOA is that all products are identified as an average product of the covering sector. A sector, however, contains many products for which the ratio price/energy-input is not necessarily the same (e.g. the price difference between a luxury vehicle and a sub-compact is much greater than the relative difference in energy requirement, but both products belong to the same sector, 'vehicles'). Another shortcoming is that the number of sectors may be limited.

The IOA also requires the relevant relationship between the economic value of the sector and the energy and emissions attributed to the sector. These are not always available. New industrial processes for which there is no historical data are difficult to assess with the input/output analysis.

2.3.3.2 Consequential LCAs

The practice of consequential LCA has gained prominence over the past decade. The topic of indirect land use from biofuels is one that can only be addressed through consequential LCA. Since economic modelling is at the core of a consequential analysis, most of the developing CLCA models are built upon existing macro economic models that are modified to consider physical changes or environmental impacts. Interestingly Brander et al suggest that CLCA models should not be used for consumption based carbon accounting as CLCA is less well defined than ALCA, and therefore allows a much greater degree of interpretation which can be used to support different viewpoints, but that is exactly how they are being used in Low Carbon Fuel Standards.

2.3.4 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, in other cases, are due to differences in method interpretation, assumptions and data issues.

Key issues in biofuel 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 gaps include the implications of land use change, nitrous oxide (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 a major impact on the 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.

2.3.5 Conclusions on LCA Application

The following conclusions about the ISO LCA standards have been drawn by Dr. James Fava, founder of the LCA Advisory Group of the Society of Environmental Toxicology and Chemistry (SETAC) and head of the U.S. delegation in the development of the ISO LCA standards.[2]

- The ISO LCA standards establish a worldwide set of rules to ensure that LCA studies are performed in a consistent, reproducible fashion. The standards provide a holistic way of thinking about product systems, a framework for analysis, and define the factors to consider in setting the goals and scope of the assessment, performing the inventory analysis, conducting an impact assessment, and how to interpret and communicate results.
- The ISO peer review and criteria review process provides a system of checks and balances to ensure that LCA studies used for public policy and decision-making undergo additional review by independent and interested parties.
- Practitioners should be able to demonstrate their knowledge of the requirements of the ISO LCA standards and that they have applied these requirements.

[2] Adapted from Fava, J., Can ISO Life Cycle Assessment Standards Provide Credibility for LCA? Building Design & Construction, Nov. 2005, www.bdcnetwork.com

- There is a learning curve in completing LCAs. A company's first LCA study (either done internally or using external consultants) often takes more time and resources than expected. Subsequent studies usually become easier to complete.
- Within the ISO LCA standards, there is sufficient flexibility to ensure that LCA studies can be completed on a number of applications, ranging from answers to questions on a select list of impact categories and/or life cycle stages, to comprehensive studies supporting environmental claims.
- Any LCA methodology used in the public context must have transparency, be publicly available, and must have undergone appropriate peer review.
- The application of LCA internally within an organization to drive continuous improvement and innovation can achieve meaningful results but it must be consistently applied.

LCA studies can provide information on environmental tradeoffs and opportunities to improve a product's performance over its life cycle. However, complementary assessments, in particular those related to site-specific environmental issues, are often necessary to provide a fuller understanding of absolute risks and opportunities.

2.4 IEA LCA ACTIVITIES

IEA Bioenergy – the International Energy Agency's Implementing Agreement on Bioenergy - has had tasks looking at Greenhouse Gas Balances of Bioenergy Systems since the mid 1990s. The current task, Task 38 (http://www.ieabioenergy-task38.org/), analyses and integrates information on bioenergy, land use, and greenhouse gas (GHG) mitigation; thereby covering all components that constitute a biomass or bioenergy system, i.e. from biomass production to bioenergy conversion and end use. The ultimate goal is to aid policy and industry decision makers in selecting mitigation strategies that optimize GHG benefits while being practical and cost effective.

Ten countries participate in the task, including a number who also participate in the AMF agreement. The Task has been led by Austria for many years. The Task organizes workshops, published papers and reports, has developed a methodology and software tool (BIOMITRE), and maintains an online bibliography of relevant reports and documents from outside of the Task.

The methodology instructions developed by Task 38 are summarized below:

> *Before initiating the GHG analysis/LCA process, **three main principles** must be followed to ensure that the study is accurate and meaningful. **First**, if a difference is to be measured, then two measurements are needed; the 'new' and the 'old'. For example both biodiesel and regular fossil diesel must be measured in order to note the different energy and GHG balances between them. **Secondly**, all the measurements must be*

made using standard methods. For example, the method and approach used to identify CO_2 emissions from the production cycles of biodiesel and regular fossil diesel should be the same, to allow comparison. ***Thirdly****, all the calculations, and any assumptions, must be transparent, so the reader can see clearly what has been considered and how.*

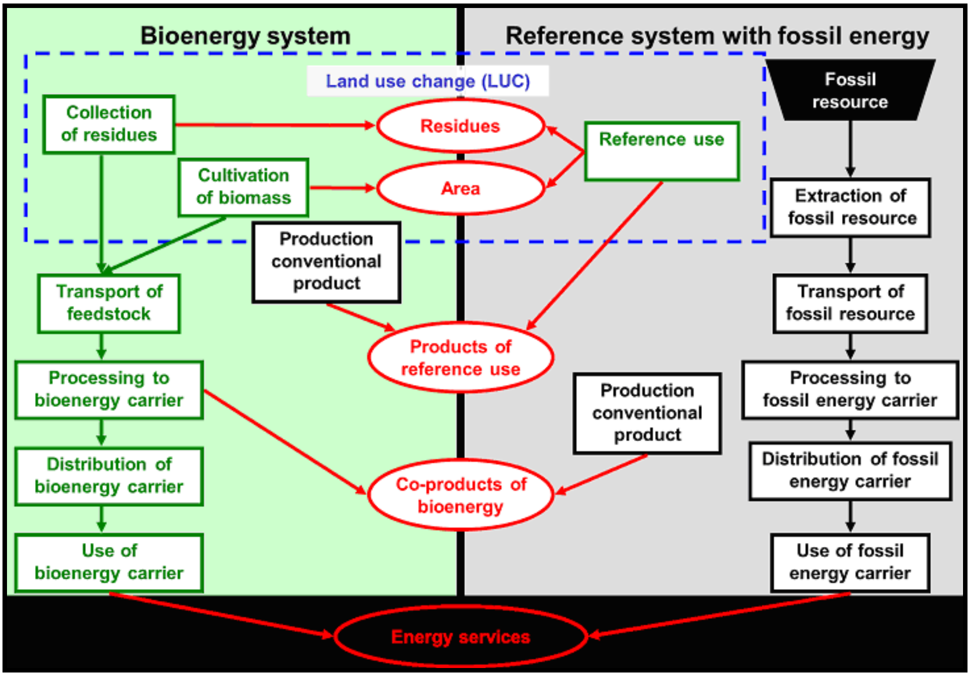
The LCA methodological approach can be adapted to examine key comparable issues, such as fossil fuel depletion and contribution to global climate change. Energy and Greenhouse Gas Accounting is undertaken using these adapted LCA practices.

The Task notes that Energy and Greenhouse Gas Analysis requires:

- *Goal and Scope definition; establishing "functional unit"*
- *Defining primary energy; quantifying relevant inputs and outputs*
- *Defining GHG emissions*
- *Drawing the System Boundary*
- *Defining the Reference System; avoided or displaced activities*
- *Allocation Process; allocate primary energy/GHG implications between main products, co-products, and by-products.*

In this Task a standard methodology for the life cycle based comparison of the greenhouse gas emissions of bioenergy systems to fossil energy system was developed. The methodology includes the time dynamic of the carbon cycle by using biomass for bioenergy. The relevant processes in the system boundaries are shown in the following figure.

Figure 2-3 IEA Task 38 System Boundaries



This methodology and requirements are completely aligned with the ISO 14040 principles and requirements.

On the issue of data for input into LCA studies of bioenergy systems Task 38 states:

> *When conducting GHG modeling, it is important to study and assemble key data required for the study. This exercise enables the user to become conversant with the key parameters and familiar with the basic LCA aspects of the particular project. This effort also provides an opportunity to define the system boundaries and level of data needed.*
>
> *There has been a great paucity of literature and relevant contacts or directory type of information on data for renewable energy use such as bioenergy systems. GHG modeling studies require energy and GHG emission data. Collating this data can prove difficult, therefore the IEA Task 38 and BIOMITRE seek to provide GHG bioenergy researchers at least a few key links to various databases.*

The task also publishes international case studies on bioenergy systems. Recent studies published include an assessment of wood pellets produced in Canada, the greenhouse gas benefits of a biogas plant in Austria, and GHG benefits of using municipal solid waste as a fuel in a thermal treatment plant in Ireland.

One earlier case study looked at the LCA emissions of biodiesel but most of the case studies published by the Task are for non-transportation bioenergy systems.

In 2008, the Task organized a workshop in Austria on “Transportation biofuels: For greenhouse gas mitigation, energy security or other reasons?” .

> *Transportation, including emissions from the production of transport fuels, is responsible for roughly one quarter of global GHG emissions. The use of biofuels in Europe and other places in the world in this sector are rapidly increasing due to policies, such as the EU liquid biofuels directive etc. One of the reasons for these policies is the attempt to meet the GHG targets in the Kyoto Protocol, another one is energy security. Biofuels may also offer social and economic benefits like employment and income generation, support for rural development and traditional industries, reduced regional trade balance, and many others.*
>
> *The debate about the sustainability of biofuels is complex and wide ranging. The impact of biomass on land use and land-use change is questioned. Examples include the spreading of oil-palm plantations in SE Asia, at the cost of natural forest ecosystems. Potential impacts on soil and water are also an issue. Other impacts of increased biofuel production include increased agricultural commodity prices (soybean price increases observed recently, maize prices in Mexico) and conflicts with the use of the same raw materials for other uses (e.g. paper industry, wood products)*
>
> *The workshop included information on*
>
> - *Trends and policies of transport biofuels*
> - *Different types of transportation biofuels (first and second generation)*
> - *The calculation of GHG on basis of a life cycle assessment with special regard to land use change issues and impact on soils*
> - *Other local environmental and social impacts, including energy security*
> - *Possible conflicts between different use of biomass resources*
> - *Concept of sustainable biofuels*
>
> *And provided a forum for government, policy and academic representatives to exchange information on current knowledge of these topics.*

At this workshop there were four presentations on LCA and greenhouse gas emissions. There were:

1. Integration of land use into LCA.
2. Measuring Carbon Neutrality

3. Fertilizer Use – N_2O
4. Biofuels for climate change mitigation and energy security.

Other presentations dealt with technology of producing transportation fuels from biomass and policy issues.

3. LCA SENSITIVITIES

An LCA will help decision-makers select the product or process that results in the least impact to the environment. This information can be used with other factors, such as cost and performance data, to select a product or process. The ability to track and document shifts in environmental impacts can help decision makers and managers fully characterize the environmental trade-offs associated with product or process alternatives. By performing an LCA, researchers can:

- Develop a systematic evaluation of the environmental consequences associated with a given product.
- Analyze the environmental trade-offs associated with one or more specific products/processes to help gain stakeholder (state, community, etc.) acceptance for a planned action.
- Quantify environmental releases to air, water, and land in relation to each life cycle stage and/or major contributing process.
- Assist in identifying significant shifts in environmental impacts between life cycle stages and environmental media.
- Assess the human and ecological effects of material consumption and environmental releases to the local community, region, and world.
- Compare the health and ecological impacts between two or more rival products/processes or identify the impacts of a specific product or process.
- Identify impacts to one or more specific environmental areas of concern.

There are a number of issues that must be considered when undertaking an LCA or when reviewing LCA reports. Understanding these issues is critical to understanding the reasons that LCA reports reach different findings.

3.1 LIMITATIONS OF CONDUCTING AN LCA

Performing an LCA can be resource and time intensive. Depending upon how thorough an LCA the users wish to conduct, gathering the data can be problematic, and the availability of data can greatly impact the accuracy of the final results. Therefore, it is important to weigh the availability of data, the time necessary to conduct the study, and the financial resources required against the projected benefits of the LCA.

LCA will not determine which product or process is the most cost effective or works best. Therefore, the information developed in an LCA study should be used as one component of a more comprehensive decision process assessing the trade-offs with cost and performance.

3.2 GOAL DEFINITION AND SCOPE

There are four important elements when undertaking the goal definition and scope stage of an LCA. These four elements are discussed below and they can have a significant impact on the outcome of the final product.

3.2.1 Functional Unit

A system may have a number of possible functions and the one(s) selected for a study depend(s) on the goal and scope of the LCA. The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis.

Most transportation fuel systems use a unit of energy or a distance travelled as the function unit. Distance travelled relates directly to the service obtained by the consumer in using the fuel, and it includes any efficiencies or inefficiencies that the vehicle or propulsion system introduces into the system. Notwithstanding the benefits of distance travelled as the functional unit some regulatory schemes (EPA RFS and CARB LCFS) have used a unit of energy as the function unit and sometimes modifying that with a vehicle efficiency factor.

Some biofuel LCA analyses will use an area of land or a mass of biomass as the functional unit. While comparisons between biomass systems can be accomplished with these functional units, a comparison to a fossil fuel system is not very meaningful.

3.2.2 Reference System

Having chosen the functional unit, the reference system must be defined. The 14040 standard states that comparisons between systems shall be made on the basis of the same function(s), quantified by the same functional unit(s) in the form of their reference flows. This can be a significant issue in complex systems such as an oil refinery, where the crude oil is processed into multiple products. Is it possible to include all of the functions of all of the products? If additional functions of any of the systems are not taken into account in the comparison of functional units, then these omissions shall be explained and documented.

As an alternative, systems associated with the delivery of an additional function may be added to the boundary of the other system to make the systems more comparable. In these cases, the processes selected shall be explained and documented.

3.2.3 System Boundaries

The system boundary determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study. The criteria used in establishing the system boundary shall be identified and explained.

Decisions shall be made regarding which unit processes to include in the study and the level of detail to which these unit processes shall be studied. The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study. Any decisions to omit life cycle stages, processes, inputs or outputs shall be clearly stated, and the reasons and implications for their omission shall be explained.

Decisions shall also be made regarding, which inputs and outputs shall be included and the level of detail of the LCA shall be clearly stated. When setting the system boundary, several life cycle stages, unit processes and flows should be taken into consideration, for example, the following:

- acquisition of raw materials;
- inputs and outputs in the main manufacturing/processing sequence;
- distribution/transportation;
- production and use of fuels, electricity and heat;
- use and maintenance of products;
- disposal of process wastes and products;
- recovery of used products (including reuse, recycling and energy recovery);
- manufacture of ancillary materials;
- manufacture, maintenance and decommissioning of capital equipment;
- additional operations, such as lighting and heating.

A common issue with many biofuel systems is that the use of the co-products is not included in the system boundary. This can introduce a significant variance in the results, particularly if the co-product is also replacing a product made from fossil fuels.

3.2.4 Multiple Products

Perhaps the issue that causes the most variation between LCA studies of the same product is found in systems that make multiple products and use different approaches to allocating emissions between the products. The guidance from the ISO 14040 series of standards is that:

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

a) Step 1: Wherever possible, allocation should be avoided by

1) dividing the unit process to be allocated into two or more sub-processes and collecting the Input and output data related to these sub-processes, or

2) expanding the product system to include the additional functions related to the co-products, taking into account the requirements of the system boundary.

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

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

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

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

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

With multiple options being available, it is not surprising that different LCA practitioners use different approaches. There is also not a universal agreement that the hierarchy outline in 14040 is appropriate. Wang et. al. (2010) argue that

> *"the displacement method[3] can generate distorted LCA results if the co-products are actually main products (for the cases of biodiesel and renewable diesel from soybeans). It is far from settled whether use of a given method should be uniformly and automatically recommended for LCA studies. We suggest that a generally agreed-upon method should be applied for a given fuel production pathway. Consistency in choice of co-product method may not serve the purpose of providing reliable LCA results. On this note, the transparency of LCA method(s) selected is important in given LCA studies and sensitive cases with multiple co-product methods may be warranted in LCA studies where co-products can significantly impact study outcomes."*

While being able to compare two studies of the same fuel and being able to eliminate any difference caused by allocation methods is useful, it is difficult to see how comparison between fuels can be made if each fuel analysis uses a different co-product allocation method.

3.3 LCA INVENTORY ANALYSIS

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system.

[3] The displacement or substitution method provides a credit for co-products based on the emissions avoided by not producing the product by an alternative production method.

The process of conducting an inventory analysis is iterative. As data is collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. Sometimes, issues may be identified that require revisions to the goal or scope of the study.

Data collection can be a resource-intensive process. Practical constraints on data collection are often considered in the scope and documented in the study report.

The calculation of energy flows must also take into account the different fuels and electricity sources used, the efficiency of conversion and distribution of energy flow, as well as the inputs and outputs associated with the generation and use of that energy flow.

3.3.1 Temporal Issues

The world is continually changing and thus any dataset that is use in LCA work is associated with a time period. The challenge for LCA practitioners is that systems all evolve at different rates and thus datasets from one period may not produce the same relative impacts in a different time period.

An even larger issue is comparing systems that have datasets from two different time periods. The temporal issues related to data sets used should be clearly identified in the LCA reports, but this is often not the case.

3.3.2 Regional Issues

There are significant regional differences in many of the important inputs into fuel system LCAs. One of the most obvious is that the carbon intensity of electric power production varies from country to country and from region to region in large countries.

There are many more examples that have an impact. Nitrogen fertilizer production emissions can vary depending on the type of fertilizer produced (nitrate vs. ammonium) and within each class by the technology employed. The following table shows the N_2O emission factors for different types of nitric acid[4] plants (US EPA, 2010).

[4] Nitric acid is a feedstock for nitrate fertilizers

Table 3-1 N_2O Emission Factors

		N_2O Emissions (kg N_2O/ metric ton Nitric Acid)		
	Pressure (atm)	Low	Average	High
Plants with NSCR		1.9	2	2.1
Plants with process-integrated or tailgas N_2O destruction		2.25	2.5	2.75
Atmospheric pressure (low pressure)	1	4.5	5	5.5
Medium pressure plants	4-8	5.6	7	8.4
High Pressure plants	8-14	5.4	9	12.6

There is a range of an order of magnitude between the highest and lowest emission plants. Different technologies are often employed in different regions and thus technology differences can manifest themselves as regional differences.

3.3.3 Primary vs. Secondary Data

The data used in an LCA strongly influences the results that the study will produce. However, many of the processes that are found in various fuel system LCAs do have the important information about the inputs and outputs monitored on an appropriate basis, and thus LCA practitioners must rely on other sources of data.

Primary data is a quantified value of a unit process or an activity within the product system obtained from a direct measurement or a calculation based on direct measurements at its original source. In practice, primary data may be emission factors and/or activity data.

Secondary data is the quantified value of a unit process or an activity within the product system obtained from sources other than direct measurement at its original source. Such sources can include databases, published literature, national inventories, and other generic sources.

Primary data is obviously preferred as it is most relevant to the product or process being studied. However, it is rarely available for all phases of the life cycle and some secondary data sources may be necessary.

There are potential issues involved with the use of secondary data, including its appropriateness for the region and timeframe in which the study is performed. There can also be interpretation issues with secondary data sources. Where energy is presented in heat units, is the data on a higher or lower heating value basis? Sometimes data may be presented in terms of primary energy (including all of the energy required to produce the energy, while at other times it is shown as secondary energy (based on quantities purchased, for example).

3.3.4 Overall Data Quality

An LCA study should use data that reduces bias and uncertainty as far as practicable by using the best quality data achievable.

ISO 14067 states that secondary data shall only be used for inputs where the collection of primary data is not possible or practicable, and may include literature data, calculated data, estimates or other representative data. Secondary data should be verified.

According to ISO 14044, the data quality requirements should address the following:

a) time-related coverage: age of data and the minimum length of time over which data should be collected;

b) geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study;

c) technology coverage: specific technology or technology mix;

d) precision: measure of the variability of the data values for each data expressed (e.g. variance);

e) completeness: percentage of flow that is measured or estimated;

f) representativeness: qualitative assessment of the degree to which the data set reflects the true population of interest (i.e. geographical coverage, time period and technology coverage);

g) consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;

h) reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study;

i) sources of the data;

j) uncertainty of the information (e.g. data, models and assumptions).

The qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundary. The collected data, whether measured, calculated or estimated, is utilized to quantify the inputs and outputs of a unit process.

When data has been collected from public sources, the source should be referenced. For the data that may be significant for the conclusions of the study, details about the relevant data collection process, the time when data has been collected, and further information about data quality indicators should be referenced in the report. If such data does not meet the data quality requirements, this shall be stated.

Since data collection may span several reporting locations and published references, measures should be taken to reach uniform and consistent understanding of the product systems to be modelled.

3.4 Impact Assessment

Life cycle analysis can be applied to a number of different environmental indicators, such as climate change, ozone forming potential, water use, eutrophication, toxicity and many others. Some of these environmental issues are global in nature, and thus ideally suited to LCA, whereas other issues may be more regional and while LCA can still be used, it is also important to understand the geographical distribution of the emissions. This report is focussed on transportation fuels and the most pressing issue with respect to these fuels and their use is their impact on climate change. Transportation fuels are also emitters of criteria air contaminants (NOx, VOC, SOx, PM, etc) but these challenges have traditionally been addressed through regulation of tailpipe emissions and not through LCA work. Most LCA models will address these CAC emissions as well as the GHG emissions.

The United Nations International Panel on Climate Change (IPCC) establishes global warming potentials (GWP) as a measure of how much each gas contributes to climate change. The GWP is based on a number of factors, including the radiative efficiency (heat-absorbing ability) of each gas relative to that of carbon dioxide, as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of carbon dioxide.

The used of GWPs allow the contribution of individual gases to be combined into a single parameter, CO_2eq.

Many governments require that the 1995 IPCC GWPs be used for reporting purposes, as these were the values used in the Kyoto Protocol. The IPCC has twice revised these values in the 2001 and 2007 assessment reports. The 100 year GWPs from the three different IPCC reports are shown in the following table.

Table 3-2 IPCC 100 Year GWPs

	IPCC 1995	IPCC 2001	IPCC 2007
Carbon Dioxide	1	1	1
Methane	21	23	25
Nitrous oxide	310	296	298
HFC 134a	1,300	1,300	1,430
SF_6	23,900	22,200	22,800

There are other gases and contaminants that are known to directly impact the climate and have GWPs such as PM, SOx, NOx, and black carbon. Some have positive GWPs and some (e.g. SOx) have negative values. The IPCC has not yet reached consensus on the GWP values for these materials, but that might change in the future.

Compounding the confusion over the correct GWPs is the fact that recently some reports have looked at the 20 year GWPs instead of the 100 GWPs. Methane is a much more potent gas when the time period is shorter, as shown in the following table.

Table 3-3 Comparison of 20 and 100 Year GWPs

	IPCC 2007	IPCC 2007
	100 Year	20 Year
Carbon Dioxide	1	1
Methane	25	72
Nitrous oxide	298	289
HFC 134a	1,430	3,830
SF_6	22,800	16,300

In the following table the impact of using the different 100-year IPCC values is shown for the life cycle emissions of gasoline as calculated by the GHGenius model. The differences between the IPCC values are relatively minor for gasoline with the increase due to methane offsetting the reductions due to N_2O.

Table 3-4 Impact of the IPCC GWPs on Gasoline Emissions – 2011

	IPCC 1995	IPCC 2001	IPCC 2007
	g CO_2 eq/km		
Vehicle operation	211.1	211.1	211.1
C in end-use fuel from CO_2 in air	0.0	0.0	0.0
Net Vehicle Operation	211.1	211.1	211.1
Fuel dispensing	0.4	0.4	0.4
Fuel storage and distribution	1.5	1.5	1.5
Fuel production	33.1	33.1	33.3
Feedstock transport	2.5	2.5	2.6
Feedstock recovery	16.1	16.1	16.2
Feedstock Upgrading	7.3	7.3	7.4
Land-use changes, cultivation	0.4	0.4	0.4
Fertilizer manufacture	0.0	0.0	0.0
Gas leaks and flares	6.2	6.2	7.1
CO_2, H_2S removed from NG	0.0	0.0	0.0
Emissions displaced by co-products	-0.2	-0.2	-0.2
Sub total (fuelcycle)	278.5	278.5	279.6

Fuel pathways with high levels of methane could see an increase in GHG emissions, whereas pathways with significant N_2O emissions (such as some biomass pathways) could see a reduction in GHG emissions with the latest IPCC GWPs. The impact on the emissions for light duty natural gas vehicles is shown in the following table.

Table 3-5 Impact of the IPCC GWPs on Natural Gas Emissions – 2011

	IPCC 1995	IPCC 2001	IPCC 2007
	g CO_2 eq/km		
Vehicle operation	181.8	182.9	183.6
C in end-use fuel from CO_2 in air	0.0	0.0	0.0
Net Vehicle Operation	181.8	182.9	183.6
Fuel dispensing	3.7	3.7	3.7
Fuel storage and distribution	4.5	4.6	4.6
Fuel production	4.6	4.7	4.7
Feedstock transport	0.0	0.0	0.0
Feedstock recovery	6.0	6.1	6.2
Feedstock Upgrading	0.0	0.0	0.0
Land-use changes, cultivation	0.0	0.0	0.0
Fertilizer manufacture	0.0	0.0	0.0
Gas leaks and flares	8.1	9.0	9.6
CO_2, H_2S removed from NG	3.0	3.0	3.0
Emissions displaced by co-products	0.0	0.0	0.0
Sub total (fuelcycle)	211.8	214.0	215.4

4. LCA MODELS AND DATABASES

There are many LCA models that have been developed around the world in the past several decades. The US EPA lists about 30 models on their website[5] and warns that the list is not complete. Many of the models have a specific focus, such as building products, or materials, other models are more versatile and can analyze a variety products and services.

4.1 MODEL OVERVIEW

A number of models that can be used to analyze transportation fuels are briefly documented here. These models were identified by Literature and Internet searches and could potentially provide a life cycle analysis (LCA) for transportation fuels. The following list, in alphabetical order, is not exhaustive and there are other models that have been or could be used for analyzing transportation fuels. Proprietary, customized models were not included in the analysis.

4.1.1 BEES

The BEES (Building for Environmental and Economic Sustainability) software was developed by the US National Institute for Standards and Technology (NIST) Building and Fire Research Laboratory. It was designed to help select cost-effective, environmentally-preferable building products. BEES measures the environmental performance of building products by using the life cycle assessment approach specified in the ISO 14040 series of standards.

In support of the US 2002 Farm Security and Rural Investment Act (P.L. 107-171), BEES was adapted for application to bio-based products (called BEES Please for USDA). The BEES Environmental Performance Score combines product performance across all 12 environmental impacts into a single score. These impacts are: 1. global warming; 2. acidification; 3. eutrophication; 4. fossil fuel depletion; 5. indoor air quality; 6. habitat alteration; 7. water intake; 8. criteria air pollutants; 9. human health; 10. smog; 11. ozone depletion; and 12. ecological toxicity. The lower the score, the better the product's overall environmental performance.

Give the adaptation to address biobased products, BEES Please for USDA may be suitable for conducting a life cycle assessment of biofuels. It has been used to analyze the impacts of the production and use of methyl esters (biodiesel) as cleaning products.

BEES is available as an online tool (http://ws680.nist.gov/Bees/Default.aspx).

[5] http://www.epa.gov/nrmrl/lcaccess/resources.html#disclaimer

4.1.2 BESS

BESS is the Biofuel Energy Systems Simulator developed at the University of Nebraska - Lincoln. The BESS model is a software tool to calculate the energy efficiency, greenhouse gas emissions, and natural resource requirements of corn–to-ethanol biofuel production systems. The non-commercial version of BESS can be downloaded over the Internet for free.[6,]

The BESS model has four components: (1) crop production; (2) ethanol biorefinery; (3) cattle feedlot; and (4) anaerobic digestion (optional).[7] The model does not include emissions from fuel distribution or use. The model includes ethanol production from corn. The developers suggest that the model will be extended to cover ethanol from corn stover and switchgrass for cellulosic ethanol in the future.

The model provides outputs in terms of:

- energy use;
- greenhouse gas emissions - CO_2, CH_4, and N_2O, as well as global warming potential based on those three greenhouse gases; and
- environmental requirements - land, grain, water, and petroleum.

The model is populated with U.S. (average) data, and a regional analysis based on north-eastern U.S. coal or natural gas inputs can be conducted.

4.1.3 BioGrace

BioGrace (www.biograce.net) deals with the harmonisation of greenhouse gas (GHG) emission calculations of biofuels throughout the European Union. The tool is designed to allow economic operators to make and verify their own biofuel GHG calculations. BioGrace is a project funded within the Intelligent Energy Europe Programme.

The project BioGrace supports the implementation of the EU Renewable Energy Directive (2009/28/EC) and the EU Fuel Quality Directive (2009/30/EC) into national laws. The project has published a uniform and transparent list of standard conversion values for GHG calculations, and developed an Excel file that users can use to duplicate the EU JRC determinations of the GHG performance of the 22 most important biofuel production pathways cited in both directives.

Currently user-friendly greenhouse gas calculators are being developed in Germany, the Netherlands, Spain, and the United Kingdom – in close co-operation with the project BioGrace. Once these calculators are finalised, economic operators may insert their individual input values into a template and the greenhouse gas emissions of their biofuel pathway are calculated immediately. The BioGrace template is adjusted to local production

[6] http://www.bess.unl.edu/download/
[7] University of Nebraska Lincoln (2007), BESS Biofuel Energy Systems Simulator Users Guide.

characteristics. However, users cannot add new kinds of input values or influence the calculation formula (as they can do in the BioGrace excel calculation tool). BioGrace aims to harmonize these calculators to use the same standard values and produce the same results.

There are no fossil fuel reference fuel pathways in BioGrace, although there are single value emission co-efficients for diesel fuel, natural gas, and coal in the model. There is currently no value for gasoline.

4.1.4 BIOMITRE

Biomass based Climate Change Mitigation through Renewable Energy is a software tool for analyzing the GHG balances and cost-effectiveness of various biomass energy technologies. It is financed jointly by the Directorate General for Energy and Transport, and IEA Bioenergy Task 38. BIOMITRE is an Excel tool and, along with the GHG balance calculation and cost-effectiveness calculation, BIOMITRE produces a flow chart specification, which summarises the main features of the biomass technology under consideration.

The current release of BIOMITRE is available through the IEA Bioenergy Task 38 website[8].

There are 3 major components to the software tool. These are:

- the flow chart specification, which summarises the main features of the biomass technology under consideration,
- the greenhouse gas balance calculation, which determines the total greenhouse gas (CO_2, CH_4, N_2O)emissions associated with the biomass technology,
- the cost-effectiveness saving calculation, which establishes the net costs of saving a given amount of greenhouse gas emissions by implementing the biomass technology.

BIOMITRE has been used mostly for the analysis of non-transportation bioenergy systems.

4.1.5 CMLCA

CMLCA is an abbreviation of Chain Management by Life Cycle Assessment (http://www.cmlca.eu/). It is a software tool that is intended to support the technical steps of the life cycle assessment procedure (LCA).

The model was prepared at Leiden University, the Netherlands. The latest version (Version 5.1) was published in June 2010. The source website reports seven reasons for using CMLCA:

1. CMLCA is free.

[8] http://www.ieabioenergy-task38.org/softwaretools/biomitre_softwaretool_download.htm

2. CMLCA is extremely flexible. Most software for LCA has a pre-cooked allocation, impact assessment, etc. In CMLCA, you can control (almost) everything.
3. CMLCA is perfect for use in classroom. Most software for LCA is designed for use by consultants. That means that ease of use has been more important than correctness and transparency.
4. CMLCA is perfect for use by scientists. It comprises the most extensive set of options for doing life cycle interpretation.
5. CMLCA is compatible with the framework and terminology of ISO 14040.
6. CMLCA does not require an administrator for installation, and can be transferred over the internet, for instance for download by your students.
7. CMLCA is extremely advanced in including IO-based and hybrid LCA, LCC and eco-efficiency analysis.

The developers also have seven reasons for not using CMLCA:

1. CMLCA has no helpdesk.
2. CMLCA contains no process data. You still have to buy or download these.
3. CMLCA contains no impact assessment data. You still have to incorporate GWPs and related characterization factors.
4. CMLCA is not so good for consultants. A consultant wants an easy and quick answer, and doesn't like having to choose from too many options.
5. CMLCA has no graphical interface for constructing flow diagrams.
6. CMLCA is only available in English.
7. CMLCA is only available for Windows.

The developers claim that CMLCA is probably the only software for LCA that has been developed entirely at a university. It has been designed with university students, PhD students and academic staff as the primary audience, whereas most LCA programs have a prime focus on consultants.

The model does not have the built-in capabilities addressing transportation fuel life cycles, but rather relies on custom builds.

4.1.6 EIO-LCA

The Economic Input Output-Life Cycle Assessment models were developed by the Carnegie-Mellon Green Design Institute. There are a dozen models using 1997 and 2002 economic data for different regions of the United States and some international locations (Canada, Germany, and Spain).

The EIO-LCA models allow for the estimation of some environmental impacts from producing a certain dollar amount of any of 500 commodities or services in the region. It provides guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the region. The impacts are from production only. Impacts from use, waste disposal, etc. are not included.

The model provides estimates of economic activity, conventional air pollutants (SO_2, CO, NO_x, VOCs, Lead, and PM_{10}), greenhouse gases (CO_2, CH_4, N_2O, CFCs), energy, toxic releases, and employment. Data can be graphed and mapped.

These models follow a significantly different methodology than most LCA models where the inputs are economic rather than physical parameters. These models have advantages for large projects, such as plant construction, but they do not have the detail required for transportation fuel applications.

4.1.7 GaBi

GaBi was developed by the German company PE Europe GmbH and IKP at the University of Stuttgart. The first version of GaBi was developed about 15 years ago. Since then a wide range of production companies have participated in the further development of the software.[9]

GaBi is available in several versions. The Professional Version comes with an extensive core database, and the option to purchase additional databases. The professional database is the standard database provided with the GaBi 4 software. The developers claim it is the most robust life cycle inventory on the market.

The GaBi 4 professional database is regularly updated and is derived from industry sources, scientific knowledge, technical literature, and internal patent information creating a solid foundation for assessing materials, products, services and processes.

It contains a large amount of PE data, the complete ELCD database[10] as well as data from Plastics Europe. It includes almost 1000 processes, predominantly cradle-to-gate, as well as parameterized unit processes to support the modelling:

- organic and inorganic chemicals
- metals
- plastics
- wood and wood products
- power generation
- transport
- production techniques
- end of life processes

[9] http://www.gabi-software.com/
[10] The ELCD core database comprises Life Cycle Inventory (LCI) data from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management

4.1.8 GEMIS

GEMIS is a life cycle analysis program and database for energy, material, and transport systems - it is available freely at no cost (public domain).[11]

The basic version 1.0 of the computer program GEMIS was developed in 1987-1989 as a tool for the comparative assessment of environmental effects of energy by Öko-Institut and Gesamthochschule Kassel (GhK). Since then, the model has been continuously upgraded and updated. GEMIS includes the total life cycle in its calculation of impacts - i.e. fuel delivery, materials used for construction, waste treatment, and transports/auxiliaries. The GEMIS database offers information on fuels (including biofuels), processes, materials, and transport. It covers the full product life cycle and a wide range of impact categories (such as air pollutants, greenhouse gases, and land use).

4.1.9 GHGenius

Dr. Mark Delucchi developed the first version of his Life Cycle Emissions Model (LEM) during the period of 1987-1993. Partial Canadianization of LEM was completed by Dr. Delucchi for Natural Resources Canada in late 1998 through to March 1999. The partially Canadianized version of the fuel cycle model was the basis for the development of GHGenius. The model was used for a number of studies for Governments and Industry between 1999 and 2011. For each study the data in the model was further refined for Canadian circumstances.[12]

GHGenius focuses on the life cycle assessment (LCA) of current and future fuels for transportation applications. All of the steps in the life cycle are included in the model from raw material acquisition to end-use. The fuel cycle segments span feedstock production and recovery, fertilizer manufacture, land use changes and cultivation associated with biomass derived fuels, leaks and flaring associated with production of oil and gas, feedstock transport, fuel production (as in production from raw materials), emissions displaced by co-products of alternative fuels, fuel storage and distribution at all stages, fuel dispensing at the retail level, vehicle operation, carbon in fuel from air, vehicle assembly and transport, and materials used in the vehicles. The model includes pathways for ethanol and biodiesel production from various feedstocks.

4.1.10 GREET

Argonne National Laboratory, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, developed a life cycle model called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) (http://greet.es.anl.gov/).

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

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[11] http://www.oeko.de/service/gemis/en/index.htm
[12] http://www.ghgenius.ca/

are GREET 1.8d.1 version for fuel-cycle analysis and GREET 2.7 version for vehicle-cycle analysis. The model is freely available over the Internet.

Greet allows researchers and analysts to evaluate various vehicle and fuel combinations on a fuel-cycle/vehicle-cycle basis. GREET includes more than 100 fuel production pathways for energy feedstocks and more than 75 vehicle / fuel system configurations.

GREET takes into consideration various stages of corn, sugar cane, and cellulosic ethanol production, as well as biodiesel from soybeans. It has been widely used for the analysis of transportation fuels in North America and elsewhere in the world.

There is more discussion of the GREET model in section 11.6 of the report.

4.1.11 KCL Eco

The KCL model was developed in Finland to evaluate environmental products and services and was primarily intended for LCA calculations related to products in the forestry industry. KCL EcoData, a continuously updated LCI database, contains nearly 300 data modules covering a range of products, including energy production, pulp and paper chemicals, wood growth and harvesting operations for spruce, pine and birch, pulp, paper and board mills.

Previous versions of this model have been in use in the industry and educational fields since 1994. KCL Eco 4.0, the most recent version, is available for download through the European Commission website under LCA Tools, Services and Data.

4.1.12 LEM

The Life Cycle Emissions Model (LEM) was developed by Dr. Mark Delucchi.

The LEM model estimates energy use, criteria pollutant emissions, and CO_2-equivalent greenhouse-gas emissions from a variety of transportation and energy life cycles. It includes a wide range of modes of passenger and freight transport, electricity generation, heating and cooking, and more. For transport modes, it represents the life cycle of fuels, vehicles, materials, and infrastructure. It includes energy use and all regulated air pollutants, plus so-called greenhouse gases. It includes input data for up to 20 countries, for the years 1970 to 2050, and is fully specified for the U. S.[13]

The model includes pathways for the production of biofuels (ethanol and biodiesel) as well as conventional fossil fuels. It is not widely available.

[13] Delucchi, M. (2002), Overview of the Life Cycle Emissions Model (http://www.its.ucdavis.edu/publications/2002/UCD-ITS-RR-02-02.pdf)

4.1.13 NL Agency Calculator

In 2006 and 2007, EcoFys developed a GHG calculator for biofuels for the Dutch government. The Greenhouse gas (GHG) calculation tool was developed following the GHG calculating methodology for biomass formulated by the project group “Sustainable production of biomass” (Cramer Commission). The tool compares direct GHG emissions of the most commonly used biofuels for transport in the Netherlands with GHG emissions of the standard fossil fuels they replace. The method follows the general rules for life cycle assessments (LCA). Because of uncertainties in the LCA-approach and in the data, the variation in the outcome of the calculation is at best +/-15%.

This model was available through to 2010. After the publication of the Renewable Energy Directive (2009/28/EC), including a European methodology established in Annex VC of that directive, the Dutch CO_2 tool was adapted to the requirements of the directive and renamed the GHG tool.

In version 3.4 of the GHG tool[14], the values are similar to those produced by the EU Directive.

4.1.14 SimaPro

SimaPro stands for “System for Integrated Environmental Assessment of Products” (http://www.pre.nl/content/simapro-lca-software). It is one of the leading commercial LCA programs available.

SimaPro includes databases with a broad international scope, including the international ecoinvent database, and a library with 17 impact assessment methods. All datasets are harmonized regarding structure, nomenclature and fit well with the impact assessment methods.

Databases included in SimaPro

- ecoinvent v.2, US LCI, ELCD, US Input Output, EU and Danish Input Output, Dutch Input Output, LCA Food, Industry data v.2.
- IVAM, Japanese input-output.
- Impact assessment methods included
    - ReCiPe, Eco-indicator 99, USEtox, IPCC 2007, EPD, Impact 2002+, CML-IA, Traci 2, BEES, Ecological Footprint
    - EDIP 2003, Ecological scarcity 2006, EPS 2000, Greenhouse Gas Protocol and others.

4.1.15 TEAM

TEAM (Tools for Environmental Management and Analysis) is Ecobilan’s Life Cycle Assessment software (https://www.ecobilan.com/uk_team.php). TEAM

[14] The tool can be downloaded at http://regelingen.agentschapnl.nl/sites/default/files/bijlagen/Biofuels_GHG_calculator_version_3.4_0.zip

allows the user to build and use a large database and to model any system representing the operations associated with products, processes and activities.

Several versions of TEAM are available and it is a commercial product.

4.1.16 UK RFA Calculator

The UK RFA carbon calculator is a standalone programme that contains default values for the carbon emissions associated with various types of biofuels. It allows fuel suppliers to calculate the carbon saved on a batch of fuels.

The latest version of the calculator is RED compliant, which means that it will have the EU default values for all of the biofuel chains and produce intentionally conservative results, the same as BioGrace and The SenterNovem calculator. The calculator is available at http://www.dft.gov.uk/zip/173186/RFA-calculator-setup.zip.

4.1.17 UMBERTO

UMBERTO was developed in cooperation between the Institut für Umweltinformatik Hamburg and the Institut für Energie- und Umweltforschung Heidelberg. The first version was released in 1995 and a commercial product, version 5.0, is now available at http://www.umberto.de/en/product/index.htm.

Umberto helps prepare life cycle assessments. This is done through the creation of individual projects. Each project is characterized by a freely definable and expandable list of products, raw materials, pollutants, and forms of energy etc. Life cycle impacts are estimated based on these projects. To facilitate this assessment, Umberto has a supporting module library that contains data sets on generic upstream and downstream processes (including Ecoinvent data).

A new version of Umberto, Umberto for Carbon Footprints is available. This appears to be a smaller version of the model.

4.2 LCA Databases

In addition to LCA models there are a number of database products that are available. Many of these can be used as plug-ins for the models.

Databases are critical to the calculation process since the results are dependent upon the inputs into the systems. There can be wide ranges of values in the different databases due to regional differences, temporal differences, processes used and system boundaries. Care must therefore be used when using third party databases to ensure that they are consistent with the systems being modelled.

4.2.1 Eco-Indicator 99

The Eco-indicator 99 is a science based impact assessment method for LCA. It offers a way to measure various environmental impacts, and shows a final result in a single score by PRé Consultants.[15]

The method is also the basis for the calculation of eco-indicator scores for materials and processes. These scores can be used as a design for environment tools for designers and product managers to improve products. The impact assessment method is widely used by life cycle assessment practitioners around the world.

Eco-indicator 99 scores can be used to make your own environmental assessment of a product in a matter of minutes (using over 200 predefined scores for commonly used materials and processes).

Eco-Indicator 99 is an impact assessment method and not a model suitable for conducting a life cycle assessment of transportation fuels.

4.2.2 Ecoinvent

The Ecoinvent database v2.2 (www.ecoinvent.ch) contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services.

It is the product of the Swiss Centre for Life Cycle Inventories, a joint initiative of several partners belonging to the Domain of the Swiss Federal Institutes of Technology (ETH) and supported by different Swiss Federal Offices. The database is sold by vendors of life cycle impact models that use Ecoinvent, for example GaBi and Sima Pro.

The database contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services. It is used by more than 2,500 users in more than 40 countries worldwide.

4.2.3 ECO-it

ECO-it (http://www.pre.nl/content/eco-it-ecodesign-software#Database) is a life cycle assessment software model offered by PRé Consultants. ECO-it is designed as a quick screening tool that calculates the environmental load, and shows which parts of the product's life cycle contribute most. It is described as being a tool for product and packaging designers.

ECO-it comes with over 500 ReCiPe environmental impact (ReCiPe) and carbon footprint (CO_2) scores for commonly used materials such as metals, plastics,

[15] http://www.pre.nl/content/eco-indicator-99

paper, board and glass as well as production, transport, energy and waste treatment processes.

Eco-it is a building block model and does not represent a transportation fuel life cycle assessment model.

4.2.4 NREL U.S. LCI Database

NREL has created the U.S. Life Cycle Inventory Database in order to aid LCA users with their calculations. The database was last updated in 2008 and contains many cradle-to-grave energy and material flow scenarios associated with producing various products. This database allows LCA users to objectively review their own findings and compare their analyses with others that are based on similar data collection and analysis methods.

All of the NREL LCI Database data's protocol is based on ISO 14048. Having this common set of data based on a single protocol will improve the quality and consistency of LCAs for all users.

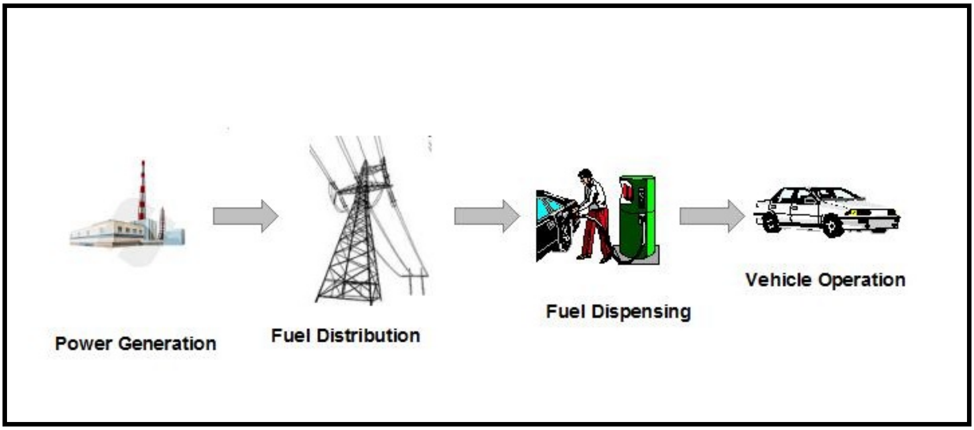
All of the LCI data are available in multiple formats and fully compatible with Microsoft Excel. The LCI Database can be accessed through NREL's website (http://www.nrel.gov/lci/).

5. ELECTRIC VEHICLES

The discussion of the LCA performance of an electric vehicle is presented first, as it is the simplest and most easily understood fuel production cycle and one with the largest variation from region to region. Electricity is also used in every other fuel cycle so a good understanding of the factors impacting electricity can partially explain some of the variation seen in some of the other fuel cycles.

Conceptually the electric vehicle system is shown in the following figure.

Figure 5-1 Electric Vehicle Life Cycle



The three factors that affect life cycle GHG emissions are power plant emissions, distribution and dispensing efficiencies, and vehicle performance. These issues are discussed below.

5.1 POWER GENERATION

The emissions from the generation of electrical power are mostly influenced by the type of power plant and by the fuel that is being used. Power generated by nuclear fission, hydroelectric facilities, wind turbines and biomass combustion tend to have very low GHG emissions, whereas facilities fuelled by the combustion of coal, oil, or natural gas have higher GHG emissions. The typical life cycle GHG emissions for the various types of generation are shown in the following table.

Table 5-1 Life Cycle GHG Emissions Electric Power Generation

Type	GHG Emissions, g CO_2eq/kWh
Coal	1,065
Oil	965
Combined Cycle Natural Gas	460
Nuclear	15
Hydro[16]	20
Biomass thermal[17]	24

Source: GHGenius 3.20a

5.1.1 System Boundaries

Data sets for emissions can have different system boundaries, in that some may include only the emissions from the generating station, whereas others may include the emissions from the extraction, processing, and transportation of the fuels consumed at the stations.

5.1.2 Allocation

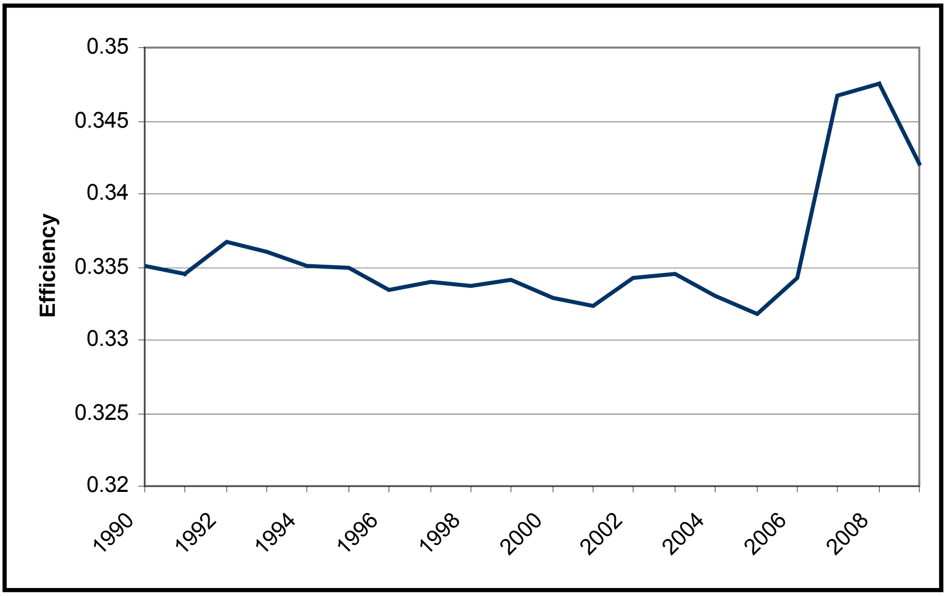
Power plants will only produce one or two products of significance: electricity and, in some cases, steam (or waste steam) for sale. The utilization of the steam will introduce allocation issues but in many regions this is not the prevalent practice. Allocation by energy product could be applied to co-generation situations.

5.1.3 Temporal Issues

While the efficiency of generating systems can change over time, changes are not generally large. The following figure shows the efficiency of coal fired power plants in the United States over the past 20 years. Only the addition of additional capacity in the past several years has had an impact on plant efficiency.

[16] Includes some methane emissions from reservoir.
[17] Excludes any indirect land use change emissions.

Figure 5-2 Power Plant Efficiency

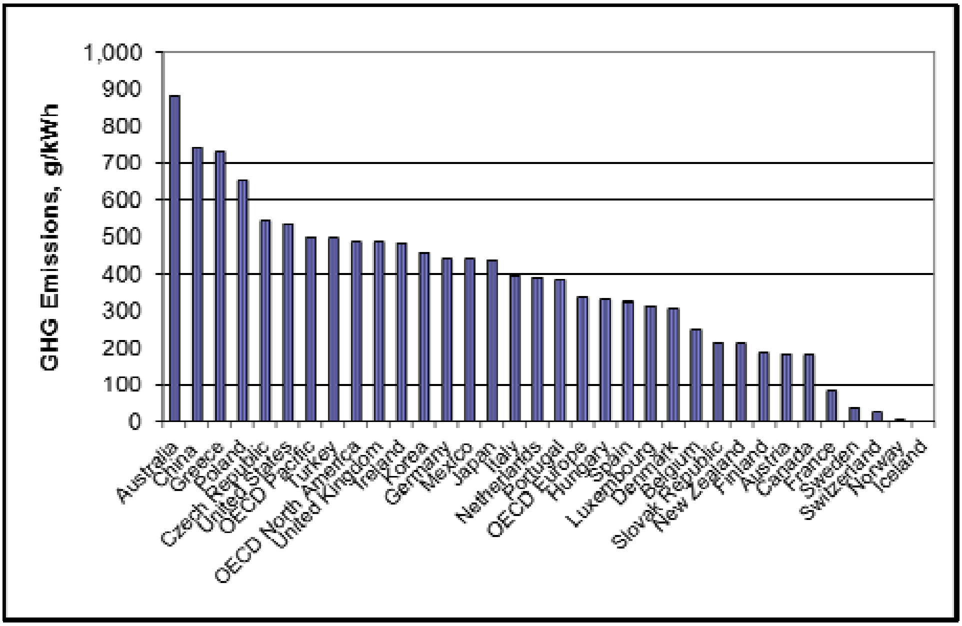


Source: Calculated from Annual Energy Review. US Energy Information Administration (EIA).

5.1.4 Regional Issues

Regional issues are by far the largest influence on the GHG emissions of electric vehicles. The power generation mix in different regions of the world varies due to the availability of local resources. As a result, the GHG emissions of electric power by region vary significantly. The following figure shows the variation in OECD countries.

Figure 5-3 Regional GHG Emissions Electric Power



Source: CO_2 Emissions from Fuel Combustion (2010 Edition), IEA, Paris.

There is an order of magnitude difference in the emission intensity of electric power production within OECD member countries. Canada, France, and Sweden are at the low end of the range and Australia, the United States, Greece and Poland are at the high end of the range. Even within countries, there can be significant regional variation. In Canada for example, there is a similar order of magnitude range between Provinces that have large hydro-electric capacity and those more reliant on thermal generation.

5.1.5 Data Quality

Notwithstanding the temporal and regional issues, data quality with respect to GHG emissions of electric power production is generally good. Fuel purchases are the major cost component of power generation and most operations do track the energy coming in to the plant and the power that is delivered to customers.

Other issues that might not be as well tracked, such as SF_6 emissions, have a very minor impact on overall GHG emissions from power generation.

Emissions associated with the production of fuels consumed in power plants are generally not reported by this sector (as they are indirect emissions), but these energy flows and emissions should be properly accounted for in most true LCA models. Simpler GHG calculators, where there are no circular references, may not be able to accurately assess the emissions from fuel production and could therefore under-report GHG emissions from the power generation sector. Most of the detailed reports that consider the environmental performance of electric vehicles use proper LCA models. Promotional and marketing materials or information in the popular press may sometimes use the simpler GHG calculators.

It should also be noted that any LCA involving future projections should account for the need to add generating capacity and the associated energy intensity/use of plant construction. One of the major shortfalls in studies that lay out blueprints for a renewables-intensive energy economy is that they underestimate or under-represent both the energy demand of the generating structures themselves (e.g., windmill construction, operation, and transmission infrastructure) and the fact that backup power (most likely gas-fired) may be needed for those sources that are not truly on-demand.

5.2 POWER DISTRIBUTION

Electric power is distributed from the generating station to the point of use through high voltage transmission systems. There are energy losses in transformers used for voltage changes, through the resistance of the transmission lines, and in some cases through load following.

Table 5-2 Transmission System Losses

Region or Country	Losses (GWh)	Final Consumption (GWh)	Losses
IEA Europe	231,612	3,074,126	7.53%
Germany	30,118	525,549	5.73%
France	32,916	433,481	7.59%
UK	28,195	341,562	8.25%
IEA North America	296,634	4,332,301	6.85%
US	246,116	3,813,520	6.45%
Canada	50,518	518,781	9.74%
Japan	51,313	964,361	5.32%
India	193,741	601,610	32.20%
China	191,829	2,841,855	6.75%
Thailand	8,954	135,450	6.61%
Finland	3,334	82,613	4.04%
Sweden	10,985	128,649	8.54%

Source: Electrical Statistics. Electricity/Heat by Country/Region. IEA, Paris.

Most systems have losses under 10%, with the exception of India. There are a number of issues in India including theft, the lack of co-ordination of different grids, as well as technical issues.

5.2.1 System Boundaries

The system boundaries for this stage are generally straightforward, although there may be cases where these losses are not accounted for. Power plants also consume some of the power that is generated so it is important that the emissions be presented on a net basis and not on a gross basis.

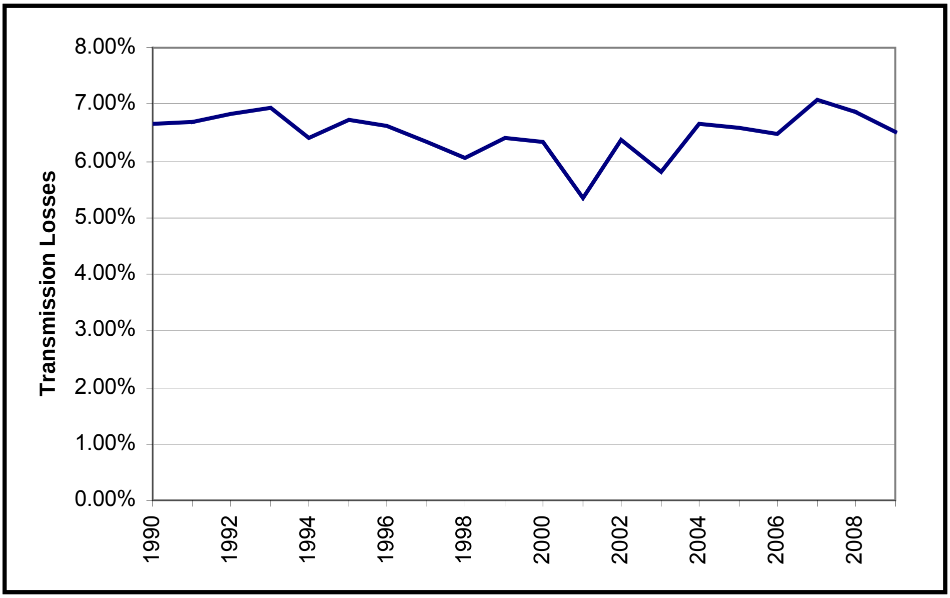
5.2.2 Allocation

There are no allocation issues with this stage of the life cycle.

5.2.3 Temporal Issues

The transmission losses can vary from year to year. The losses for the United States from 1990 to 2009 (EIA) are shown in the following table.

Figure 5-4 Time Series Transmission Losses - US



Source: Supply and Disposition of Electricity, 1990 Through 2009. US EIA.

5.2.4 Data Quality

Losses in the electrical distribution system are usually derived from national statistical agencies. Small errors can be introduced because of temporal changes or from applying data from one region or country to another region.

5.3 VEHICLE PERFORMANCE

Reliable data on the performance of electric vehicles has been a problem for LCA work. Performance claims were difficult to compare since they were often performed with different driving cycles than other electric vehicles and from vehicles with internal combustion engines.

Recently, the US EPA has established a protocol for testing electric vehicles that makes comparisons between vehicles less problematic. The available data is summarized in the following table.

Table 5-3 EV Performance

Vehicle	Curb Weight	Energy Consumption		Energy Ratio
	kg	EV kWh/100 km	Gasoline l/100 km	
Chevrolet Volt	1,715	22.5	6.4	2.5
Nissan Leaf	1,521	20.0		
Smart Fortwo ED	854	24.4	6.5	2.4
Tesla Roadster	1,235	17.6		

The energy consumption of the electric vehicles is much higher than earlier manufactures' claims, where they were in the range of 12 to 15 kWh/100km. The Volt and Smart ED are about 2.5 times more energy efficient on electricity than the equivalent vehicle running on gasoline. This is a lower ratio than found in many LCA reports. Early experience of EV owners is that range can be significantly decreased in cold ambient temperature conditions.

5.3.1 System Boundaries

An issue for the comparison of electric vehicles to traditional internal combustion engine vehicles is the inclusion of the vehicle materials and assembly inside the system boundary. The materials that are used in an EV are quite different than those used in a gasoline or diesel powered vehicle and they can have different quantities of GHG emissions embedded in them. It is important that this factor is taken into account when EVs are compared to traditional vehicles. Unfortunately, many LCA models do not include this stage of the life cycle.

5.3.2 Allocation

There should not be any allocation issues with the analysis of the electric vehicle. There will be an amortization issue. Over how many kilometres should the emissions embedded in the vehicle during manufacture and assembly be amortized? Should the amortization distance for EVs and traditional vehicles be the same? Related to this, should end of life treatment be the same for both types of vehicles? The answers to these questions will be speculative until more real world experience is gained with the electric vehicles.

5.3.3 Temporal Issues

Like all new technologies, the performance of electric vehicles should improve as more experience is gained with their manufacture and use. The performance and relative performance shown in the previous table could look quite different in five or ten years time.

5.3.4 Regional Issues

It may be that there will be regional differences in relative performance of EVs due to climate issues, but no data exists today to prove or disprove this hypothesis.

5.3.5 Data Quality

There is very little primary data available on the performance of electric vehicles as they are just being introduced to the market.

5.4 SUMMARY

While the electric vehicle system is a relatively simple system it has been shown that there is a very large variation in how it is practiced from country to country and even from region to region in a single country. This variation in how power is generated is the single most important issue in the electric vehicle life cycle. The other issues such as system boundaries, temporal issues, and EV performance, while important, all have less impact on the life cycle results.

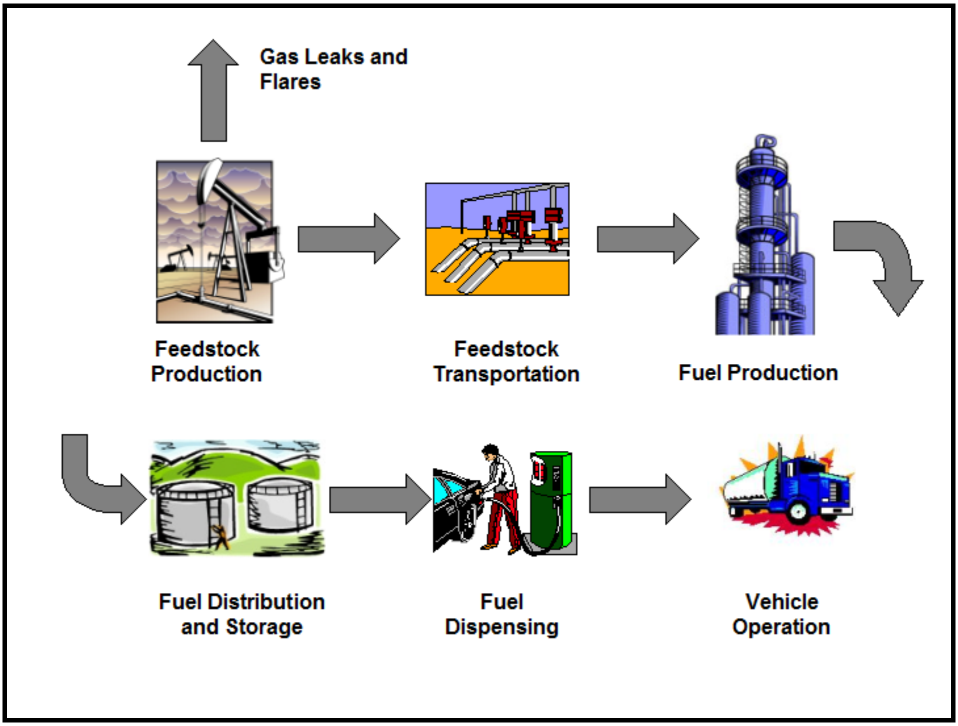
The implication of this finding goes beyond the analysis of electric vehicles, as electricity is an important input parameter for almost every other fuel and vehicle system. One should therefore expect to get different results for the same production pathway when it is practised in different regions just from the difference in the carbon intensity of the electric power. Of course, the carbon intensity of other inputs could also vary by region, either reinforcing the variation in electric power or countering the effect.

6. PETROLEUM FUELS

The petroleum fuels, gasoline and diesel, are the dominant transportation fuels in the world today. Many of the regulations that are looking at reducing the carbon intensity of the transportation sector use these two fuels as reference or baseline fuels against which other fuels are compared, and yet many of the models described in the previous section only focus on biofuels and other alternatives and do not have pathways for the reference fuels.

The system for fossil fuels is shown in the following figure.

Figure 6-1 Life Cycle Stages for Fossil Fuels



The three major components of this system are the feedstock production or resource recovery stage, the fuel production or refining stage, and the vehicle operation or end use stage. The issues with each of these three stages are discussed below.

6.1 RESOURCE RECOVERY

The production of crude oil is the first major stage of the life cycle. The emissions from this stage arise from both the use of energy and fugitive emissions (particularly methane). The emissions can represent from 2% to 25% of the diesel or gasoline life cycle emission. The large range is due to the different crude oil types that are produced, the lack of control of fugitive emissions in some cases, and the need to upgrade very heavy bitumen oils to lighter oils that can be more easily transported and refined. In spite of world production of crude oil approaching 90 million barrels per day and the activities having been undertaken for more than 100 years, there is a lot of uncertainty about the performance and emissions from this stage. These issues are discussed below.

6.1.1 System Boundaries

There are some system boundary issues related to the crude oil stage. Many studies and models start the life cycle once the oil field has been found, the well drilled, and production has started. Other studies include the energy use and emissions from the exploration and drilling stages.

There is some very high level information available from the US Census on the dollar value of fuels and electric power used by the various upstream oil and gas sectors in the United States (US Census, 2009). This data is summarized in the following table.

Table 6-1 2007 US Census – Mining Sector

SIC Code	Description	Fuels Consumed ($1,000)	Power Consumed ($1,000)
211111	Crude petroleum and natural gas extraction	1,873,125	Withheld
213111	Drilling oil and gas wells	875,355	100,409
213112	Support activities for oil and gas operations	76,075	14,409
Total		2,824,555	

The data set is not complete due to information that is withheld to protect confidentiality, but it would suggest that the energy consumed in drilling and support activities is about 50% of the energy used in the actual extraction process. If the reserves are constant, oil found in a year is equal to the oil produced in a year, then the use of only the energy used for production underestimates the energy use (and emissions) for this stage by 50%. There is very little data on the fugitive emissions during the well drilling stage but these could also be significant.

The GHGenius model and the LEM model include these emission sources, or at least the energy use. Most other models would appear to exclude this stage. It is likely that the GHG emissions for crude oil production are underestimated in almost all models.

6.1.2 Allocation

Many oil wells also produce some natural gas (associated gas) at the same time. In most parts of the world this gas is captured and utilized but in some parts of the world it is vented or flared. Where gas is co-produced with the oil, the input energy and the fugitive emissions must be allocated to each product. In most instances this allocation is done on an energy basis, that is the GHG emissions per GJ of energy produced is the same for crude oil as it is for natural gas.

The US LCI database (NREL, 2011) follows this approach by taking the information from the 1997 US census for oil and gas production and allocating it according the energy content of the oil and gas produced. This inventory includes the energy for oil and gas well drilling but not for the support activities.

There are other approaches that could be used. There are some gas wells that are not associated with the production of crude oil. The energy and emissions of these systems could be used as a credit applied to the gas production. Depending on the oil and gas data for a particular region, this could result in an increase or decrease in the GHG emissions for crude oil production.

6.1.3 Temporal Issues

The energy required to produce crude oil is changing all of the time. As wells get depleted, the energy required to produce the remaining oil increases. Oil discoveries are also happening in more remote and difficult to access regions of the world and this also tends to increase the energy requirements.

There are not very many datasets for crude oil production that have a time series of information. The International Association of Oil and Gas Producers (OGP) has been publishing energy and emission data for various regions of the world. The data is collected from its members and represents about one third of the world's oil production. Data is available for the period 2001 to 2009. The geographic coverage as a proportion of the production reported by BP in their Statistical Review of World Energy is summarized in the following table.

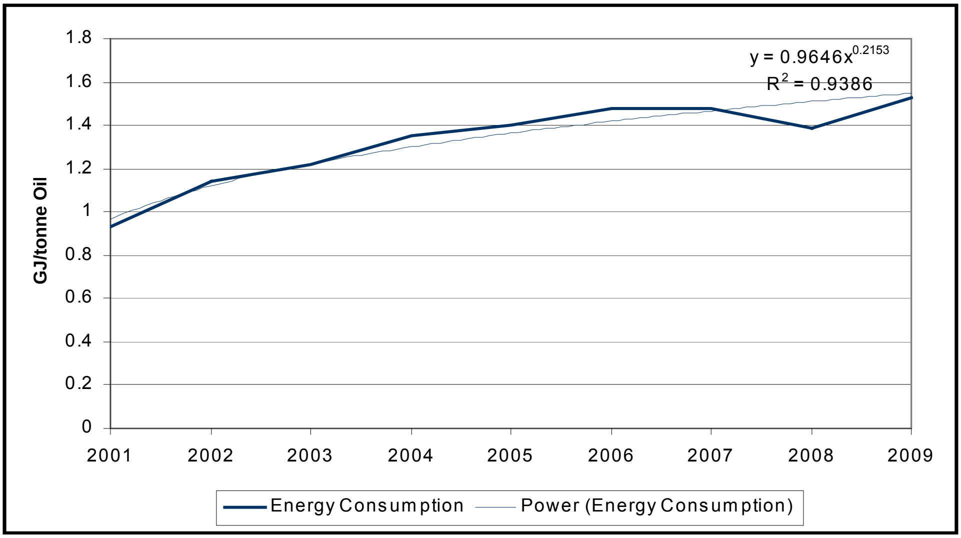
Table 6-2 Coverage of OGP Data

Region	2001	2002	2003	2004	2005	2006	2007	2008	2009
Africa		63%	63%	62%	66%	63%	61%	59%	59%
Asia/Australasia		40%	43%	47%	46%	44%	43%	45%	42%
Europe	102%	104%	99%	94%	98%	100%	103%	98%	104%
FSU	10%	10%	11%	4%	4%	5%	8%	8%	10%
Middle East	10%	9%	16%	15%	16%	17%	15%	20%	33%
North America		53%	51%	30%	29%	27%	25%	23%	25%
South America		47%	57%	58%	53%	42%	41%	40%	40%
Total		40%	41%	34%	34%	32%	32%	32%	36%

There is good coverage for some regions of the world but other regions have limited coverage. There is also the possibility that the data is skewed since the members of OGP are large multi-national oil companies and therefore do not represent the full cross section of oil producers. Nevertheless, it is the best single source of data available. The 2002 data is the basis of the energy consumption for crude oil production in GaBi, and that tool was used by the EPA for their determination of the emissions of gasoline and diesel for the RFS2 LCA work.

It is apparent from the OGP data that there is a significant trend towards increased energy consumption for oil production that is evident from the data and is shown in the following figure.

Figure 6-2 Energy Consumption Trend – Crude Oil Production



The latest information for 2009 shows world wide energy consumption in the petroleum production stage has risen to 1.53 GJ/tonne of oil. It has risen by 53% over an eight year period.

This OGP dataset does not include the energy used in, or emissions from, the oil exploration and drilling stages of the life cycle.

6.1.4 Regional Issues

The energy required to produce crude oil is different for different parts of the world and can vary significantly for different types of crude oil. The 2009 data from the OGP reports (OGP, 2010) is shown in the following table.

Table 6-3 OGP Energy Use Data

Region	% Onsite combustion	% Purchased	% Unspecified	Total energy consumption (GJ/t)
Africa	78	3	19	1.13
Asia/Australasia	55	2	43	1.59
Europe	93	5	1	1.12
FSU	71	2	27	1.06
Middle East	97	4	5	1.00
North America	78	6	15	3.08
South America	95	3	2	1.69
Overall	80	4	16	1.53

It can be seen from the table that there is considerable regional variation in energy consumption for crude oil production. When the total GHG emissions are considered there can be even greater variation, since venting and flaring of associated natural gas tends to be a regional issue. It is not clear from the original data source if the North America value is high because of the inclusion of some oil sands production in the data.

The International Council on Clean Transportation (ICCT) contracted Energy-Redefined, LLC to determine the carbon intensity of Crude Oil in Europe (2010). Energy-Redefined modeled the carbon intensity of crude oil from over 3,000 oilfields located in countries that supplied oil to Europe in 2009.

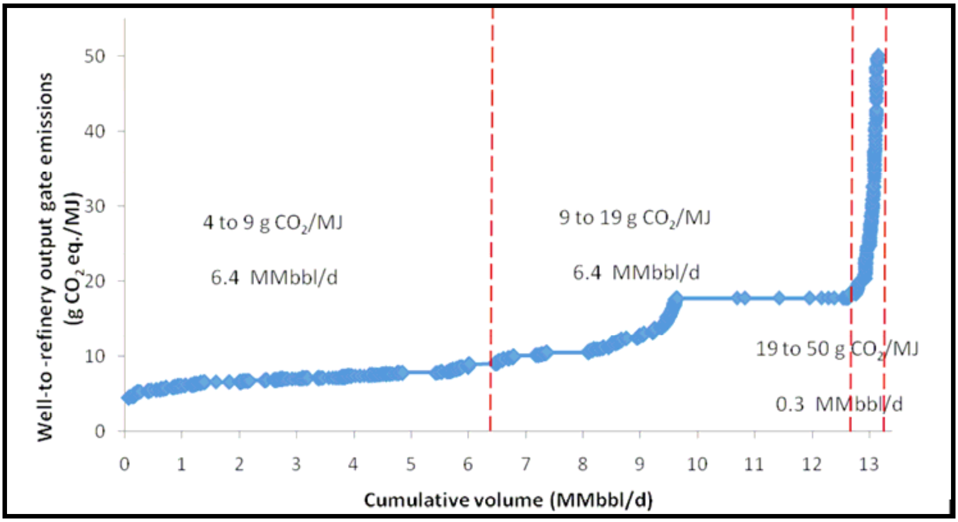
Energy-Redefined, LLC has used a proprietary model that estimates the impact of individual crude oils on carbon emissions across the value chain. It incorporates data on field attributes such as API gravity, viscosity, reservoir pressure, and transportation distance. The model does the following:

- Uses engineering-based calculations to estimate energy use for different field types with different depths and pressures,
- Estimates flaring at the field, based on gas-to-oil ratio (GOR) data and energy use at the field,

• Calculates venting and flaring according to field type,
• Takes into account the maturity of the field,
• Estimates emissions from the above sources.

The following figure shows the variation among individual oil fields in extraction-to-refining emissions against the cumulative volume of crude oil production that is exported to Europe. The carbon intensity of crude oils ranges from 4 to 50 grams of CO_2 equivalent per megajoule (g CO_2 eq./MJ) with an average of 12 g CO_2 eq./MJ.

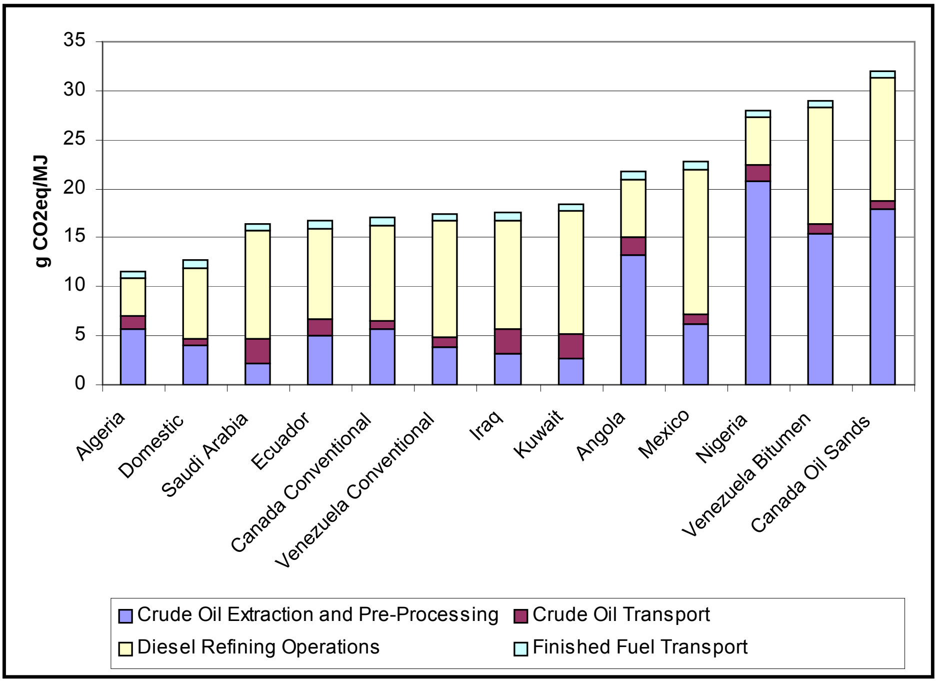
Figure 6-3 GHG Emissions Crude Oil Delivered to Europe



Source: Energy-Redefined, LLC.

The US National Energy Technology Laboratory (NETL, 2009) looked at the well to tank emissions of diesel fuel produced from different regions of the world. Their results are shown in the following figure. Note that the refining emissions vary with crude oil source as well. Their work included refining emission adjustments for crude oil density and for sulphur content.

Figure 6-4 GHG Emissions for Different Crude Oils



Source: NETL.

6.1.5 Data Quality

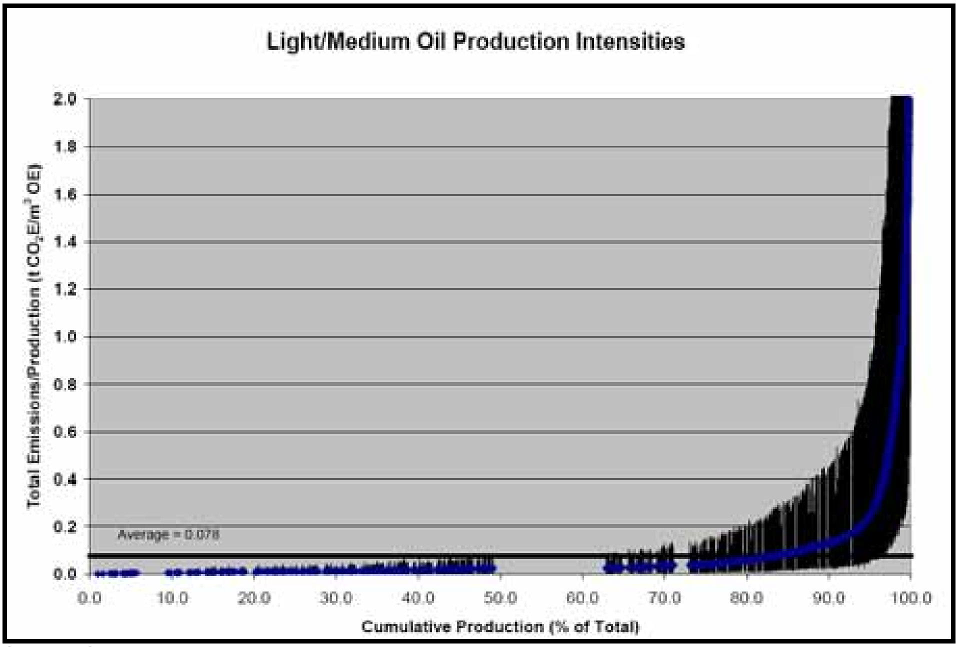
Finally, there are issues with the quality of the data that is used to generate some of the energy use information and GHG emissions. Even the best data sets, like the OGP information, have shortcomings. The OGP reports do not state whether the energy use is provided on a lower or higher heating value basis, this could increase or decrease the energy use and calculated emissions by about 10% depending on what was assumed compared to the actual basis.

The OGP reports also do not have complete coverage in most regions. It is entirely possible that the oil fields for which data is collected are the largest, most efficient fields, operated with the highest environmental standards since there are generally operated by large multi-national corporations.

The Canadian Association of Petroleum Producers undertook an extensive energy use and emission inventory process in 2002 (CAPP, 2004). The following graph presents the cumulative GHG emissions for conventional and light and medium oil production batteries, plotted as a function of the cumulative production for individual facilities. The vertical lines drawn through the plotted points depict their associated confidence limits.

The graph has a point for each facility's intensity (the blue diamond) as well as the uncertainty bars on the estimated intensity value. In many cases, the uncertainty in the estimated emissions is on the order of ±100 percent. Finally, the graph has a line showing the weighted average intensity for the sector (i.e., total emissions for the sector divided by total production for the sector).

Figure 6-5 Individual Facility Emissions



Source: CAPP.

One of the key messages in this figure is that the median and the mean emission intensities are significantly different. This demonstrates that production statistics that represent 50% of the production could result in emission intensities that are significantly lower than the average value for all producers.

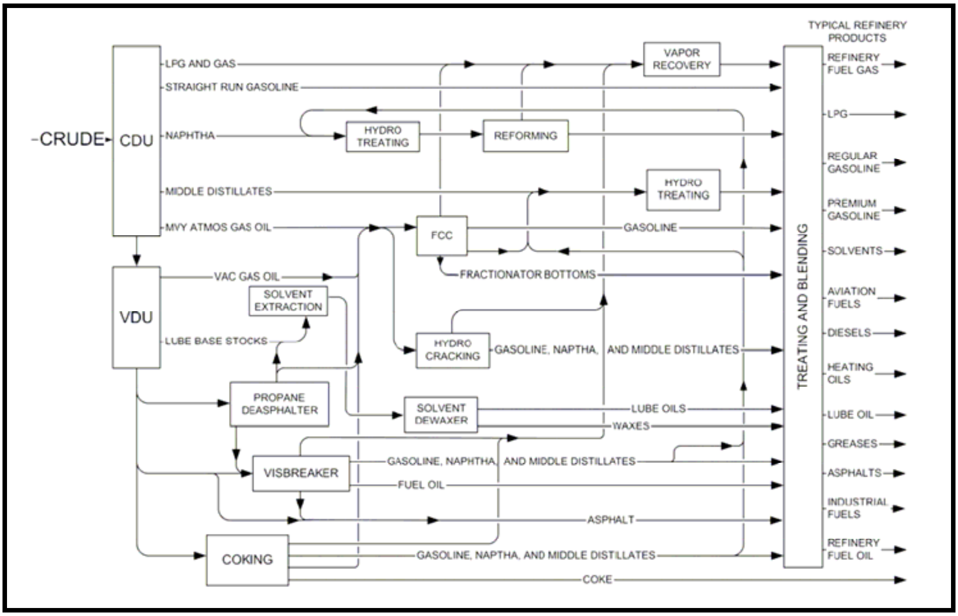
For most countries the emission estimates for crude oil production are based on models and calculations and not on actual measured statistics. In some cases these would almost be tertiary sources of data. This lack of transparency of the reported results is troubling as it is not possible to independently verify the information.

6.2 REFINING

Petroleum refineries produce liquefied petroleum gases (LPG), motor gasoline, jet fuels, kerosene, distillate fuel oils, residual fuel oils, lubricants, asphalt (bitumen), and other products through distillation of crude oil, cracking, or reforming of unfinished petroleum derivatives. Refineries can take many different forms depending on the crude oil processed and the demand for products in the local area.

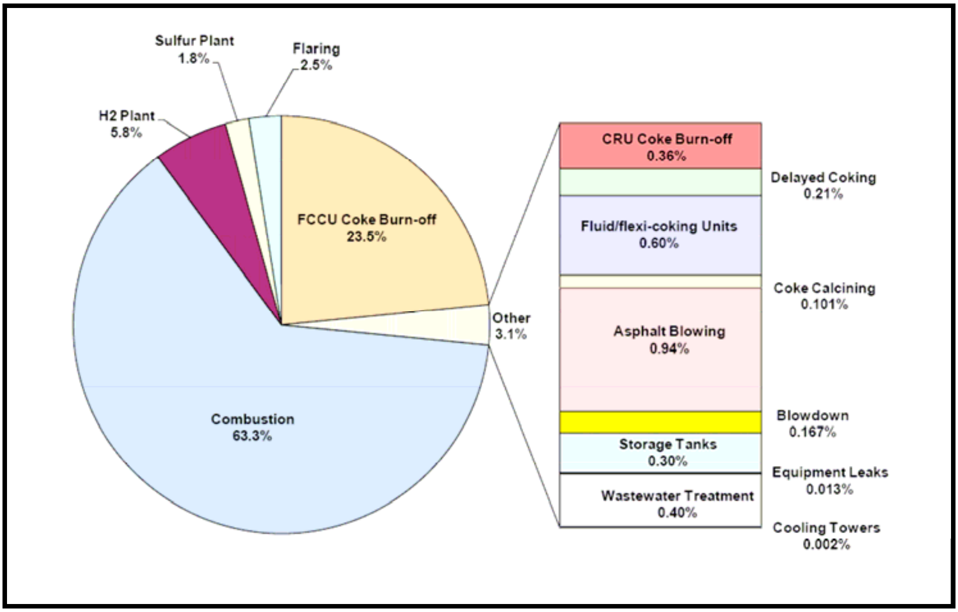
The flow of intermediates between the processes will vary by refinery, and depends on the structure of the refinery, type of crude processes, as well as product mix. The first process unit in nearly all refineries is the crude oil or “atmospheric” distillation unit (CDU). Different conversion processes are available using thermal or catalytic processes, e.g., delayed coking, catalytic cracking, or catalytic reforming, to produce the desired mix of products from the crude oil. The products may be treated to upgrade the product quality (e.g., sulphur removal using a hydrotreater). Side processes that are used to condition inputs or produce hydrogen or byproducts include crude conditioning (e.g., desalting), hydrogen production, power and steam production, and asphalt production. Lubricants and other specialized products may be produced at special locations. A typical refinery configuration is shown in the following figure.

Figure 6-6 Typical Refinery Configuration



Petroleum refineries are significant consumers of energy and almost all of the energy consumed in the refinery is fossil in origin. In addition to the combustion-related sources (e.g., process heaters and boilers), there are certain processes, such as fluid catalytic cracking units (FCCU), hydrogen production units, and sulphur recovery plants, which have significant process emissions of CO_2. Methane emissions from a typical petroleum refinery arise from process equipment leaks, crude oil storage tanks, asphalt blowing, delayed coking units, and blow down systems. Asphalt blowing and flaring of waste gas also contribute to the overall CO_2 and CH_4 emissions at the refinery. The US EPA (US EPA, 2008) has estimated the US GHG emissions from petroleum refineries and determined that the average distribution of emissions within the refinery is as shown in the following figure.

Figure 6-7 Distribution of GHG Emissions within the US Petroleum Refining Sector



Source: US EPA.

Refining emissions can vary from 5% to 20% of the total life cycle of transportation fuels. The range is caused by the energy efficiency of the refineries, the types of crude oil processed, the product slate produced, and the quality of the products produced. These issues are discussed below.

6.2.1 System Boundaries

There are relatively few system boundary issues associated with oil refineries, as the stage is relatively simple. Oil is delivered to the refinery and products are stored ready for shipment to the end user. One of the few issues could be the inclusion of fugitive emissions of methane and non-energy related GHG emissions. These could account for 5% to 10% of the refinery emissions.

6.2.2 Allocation

One of the more significant areas of uncertainty in the petroleum refining stage is the allocation of the emissions to individual products. As shown in Figure 6-6, refineries make many products and it is necessary to undertake some sort of allocation of the emissions to the individual products such as gasoline or diesel fuel.

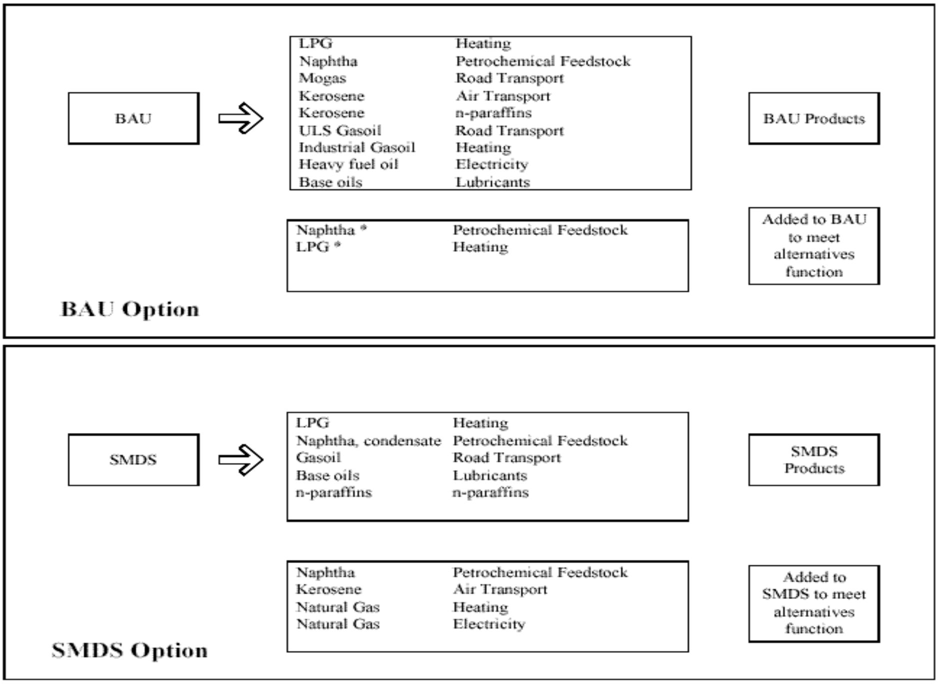
Most models have attempted to estimate the process energy required for producing an individual product. Heavy fuel oil or asphalt that might only involve the initial atmospheric distillation step and perhaps one other, would have lower emissions, while products like gasoline or ultra low sulphur diesel fuel, which go through many processing steps, would have higher emissions.

Some models have allocated the emissions based on the energy content of the products. This approach results in lower emissions for transportation fuels than the more typical allocation by process energy.

Some analyses of transportation fuels have used a displacement approach. This approach has merit but can produce very different results in different regions of the world. The issue is that if no residual oil is produced, another fuel such as natural gas, would be used in its place and the difference in GHG emissions for the combustion of the residual fuel and the natural gas would be a credit for the crude oil that produces fewer bottoms. This concept has been applied before for LCA studies on transportation fuels in Europe (PriceWaterhouseCoopers, 2003).

The approach used in the PWC study on a gas to liquids (GTL) project for Shell (SMDS) is to make the two systems functionally equivalent. This requires the addition of a number of products to each option. In particular, the SMDS case has the combustion of natural gas added for thermal energy requirements and power generation. This approach is demonstrated in the following figure.

Figure 6-8 Functional Equivalence for Oil Refinery and SMDS Process



Source: PWC.

The GHG bonus for products with lower bottoms would be the difference in natural gas life cycle emissions and heavy fuel oil life cycle emissions times the difference in the fraction of heavy fuel oil products produced from the average crude and the study crude. In the PWC case, this amounted to about 8.5 g CO_2eq/MJ for the GTL product.

The same concept was utilized Abbott et al (2003) for a study for ConocoPhillips on producing Fischer-Tropsch (FT) distillate from natural gas in North America. They did a system expansion to deal with the functional equivalency of the two systems but, instead of substituting natural gas for the residual fuel, they substituted coal. This had little impact on the overall emissions. Both studies could be correct and just reflect the differences in the energy systems in the two different regions.

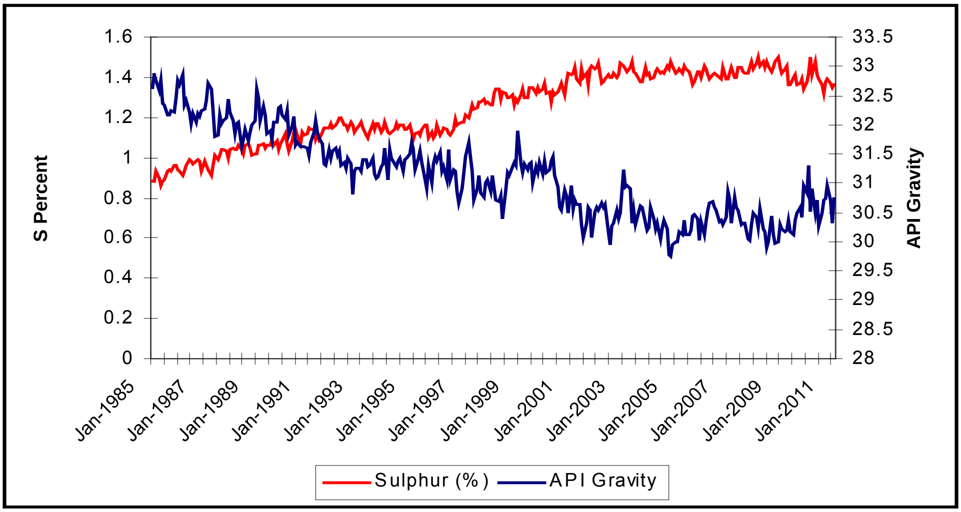
This issue of functional equivalency could also be important for some unconventional crude oils that don't produce residual oils, like synthetic crude oil from Canada and some of the Venezuelan synthetic crude oils.

6.2.3 Temporal Issues

Refining emissions do change over time. There are at least three competing forces. Refiners have been improving the energy efficiency of their facilities due to economic pressures but, at the same time, product specifications have been moving to lower sulphur limits (which require more energy to produce) and the crude oil that is refined is becoming heavier and has a higher sulphur content.

The following two figures demonstrate the trends in the United States; similar trends are expected in other countries. The first figure shows a long term trend to heavier crude oils with higher sulphur contents.

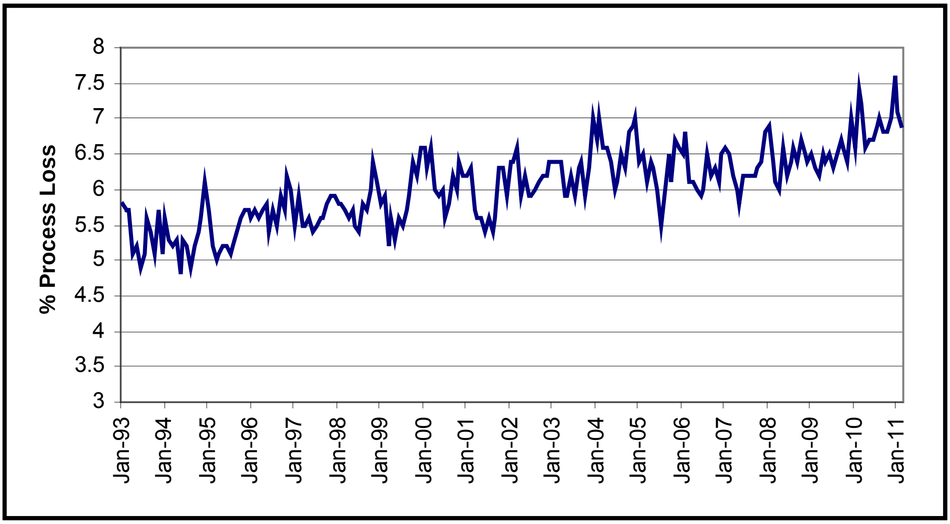
Figure 6-9 Crude Oil Quality



Source: Crude Oil Input Qualities. US EIA.

The second figure shows processing loss over time for the United States. This is a proxy for energy use in the refinery. It represents the own fuels consumed but does not include purchased electricity or natural gas.

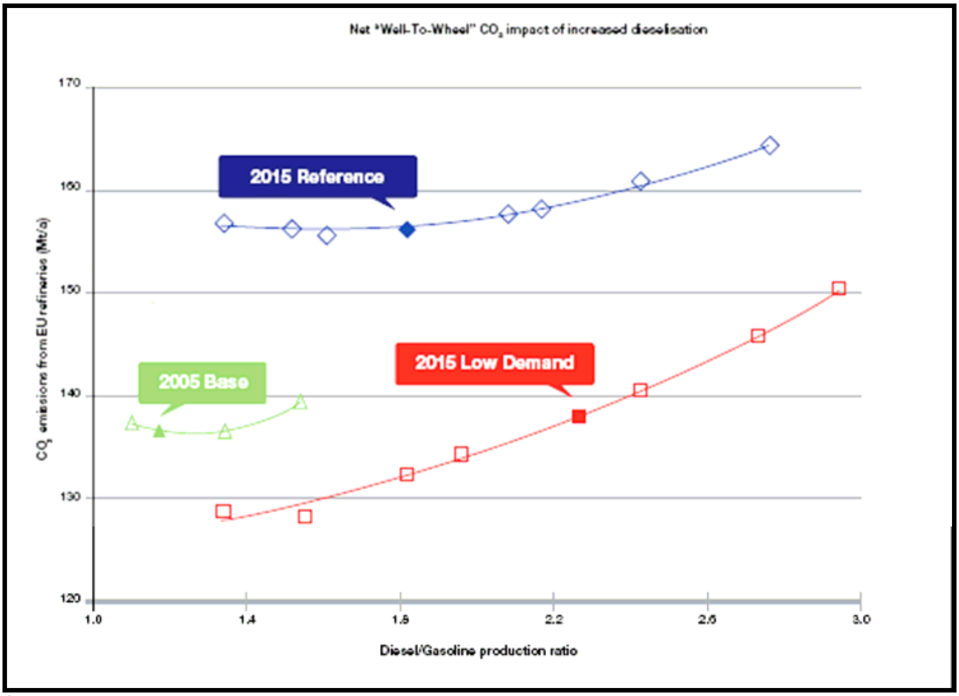
Figure 6-10 Refinery Processing Loss



Source: Refinery Yields. US EIA.

A change in the product slate can also impact the emissions. The EU has experienced a trend to increased dieselization in the transport sector. Concawe (Europia, 2010) has projected that if the trend continues, GHG emissions from refineries will increase, as shown in the following figure.

Figure 6-11 Projected Increase in EU Emissions



Source: Europia.

6.2.4 Regional Issues

Refining emissions can vary from region to region due to the quality of crude oils produced, the products produced (both the quantities and qualities), and the level of efficiency in the refining sector. This can be influenced by the size and age of the refining sector in different regions of the world.

A comparison of the own fuel consumption as a fraction of crude oil input for various regions and countries is shown in the following table. All of the information in the table is taken from the IEA statistical database (http://www.iea.org/stats/prodresult.asp?PRODUCT=Balances).

Table 6-4 Refinery Energy Own Use

Region or Country	Crude Refined (ktoe)	Own Use Energy (ktoe)	% own Use
IEA Europe	730,883	38,214	5.23%
Germany	119,788	6,539	5.46%
France	89,000	4,673	5.25%
UK	83,572	4,796	5.74%
Sweden	21,881	782	3.57%
Finland	14,951	589	3.94%
IEA North America	949,391	57,643	6.07%
US	851,222	48,555	5.70%
Canada	98,169	9,088	9.26%
China	340,953	20,682	6.07%
Japan	198,277	8,547	4.31%
India	166,184	11,887	7.15%
Thailand	48,064	2,671	5.56%

Source: IEA Statistics. Balances by Country/Region. IEA, Paris.

If there is significant variation from country to country, and even for individual countries, different databases will show different results. This is summarized in the following table.

Table 6-5 Comparison of Refinery Own Use Energy

Country	IEA	Country Source	Country Value
Germany	5.46%	Federal Office of Economics and Export Control[18]	6.12%
USA	5.70%	US DOE EIA	7.5%
Canada	9.26%	NRCan	7.57%

The values from the individual country sources are quite different than the IEA reported values, even though the IEA relies on data supplied by the countries themselves. There are obviously interpretation issues that demonstrate the care that must be used when collecting the data for modelling purposes.

6.2.5 Data Quality

Various industry associations (API, IPIECA, OGP, 2003, CPPI, 2009) have developed guidelines for estimating GHG emissions from petroleum refineries. Some of these documents establish various Tiers for estimation, similar to the IPCC Tier approach for emission factors. It is clear from these documents that

[18] http://www.bafa.de/bafa/de/energie/mineraloel_rohoel/amtliche_mineraloeldaten/2010/dezember.xls

the emission estimates for refineries are not as straight forward as some other process industries. Some of these issues are identified below.

The largest single fuel used in refineries is Refinery Fuel Gas. It can account for more than 50% of energy consumption in most refineries. This fuel is self-generated, so there is not always the same level of metering that one would expect from a purchased fuel. In addition to uncertainty regarding the quantity of fuel consumed, refinery fuel gas composition will vary from refinery to refinery and even from day to day as process conditions change.

The second largest source of combustion emissions is from the regeneration of the FCCU coke. These emissions are usually calculated based on mass or energy balance calculations augmented by spot determinations of coke composition.

Even for the highest level Tier in the API/IPECA/OGP guidelines, it is recognized that mass balance calculations and default emission factors may be required for some fuels. These guidelines identify the uncertainty of the GHG emissions from combustion sources as +5% to –10% in the best case.

Flaring emissions are usually based on estimates of the quantity and composition of material sent to the flares. In some instances gas is metered prior to combustion.

The emissions from hydrogen plants will be relatively good when the hydrogen plant is located within the refinery. Some refineries will purchase hydrogen from a third party supplier and these emissions will generally not be included in a refinery emission inventory.

Fugitive emissions are always difficult to estimate since they are generally small and occur over long periods of time.

In addition to the uncertainty in the actual measurement or calculation of energy use in refineries, there are few databases that include own consumption and purchased energy in the same database.

6.3 TRANSPORTATION AND END USE

The final stages in the fossil fuel life cycle involve the transportation from the refineries to the final distribution point and the use of the fuel in the vehicle.

This should be one of the most straightforward aspects of the emission calculations, provided that the composition of the fuel is known. However, there are some differences between the values that are used in some models. These are shown in the following tables.

Table 6-6 Gasoline Properties

Model	Specific Gravity	Carbon Content	GHG emissions, g/MJ
GHGenius	0.739	0.862	69.4
GREET	0.745	0.863	72.6
JRC (EU values)	0.750	0.870	74.3

Table 6-7 Diesel Fuel Properties

Model	Specific Gravity	Carbon Content	GHG emissions, g/MJ
GHGenius	0.843	0.858	75.2
GREET	0.847	0.865	75.3
JRC (EU values)	0.835	0.862	73.5

6.4 SUMMARY

The fossil fuel life cycle is extremely important as not only does it produce dominant fuels used in the transportation sector today but it is also the reference fuel against which alternatives are compared. Despite this, there are significant uncertainties with respect to the system boundaries of many analyses, the data quality and completeness, and the way that the emissions are allocated between the products produced by refineries. The key conclusions from this review are:

1. Not all analyses include the emissions associated with exploration and drilling for oil.
2. The quality of data on the emissions associated with oil production is poor and may underestimate GHG emissions.
3. These emissions appear to be increasing with time and models that do not account for this will underestimate emissions.
4. There are significant regional differences in the emissions associated with crude oil production.
5. Refining emissions should be easier to estimate but even the primary data for energy use has some uncertainty associated with it due to the difficulty in measuring the quantities of refinery fuel gas and coke burned. Different data sources can report different results, even for the same process and country.
6. The allocation of refining emissions to specific products is a complex issue and there may not be a single correct approach.
7. Refining emissions can vary with the quality of the crude oil processed and systems that analyze the emissions of crude oil

production and refining independently will not produce accurate results.

8. The specifications of the final product can influence life cycle emissions.

7. NATURAL GAS

Like electricity, natural gas can be considered a vehicle fuel as well as a major input into other production systems. It is therefore an important pathway in LCA modelling systems. Natural gas production is widely distributed throughout the world, even more so than crude oil production.

7.1 FUEL PRODUCTION

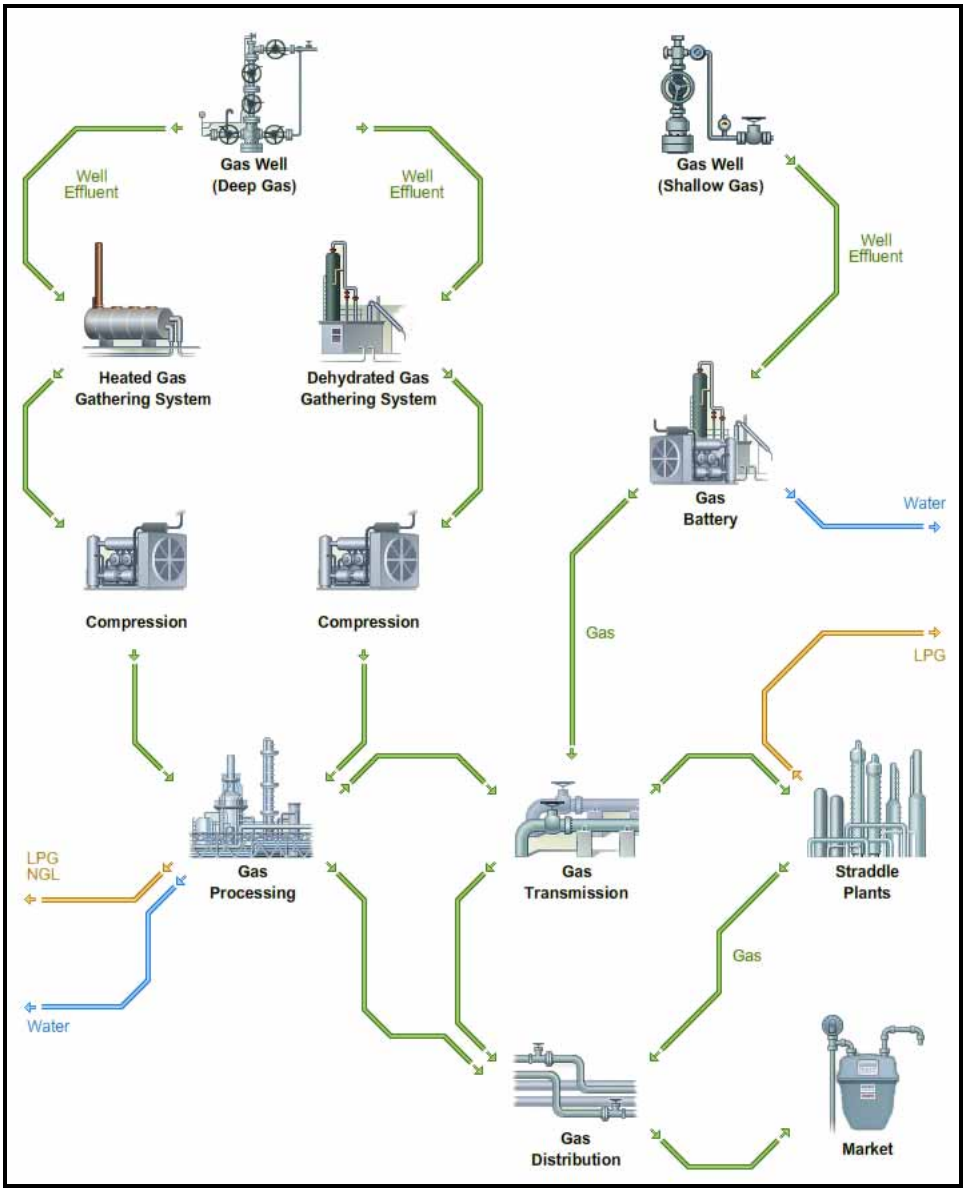
Oil and natural gas systems encompass wells, gas gathering and processing facilities, storage, and transmission and distribution pipelines. These components are all important aspects of the natural gas cycle - the process of getting natural gas out of the ground and to the end user – and they can generally be broken out into four sectors, defined as follows:

- Production focuses on taking raw natural gas from underground formations.
- Processing focuses on stripping out impurities and other hydrocarbons and fluids to produce pipeline grade natural gas that meets specified tariffs (pipeline quality natural gas is 95-98 percent methane in North America, while in Europe and Asia gas quality can be more variable).
- Transmission and Storage focuses on delivery of natural gas from the wellhead and processing plant to city gate stations or industrial end users. Transmission occurs through a network of high-pressure pipelines. Natural gas storage also falls within this sector. Natural gas is typically stored in depleted underground reservoirs, aquifers, and salt caverns.
- Distribution focuses on the delivery of natural gas from the major pipelines to the end users (e.g., residential, commercial and industrial).

In the oil industry, some underground crude contains natural gas that is entrained in the oil at high reservoir pressures. When oil is removed from the reservoir, associated or solution natural gas is produced. Both associated and non-associated gases are considered conventional natural gas as part of this work.

The following figure shows the flow of gas from the well to the end market.

Figure 7-1 Natural Gas Production System



Source: Methane to Markets. Sponsored by NRCan.

It is apparent from the figure that the emissions from different gas fields could be quite different, as the processing of the gas that is required will be a function of the impurities in the gas. Dry shallow wells may receive minimal processing prior to compression, transmission and distribution, whereas deep wet gas may require significantly more processing to achieve the same composition that is suitable for downstream use.

In many fields, natural gas is also used to drive pneumatic devices, as compressed air is not available. This gas is usually exhausted to the atmosphere as a component of gas leaks and flares.

7.1.1 System Boundaries

Natural gas production emissions are those associated with drilling wells, and producing and processing the gas. For conventional gas, the main emission sources are from the use of energy for drilling, heating and compressing the gas, and from leaks and flares from equipment. These emissions vary between regions depending on development practices; in Nigeria for example; gas venting and flaring is common and leads to relatively high upstream emissions, while in Canada upstream emissions are small as a result of focussed attention by industry. There is some debate about data on production emissions for shale gas where horizontal drilling and fracking technology is used. The emissions vary with the type of shale deposit and particularly with the number of times the wells are subjected to re-fracking over the well lifetime. Well lifetimes, and thus estimates of ultimately recoverable gas from shale gas wells are uncertain since shale gas production is a very young industry. A source of methane from shale gas is from flowback water used in pressurizing wells; some of this methane can be recovered, although in some regions this is not always the current practice. Once the well is producing, there is little difference between a conventional well and a shale gas well.

Natural gas systems have similar system boundary issues to crude oil systems. Some modelling schemes include the exploration and well drilling steps and others do not.

7.1.2 Allocation

In countries where the data for the energy use in natural gas systems is combined with that of oil systems, an allocation of emissions between the two products is required. Most models use allocation by energy content for this calculation. This allocation could be avoided if better quality data is available.

Some allocation is also required at the gas plant level, since these plants produce pipeline quality natural gas and some natural gas liquids. Energy allocation is also most often used here.

7.1.3 Temporal Issues

There are no high quality time series of information available for natural gas production, as there are for many of the other important parameters for transportation fuel production systems.

Gas is mostly brought to the surface under its own pressure so unlike crude oil production the energy requirements for gas production should be relatively constant. Equipment and field age could be an issue with respect to system leaks; whereas increased attention to leaks by the industry in the past decade will tend to reduce emissions, this improvement could be partially offset by the increasing age of the systems.

The energy requirements of gas processing plants will be a function of the level of impurities (CO_2, water, and other hydrocarbons) and while these could change with time, such changes will not necessarily exhibit any trends.

7.1.4 Regional Issues

Gas quality, and thus processing energy, will vary from region to region. Another significant issue will be the leakage rate from production, transmission and distribution systems. Ages of these systems can vary widely, which means that they could be constructed with different materials and different control systems.

7.1.5 Data Quality

As for crude oil systems, data availability and data quality for gas systems is not very high in most regions of the world.

7.2 Fuel Transmission and Distribution

Natural gas generally moves through large diameter pipelines from the gas plants to the regions where it is consumed. In the consuming regions the gas generally moves through smaller diameter pipelines to the final consumer of the gas. There is energy required for the compression of gas upon entry into the pipeline system and at periodic distances along the system to overcome the frictional losses. This energy can be supplied by natural gas driven compressors or in some instances large electric motors. There is a significant difference in energy demand, efficiency, and emissions between reciprocating piston and turbine compressors; whilst the former have all but disappeared from North American transmission systems, that may not be true globally. Transmission distances and pipe size also influence the energy consumed.

Leaks and losses of methane are also sources of GHG emissions and vary significantly from one region to another.

7.2.1 System Boundaries

System boundaries are relatively well established for natural gas transmission and storage stages.

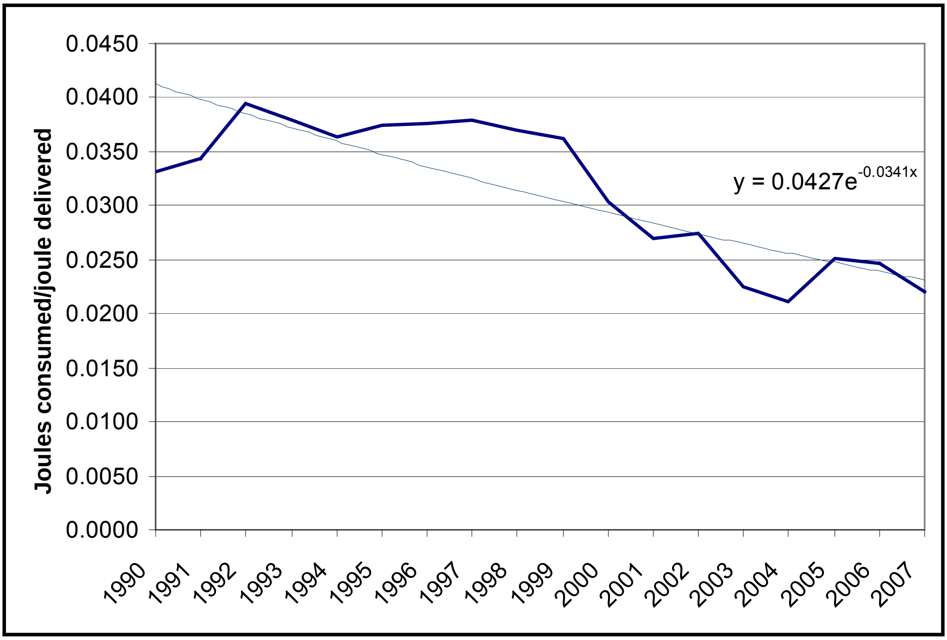
7.2.2 Allocation

With mostly just one product in this stage of the life cycle, allocation is not an issue for gas transmission and storage. The one exception is when waste heat is captured at compression stations. This can be treated by displacement or energy allocation.

7.2.3 Temporal Issues

In some regions good datasets on energy consumed per unit of gas transported are available. Statistics Canada reports information on the supply and disposition of natural gas on a monthly basis. The data includes fuel consumed and the quantity of gas transported. The quantification of the gas transported is a complex issue as it depends on receipts and deliveries at multiple points over a long distance. In the following figure the fuel consumed as a fraction of total net gas disposition is presented. Energy consumption has been declining over time.

Figure 7-2 Pipeline Fuel Consumption



7.2.4 Regional Issues

GHG emissions for natural gas transmission and distribution will be mostly influenced by the transportation distance and local leakage rates. Both factors will vary significantly from region to region.

7.2.5 Data Quality

In some regions the data on energy use is quite good and is updated on an annual basis, but data on leakage rates are not updated on a frequent basis. Due to the high GWP for methane, this can introduce significant uncertainty into emission estimates.

7.3 CONVERSION TECHNOLOGY

Natural gas has a low energy density at ambient temperatures and pressures. In order to improve the cost effectiveness of natural gas transportation, the gas must be compressed or liquefied in order to increase its energy density and make it acceptable for mobile applications.

7.3.1 Compressed Natural Gas

The energy and emissions associated with compressing natural gas to between 20 and 30 MPa depend on a variety of factors, one of the most important being the gas inlet pressure. This parameter can vary from 0.1 to 4.0 MPa in practice.

Other drivers of the energy requirements are the type of motor used (gas or electric), and the design of the compressor.

As a result of this variability, emissions for the compression stage can be expected to vary considerably from region to region.

7.3.2 Liquefied Natural Gas

Liquefied natural gas can store more energy in the same volume than compressed natural gas and thus this storage medium is found more frequently in medium and heavy-duty truck applications where more fuel storage is required.

Energy use and emissions are a function of the efficiency of the liquefaction unit, the motors used (gas or electric) and leakage rates. Liquid natural gas is stored at –160°C and keeping the NG at that temperature can be a challenge. As the temperature of the fuel is raised, it boils off and there can be significant quantities of gas released to the atmosphere as a result. In stationary applications the gas can be recovered and re-liquefied but in mobile applications that might not be possible.

A wide range of data is available in the literature on liquefaction energy requirements and thus LCA results can also vary significantly. Data availability on industry wide averages is very poor.

7.4 VEHICLE USE

Natural gas releases the lowest amount of CO_2 per unit of energy of all of the hydrocarbon fuels. This advantage provides a significant benefit to users of the fuel. Some of this benefit can be offset by a lower efficiency in the engine, but this varies between engines depending on the technology used.

Natural gas can be used in light duty spark ignited engines, in medium duty spark ignited engines that have been converted from compression ignited engines, and in some compression ignited heavy duty engines. The relative performance of each of the families of engines varies widely and even within the same family there can be differences between manufacturers.

Some natural gas engines are aftermarket converted gasoline engines and the efficiency of these engines can vary significantly. Variability in the GHG emission performance of natural gas as a vehicle fuel can therefore be expected.

7.5 SUMMARY

Natural gas is an important transportation fuel in many parts of the world. It has an inherent advantage over other hydrocarbon fuels in that it produces less CO_2 per unit of fuel energy than all other hydrocarbons. There can be significant differences in natural gas production and utilization pathways in different parts of the world, and thus differences in reported emissions between studies may be a function of real system differences rather than differences in LCA methodology.

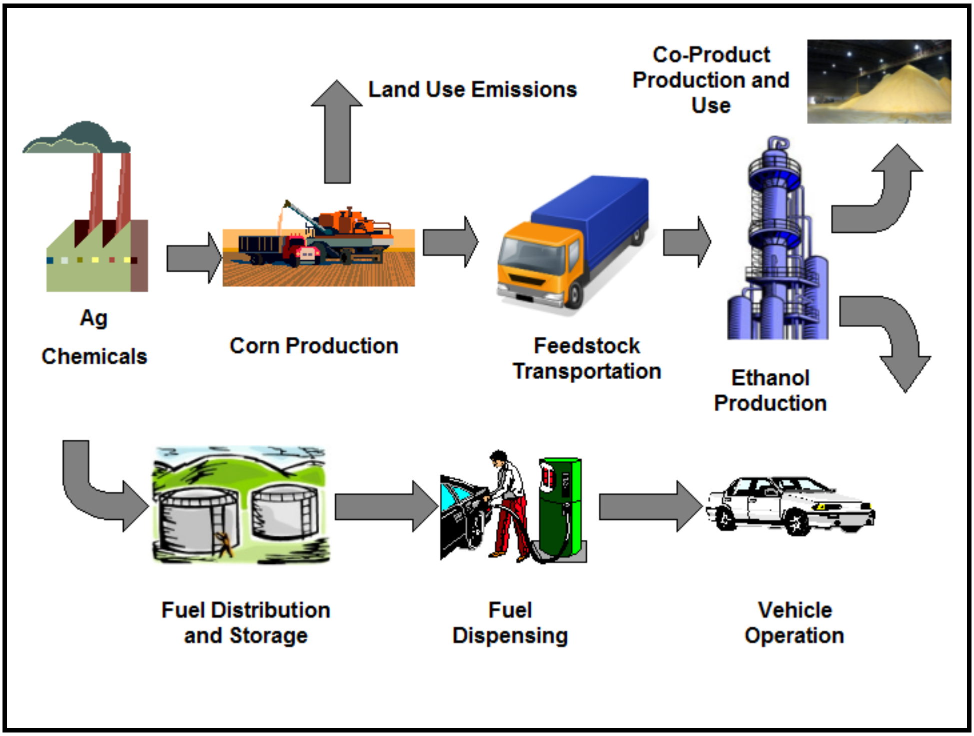
There is, however, potential for significant differences in LCA methodology:

1. Not all analyses include the emissions associated with exploration and drilling for natural gas.
2. The quality of data on emissions associated with gas production is poor, particularly with respect to leaks, and may underestimate the GHG emissions.
3. There can be significant regional differences in the emissions associated with gas production.
4. Different LCA practitioners may use different GWPs or different time horizons.
5. The energy requirements for gas compression are very dependent on local conditions and this can influence the life cycle results.
6. The conversion of gas energy to work in the vehicle is a function of engine design and this can vary widely.

8. ETHANOL

Ethanol is the largest volume biofuel used in the transportation sector today. It is made primarily from corn (maize) and sugar cane. A number of other feedstocks are used including sugar beets, wheat, rye, barley, cassava and other starch bearing crops. A large number of process developers are working on developing technologies that could produce ethanol from lignocellulosic materials rather than from sugar or starch crops. The basic ethanol life cycle is shown in the following figure.

Figure 8-1 Ethanol Life Cycle



The ethanol life cycle is one of the most studied fuel life cycles and one with the largest variation in results. There are a number of reasons for this variation, some are modelling related, but others represent actual differences in the production systems.

There are two new stages in the figure above compared to the fuel systems considered in the previous chapters, fertilizer manufacture and land use emissions. Both of these stages contribute to the large variation in results for biofuel LCAs. All of the stages are discussed in this section.

8.1 AGRICULTURAL INPUTS

The production of crops requires the input of nitrogen, phosphorus, and potassium fertilizers, sometimes the addition of lime for soil ph adjustment, and often the application of pesticides to control weeds and insects.

The fertilizer requirements of all crops are different; some crops have the ability to fix their own nitrogen requirements from the air, whereas others require the addition of synthetic nitrogen fertilizers.

8.1.1 System Boundaries

The production of fertilizer is included in most biofuel LCAs. Some include packaging and details on transportation, but these portions of the production cycle are generally low compared to the actual manufacturing of the materials.

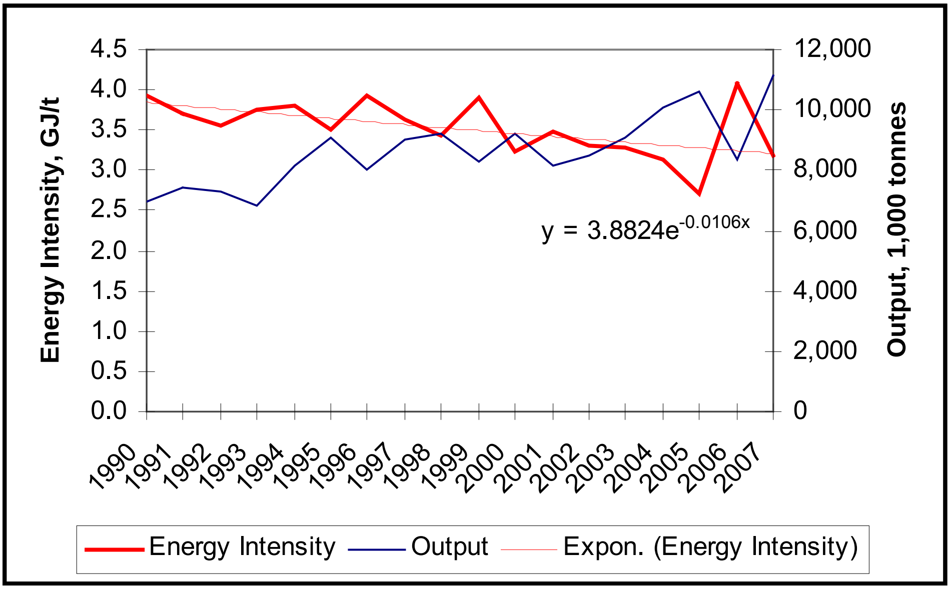
8.1.2 Allocation

Many fertilizer and pesticide production facilities produce more than one product and so that if primary data is available then some allocation might be required. In many cases it may be possible to look at the parts of the production system and avoid allocation. Unfortunately, very little primary data is available for these materials and allocation has not been feasible.

8.1.3 Temporal Issues

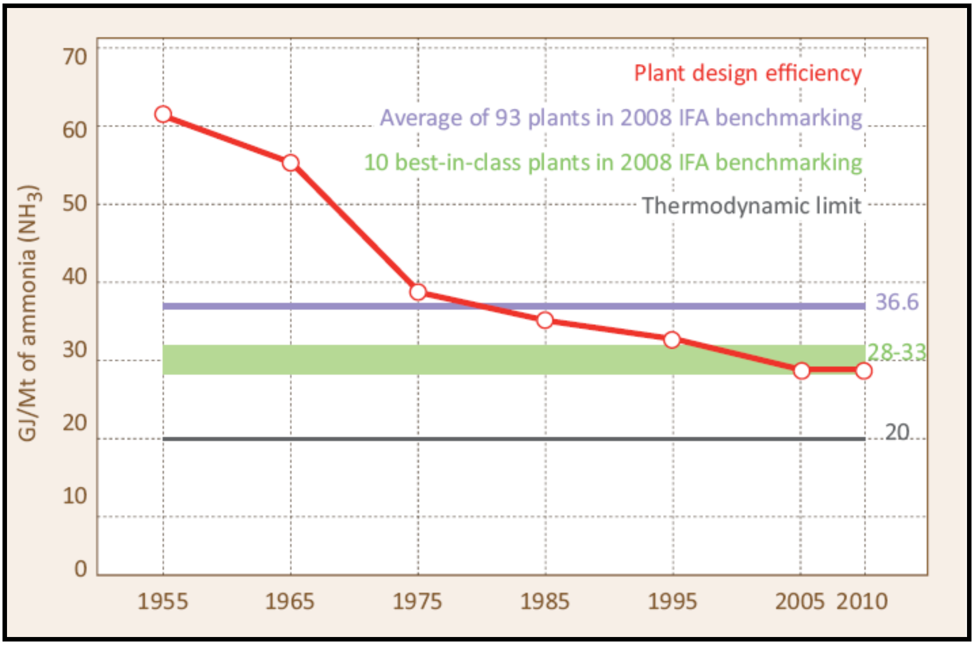
All manufacturing processes tend to become more efficient over time. This will generally lead to a reduction in GHG emissions. In the case of some nitrogen manufacturing processes, companies have implemented measures to reduce emissions of N_2O from their process and this can have a significant impact on emissions. There are relatively few time series of data that are available to document the reduction in emissions for all types of fertilizers. Two time series are shown below.

Figure 8-2 Canadian Potash Energy Intensity



Source: CIEEDAC Database. Canadian Industrial Energy End-Use Data and Analysis Centre.

Figure 8-3 Energy Ammonia Manufacturing



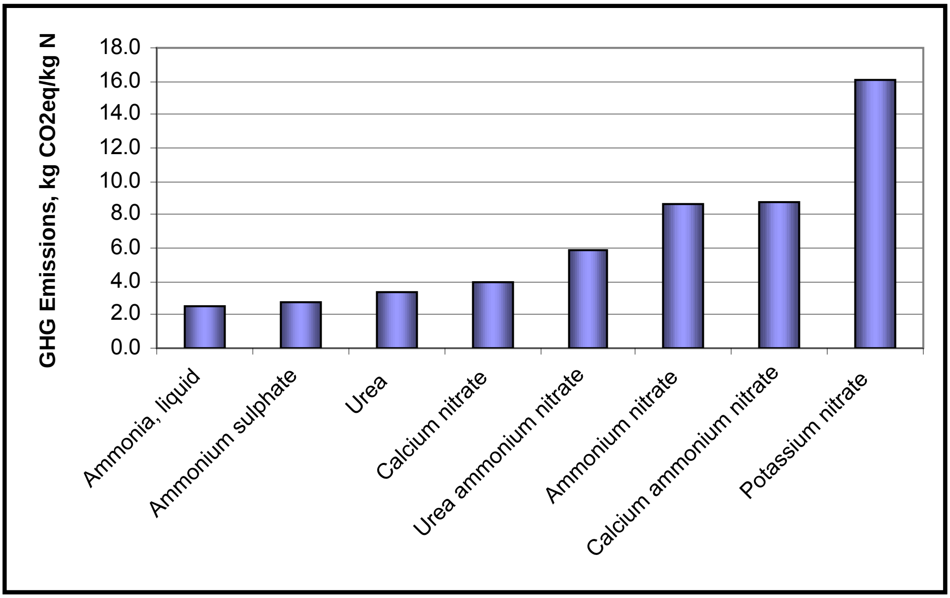
Source: IFA. 2009

8.1.4 Regional Issues

A larger issue is that there are many different types of nitrogen fertilizers used and they have very different GHG emission profiles. The mix of fertilizers can change from region to region, so therefore the GHG emissions will change between regions.

The following figure shows the GHG emission intensity for nitrogen fertilizer types in the Ecoinvent database. The data is for Europe and is based on year 2000 production efficiencies.

Figure 8-4 GHG Emissions Nitrogen Fertilizer Manufacturing



Source: ecoinvent version 2.

There is almost an order of magnitude range between the lowest and highest emissions, with nitrate fertilizers having much higher GHG emissions than ammonium type fertilizers.

There are large differences in the types of nitrogen fertilizer applied in the different regions. The types of nitrogen fertilizer used in Canada (CFI, 2009), the UK (DEFRA, 2010), and Western Europe (EFMA, 2010) are summarized in the following table.

Table 8-1 Types of Nitrogen Fertilizer Applied, as Percentages

	Canada	United States	UK	Western Europe
Urea	54.3	21.1	13.7	18
Urea ammonium nitrate	10.6	UAN is included as part of Ammonia in the US.	6.2	12
Calcium ammonium nitrate	0.0	0	1.5	24
Ammonium Nitrate	0.0	8.2	51.8	19
Ammonia	27.9	70.7	0.0	0
Other	7.2		26.8	27

The emission factor for nitrogen fertilizer varies widely in the various models that are available. The factors from some of the models are compared in the following table.

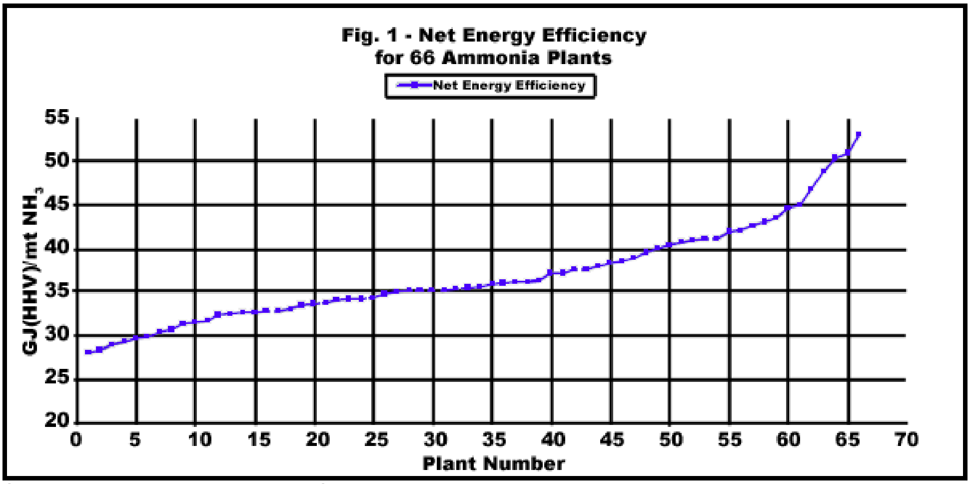
Table 8-2 Comparison of Nitrogen Fertilizer Emission Factors

Model	Value, g CO_2eq/kg N	Comment
BioGrace	5.88	Reference is IFEU (1997)
Gemis	6.95	Reference is IFEU (1997)
GREET	2.97	US data
GHGenius	2.79	Canadian data (mostly NH_3 and Urea)

The European models have GHG emission factors about twice that of the North American models. Given the higher use of nitrate fertilizers in Europe this is not surprising, but the reference used is almost 15 years old and it in turn was based on secondary data sources, some of which were more than a decade old at the time the reference was prepared.

In addition to the differences caused by the type of fertilizer produced, there are also significant differences from plant to plant. The IFA published the results of a benchmarking study of ammonia plants around the world in 2004 and found that the energy use at the most efficient plant was about half of that at the least efficient plants.

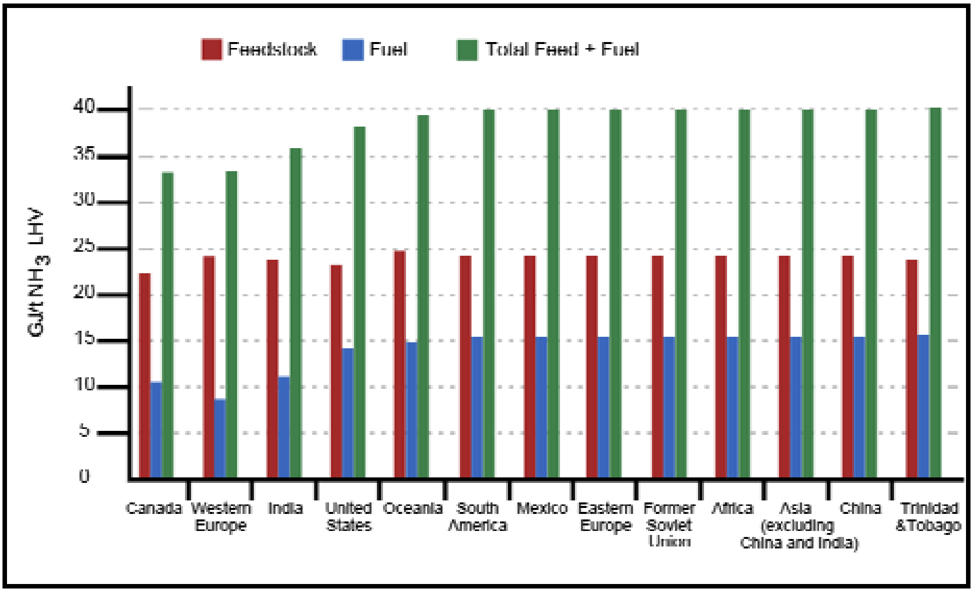
Figure 8-5 Net Efficiency Ammonia Plants



Source: IFA 2004 Benchmarking Study.

It is also known that there are regional differences in technology and efficiency, which are reflected in the values shown here. The following figure is from an NRCan report (2007) that benchmarked the energy efficiency performance of the Canadian ammonia industry. There would be a similar trend in GHG emissions.

Figure 8-6 Regional Ammonia Plant Energy Efficiency



The emissions for the production of phosphorus and potassium are not as high as they are for nitrogen and the application rates are lower for most crops, but there is still significant variation between the LCA models. The emission factors are summarized in the following table.

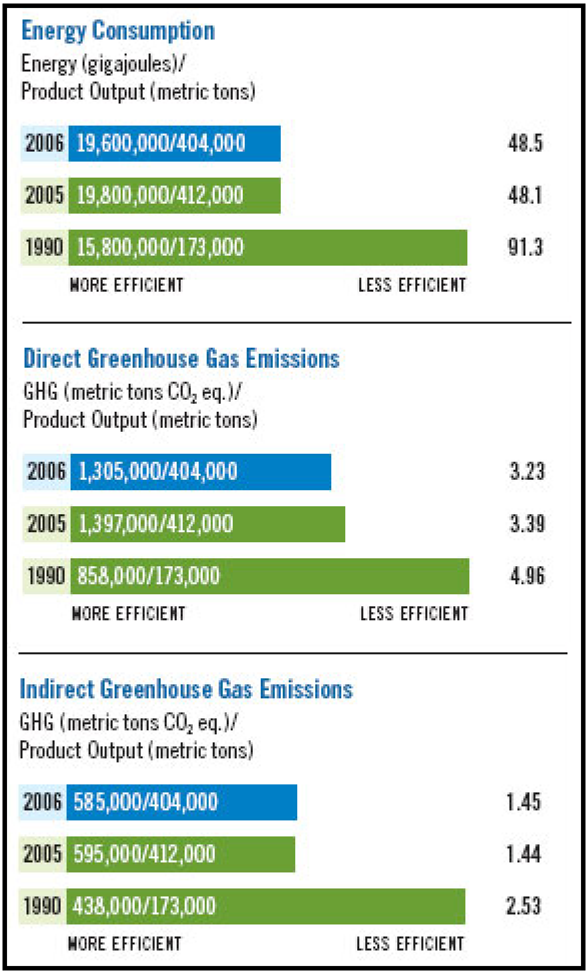
Table 8-3 Comparison of Phosphorus and Potassium Fertilizer Emission Factors

Model	Value, g CO_2eq/kg P_2O_5	Value, g CO_2eq/kg K_2O	Comment
BioGrace	1.01	0.576	Reference is IFEU (1997)
Gemis	0.70	0.492	Reference is IFEU (1997)
GREET	1.01	0.664	US data
GHGenius	0.73	0.348	K is primary data
ecoinvent	2.4	0.529	Europe 2000

Information on the emission intensity of pesticide production is quite poor. The manufacturers generally have not published any details on their processes due to confidentiality and intellectual property concerns. The values that have been published are estimates made by researchers making assumptions about the production processes. Information on the energy intensity and related GHG emissions for individual chemicals is generally old and based on estimates of processes used rather than on actual plant data. Two of the most commonly referenced sources of information are Green (1987) and Helsel (1992). These estimates also do not cover newer chemicals.

Monsanto, a manufacturer of some of the chemicals, published (2007) some environmental performance data for their manufacturing plants and that information is shown in the following figure. Between 1990 and 2006, energy use declined by 47%, direct GHG emission intensity by 35% and indirect GHG emissions by 43%. For these metrics, Monsanto normalized the data so that the same product mix was being compared.

Figure 8-7 Monsanto Energy Performance



The most recent estimates of energy and emissions for chemical manufacture were by Audsley et al (2009). In many cases, they reported lower energy intensity for the chemical manufacturing process than that reported decades earlier by Green and Helsel. In almost all cases, emissions have been developed without access to actual plant performance data, which accounts for a portion of the reasons for the wide range in data.

Table 8-4 Comparison of Pesticide Emission Factors

Model	Value, g CO_2eq/kg AI	Comment
BioGrace	10,971	1999 German Biofuel LCA study
GREET	21,142	
GHGenius	21,694	
ecoinvent	3,000 to 17,000	Different values for different products

8.1.5 Data Quality

Overall data quality for the emissions associated with agricultural chemicals is not good. There are only a few instances where emission factors are based on current primary data sources. This low quality of information is part of the reason why the GHG emissions for biofuels vary significantly between studies.

1. From this review it has been shown that GHG emission performance is changing significantly with time.
2. There are a number of products used to supply nitrogen to plants and they have different emission profiles. The type of products used varies by region.
3. Most of the emission factors used in LCA models are based on secondary data. This data is either an estimate or is based on literature surveys. Very few are based on actual measurements at the plant level.

8.2 LAND USE EMISSIONS

There are basically two categories of land use emissions that need to be considered in a biofuel LCA, the emissions of N_2O associated with the application of nitrogen fertilizer and the decomposition of agricultural residues, and decreases or increases in soil carbon associated with the management of the soil. Even small quantities of the N_2O emissions are important, since the gas has a relatively high GWP of 296-310.

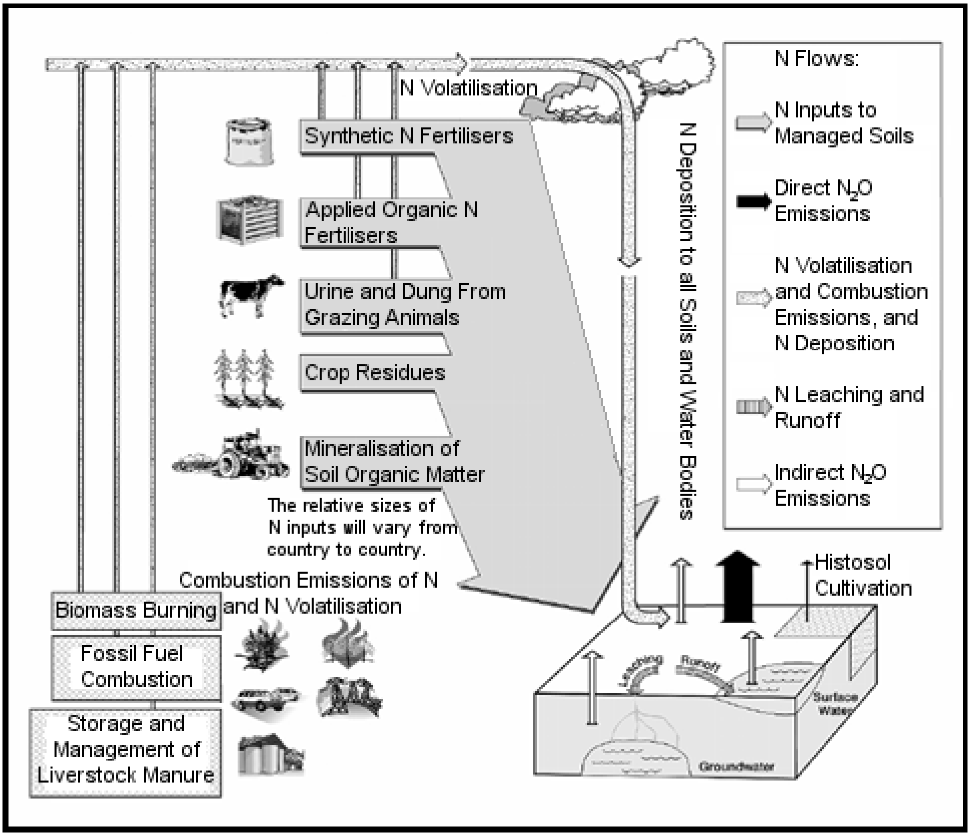
8.2.1 N_2O Emissions

The application of nitrogen fertilizers creates N_2O emissions. The rate of N_2O emitted is a function of soil type, moisture levels, temperature and other factors. All of these factors will vary from region to region.

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) have been built upon a body of work that has evolved since the first Guidelines were published in 1996 (IPCC, 1996). These new guidelines include new sources and gases as well as updates to the previously published methods, whenever scientific and technical knowledge had improved since the previous guidelines were issued.

The sources of N_2O emissions covered by the IPCC are shown in the following figure. Most of the sources are an important part of the biofuel production pathways with the exception of animal manure and dung.

Figure 8-8 Nitrogen Cycle



Source: IPCC

For biofuel systems the most important parameters from a regional perspective are the application rate and emission factor for synthetic nitrogen fertilizer (EF_1), the nitrogen content of the crop residues, and the leaching rates and run-off emission factor (EF_5).

The 2006 IPCC Guidelines generally provide advice on estimation methods at three levels of detail, from Tier 1 (the default method) to Tier 3 (the most detailed method). The advice consists of mathematical specification of the methods, information on emission factors or other parameters to use in generating the estimates, and sources of activity data to estimate the overall level of net emissions (emission by sources minus removals by sinks). The uncertainty can be very large when using Tier 1 methods but is expected to be lower when Tier 2 or Tier 3 approaches are used.

Properly implemented, all Tiers are intended to provide unbiased estimates, and accuracy and precision should, in general, improve from Tier 1 to Tier 3. The provision of different tiers enables inventory compilers to use methods consistent with their resources and to focus their efforts on those categories of emissions and removals that contribute most significantly to national emission totals and trends.

Some LCA models (e.g. GHGenius) include the complete set of IPCC equations for calculating the N_2O emissions. Other models (e.g. GREET) do the calculations outside of the model and use a single number inside the model to multiply by the synthetic nitrogen applied to arrive at N_2O emissions. Other models use an approach in between these approaches.

Not only do the various LCA models take different approaches to modelling these emissions, but different countries use different approaches to estimating these emissions in their national inventories. Three regions are compared here to demonstrate the variability, the emission factors and Tier employed in each country's National Inventory Reports (Environment Canada, 2010, German Federal Environment Agency, 2010, AEA Technology plc., 2010). The results are summarized in the following table.

Table 8-5 Summary Of N_2O Emission Factors

	Canada[19]	UK	Germany
Approach	Tier 2	Tier 1	Tier 1
EF_1	0.0076	0.0125	0.0125
Fraction leached	0.05	0.30	0.30
EF_5	0.0075	0.025	0.0075

The UK and German values for EF_1 are from the 1996 guidelines and the new value for this factor from the 2005 guidelines is 0.010. However, with the moisture that is available for crops in these countries, it is likely that the actual emission factor is above the default value. Both countries are still using the 0.0125 value in their 2008 National Inventory reports.

The EF_5 value use by Germany is the default value from the 2006 guidelines and the UK value is at the upper end of the range for this parameter in the 2006 guidelines, but it was the default value in the 1996 guidelines.

The Canadian values represent the semi-arid production region of western Canada that produces the majority of canola and wheat in Canada. These values are significantly different from the Tier 1 values used in the UK and German inventory reports. Both the UK and Germany employ the Tier 1 approach so it is possible that the actual emission factors are different from the default values employed. Some European analyses also incorporate nitrogen loss as nitrous oxide in transpiration from fields during winter (after growing season and during fallow periods), which turns out to be rather significant.

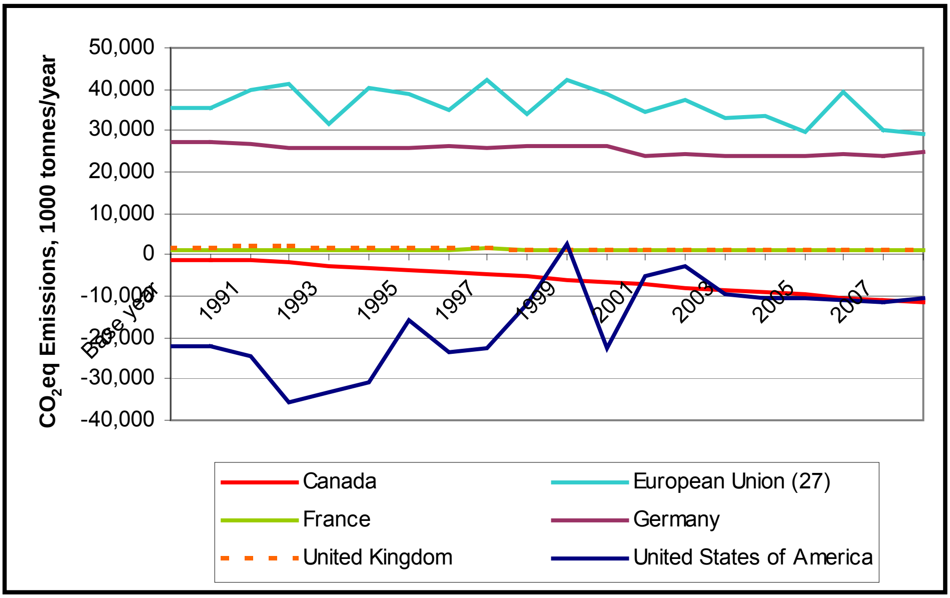
[19] Canadian Prairies.

8.2.2 Carbon Pool Changes

The second important class of sources of potential emissions are changes in the carbon pools associated with the land use. These changes may evolve from different land cover types (such as the conversion of forest land to agricultural land) or from land management changes (such as the conversion from full tillage to no till agriculture).

Most biofuel LCAs assume that there is no change in the land use (ag land stays ag land) but some do include the impact of soil carbon changes through land management practices. The importance of including these emissions varies from country to country. Selected data from the UNFCCC is shown in the following figure. As a whole, the EU 27 is losing agricultural soil carbon, but some countries, such as France and the UK, report very low levels of carbon loss. Germany accounts for a large portion of the EU soil carbon loss in agricultural lands. Conversely, Canada and the United States report increases in soil carbon in their agricultural soils. In the United States, the Conservation Reserve Program (CRP) accounts for some of the increase, whereas in Canada most of the increase is attributed to the adoption of no till management practices and some shifting from annual to perennial crops.

Figure 8-9 Soil Carbon Changes



Source: UNFCCC

8.2.3 System Boundaries

While essentially all biofuel LCA models include some estimate of N_2O emissions, the calculation approach is sometimes simplified to the point where it is not possible to determine what is included in the system boundaries and what is not.

The changes in the carbon pools, particularly the soil carbon pool, is often excluded from the system boundary. The models essentially assume that there is no change in soil carbon resulting from the management of the soil to produce the crop. This assumption is appropriate for some regions (such as France and the UK), as shown in the previous figure, but it is not appropriate in other regions. This could increase or decrease the emissions from crop production.

The magnitude of the impact on emissions is difficult to generalize since it depends on crop yield and management practices, but it can be significant. For a crop such as canola in western Canada, inclusion of soil carbon changes can reduce emissions by 5 to 10 g CO_2eq/MJ (5% to 10% of the life cycle emissions of the reference fuel, petroleum diesel).

8.2.4 Allocation

There are usually no allocation issues with the emissions related to the use of land. All emissions are attributed to the production of the crop. In some regions, the crop residue may be collected and utilized in addition to the primary crop. If the residues are used for an activity outside of the biofuel production activity then some allocation of feedstock production emissions will be required. Note that regulatory requirements may differ and may specify that no allocation should be done for the residues if they are later considered as emission free raw material. This is the case, for example, in the EU Renewable Energy Directive (RED) guidelines for calculating the GHG emissions of biofuels (same methodology followed in the Biograce). In the RED it is stated that the calculation of GHG emissions of a biofuel produced from residues only starts from the collection of the residue raw material (so zero emission for residue cultivation). It may be possible to determine the emissions that should be allocated to the residue by analyzing the specific activity related to collection of the residue, or by looking at the difference in the GHG emissions between a system that collects residues and one that doesn’t.

8.2.5 Temporal Issues

Management practices do change with time, so the land use emissions have the potential to change. New technologies, such as slow release nitrogen fertilizers, have been developed that have the potential to change some of the N_2O emission factors that are used in models. This will be a difficult challenge for modellers as while there is some information on the effectiveness of these products, there is little information available on their market penetration.

8.2.6 Regional Issues

As noted above, the N_2O and soil carbon emissions from land use are very dependent on regional factors. There are only a few LCA models that attempt to apply regional emission factors. There is also a wide range in the emissions reported in National Inventories, as some Governments use the 2006 IPCC Guidelines, others use earlier versions, and different countries uses different Tiers in the IPCC guidelines. Overall, these emissions are a source of significant variation between models and reports on biofuel GHG emissions.

8.2.7 Data Quality

Related to the regional variation, there is also a wide range in the quality of the data used to calculate these emissions. Some modelling approaches simplify the complex equations into a single overall emission factor, while others calculate the emissions from fertilizer, residue decomposition, leaching and run-off separately, using regionally appropriate emission factors. A number of models fall in between these two approaches due in large part to the lack of available data.

8.3 CROP PRODUCTION

All crops require fertilizers, pesticides, and energy for implements for the preparation of the land, planting, growth and harvesting of the crop. These activities create either direct (occurring at the site) and/or indirect (remote from the site) GHG emissions. The specific inputs vary from crop to crop.

8.3.1 System Boundaries

The most common system boundary issue with crop production is the inclusion or exclusion of the energy embedded in farm machinery. The overall impact is relatively small; in GHGenius the impact is 0.05 to 1.75% of production emissions for ethanol feedstocks.

8.3.2 Allocation

The primary allocation issue associated with crop production is the allocation of emissions between the crop and the crop residue, in cases where the residues are also collected and utilized.

In many cases it should be possible to break down the inputs so that no allocation is necessary. For example the nutrient content of the crop and residue could be used to determine how much of the fertilizer is used by the crop vs. the residues. If the residue is collected in a separate pass of the field then the fuel used for that operation can be determined separately.

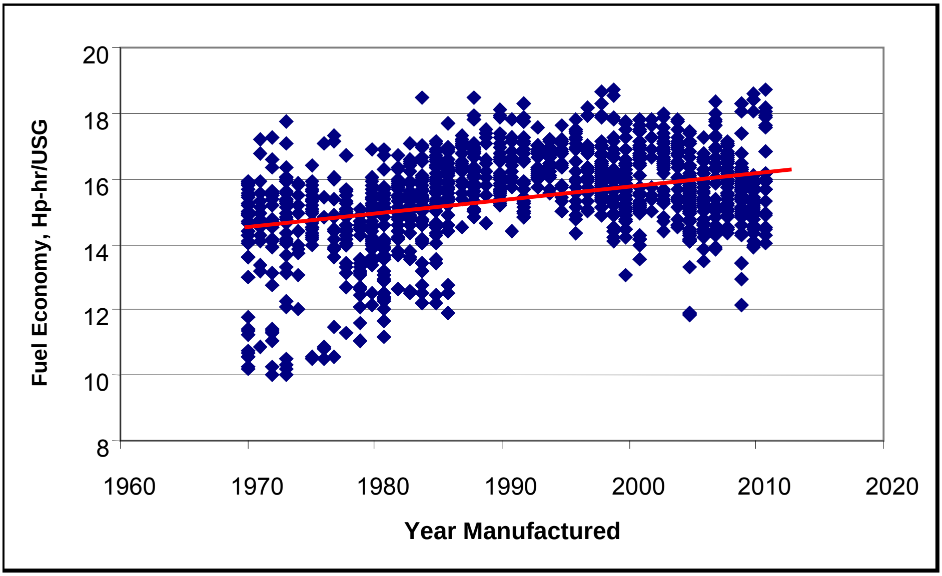
The secondary allocation issue for crop production is that most crops produce a primary product and a co-product. The emissions must be allocated across these two categories. This issue will be discussed later at the biofuel production plant level as it also applies to other portions of the life cycle.

8.3.3 Temporal Issues

There are very significant temporal issues related to crop production inputs. For life cycle analysis the relevant input is the quantity of fertilizer or fuel per unit of output produced. For inputs like fuel, the consumption is mostly a function of area, and thus the crop yield influences the actual fuel consumed per unit of biomass produced. Other inputs, like fertilizer, are more related to the quantity produced but there is still the potential to reduce the input quantities through precision farming and other advanced techniques.

Tractor efficiency is also changing over time. The following figure summarizes the results of about 1700 Nebraska tractor tests. Engine efficiency has improved significantly over the past 40 years.

Figure 8-10 Tractor Fuel Efficiency



8.3.4 Regional Issues

Agricultural practices vary widely from region to region. Soil and climatic condition play a large role in the variation, but the adoption of new technologies such as no till agriculture and precision farming are also important. The adoption of new technologies is partly a social issue and thus it should be expected that different regions adopt technologies at different rates.

8.3.5 Data Quality

Data quality is an issue for crop production, especially good time series related to fuel consumption. Producers generally do have good quality information on fuel purchased, but since they typically grow multiple crops the allocation of the fuel consumed to individual crops is often an issue.

Information on fertilizer and pesticide application rates is usually of higher quality as producers do keep good records of the quantities applied by field (and thus by crop).

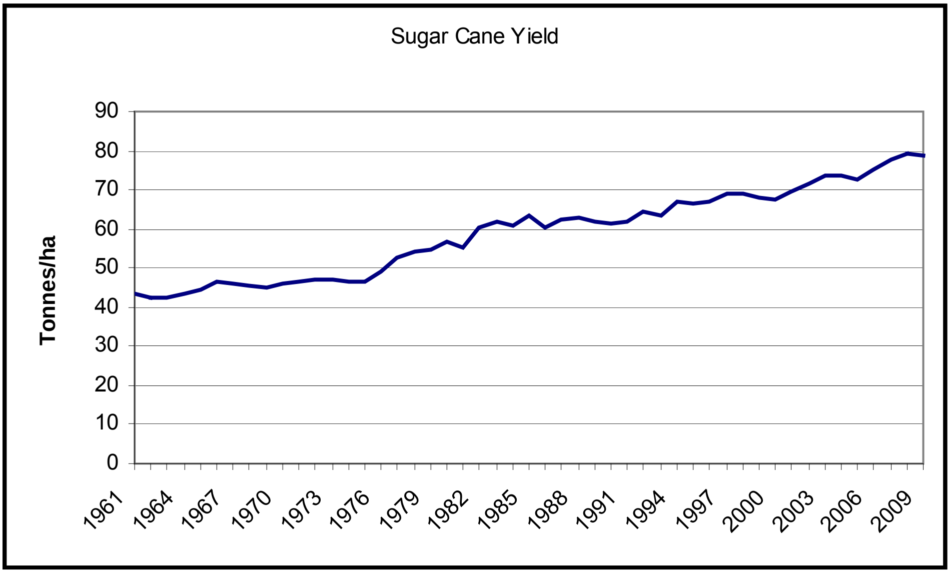
8.3.6 Specific Crop Information

In the following sections a selection of data is presented to show the temporal and regional issues with data for biofuel pathways. The data clearly demonstrates the need for timely regional specific data for accurate assessment of bio-ethanol pathways. All crops exhibit significant growth in yield and regional variation in yield.

8.3.6.1 Sugar Cane

Sugar cane is the primary feedstock for ethanol production in Brazil and a number of other tropical regions. Time series data is available for Brazilian sugar cane yields as shown in the following figure. The yield has almost doubled in 50 years. Up to date yield data is particularly important for mechanized harvest systems where fuel consumption is a function mostly of area and not the quantity produced.

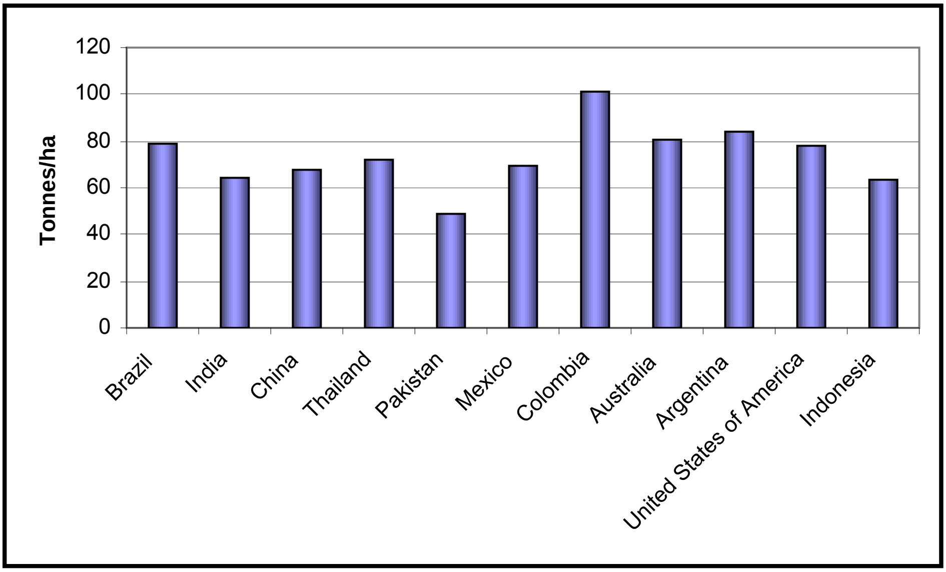
Figure 8-11 Brazilian Sugar Cane Yield



Source:FAO

Sugar cane yield can be quite variable from region to region. The yield results for the top 10 producing regions in the world in 2009 are shown in the following figure. The countries are arranged in order of total production from left to right, Brazil being the largest producer and Indonesia being the tenth largest. There is a two to one range between the top and tenth yield (Columbia to Pakistan). Care must therefore be applied when applying data collected in one sugar cane growing region to another.

Figure 8-12 Regional Sugar Cane Yield



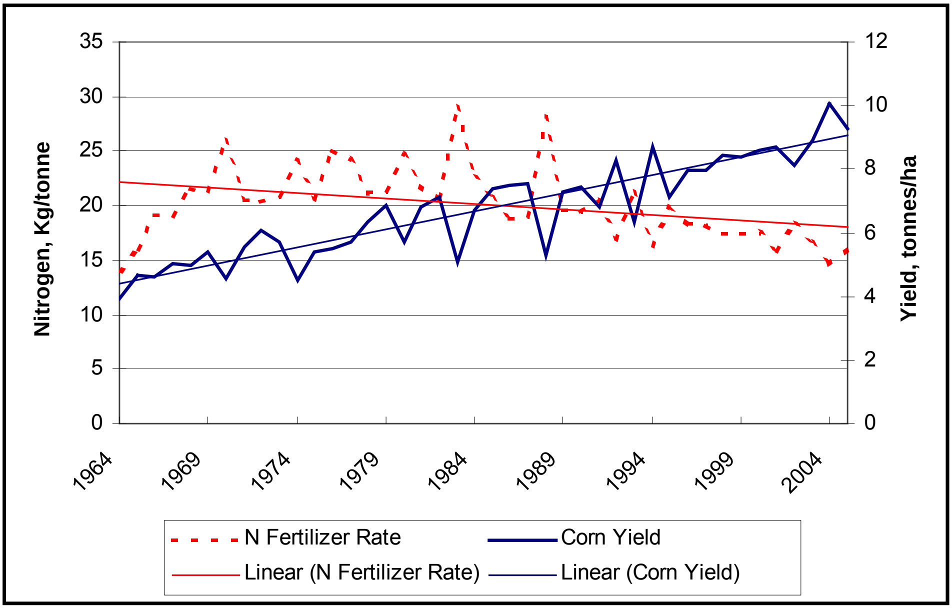
Source:FAO

There are a number of other factors that can influence the emissions from the production of sugar cane, including whether the cane is harvested mechanically or manually, whether the field is burned prior to harvest, and the presence of irrigation systems.

8.3.6.2 Corn

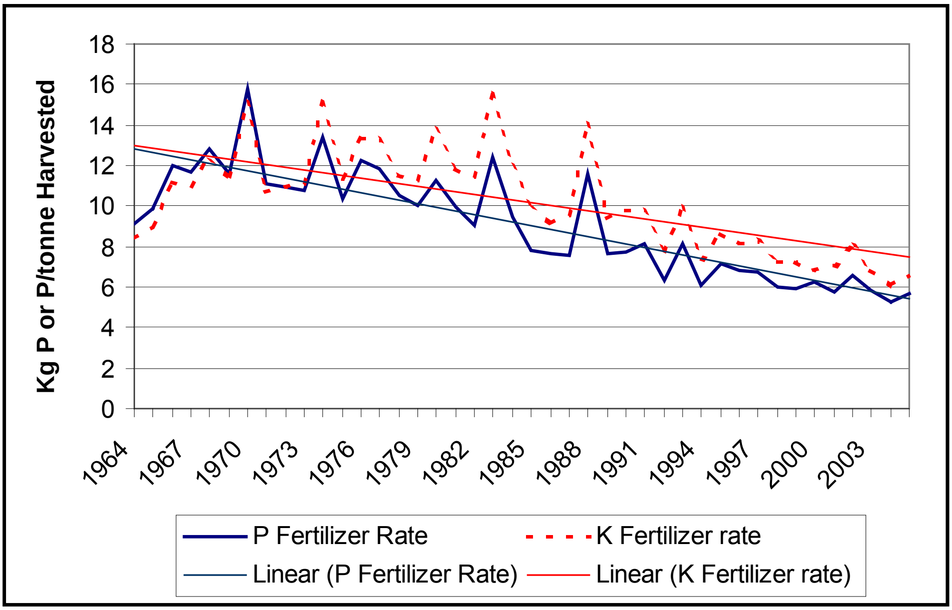
Corn (maize) is the primary ethanol feedstock in the United States. It is also used as a feedstock in Canada and some European countries. Like sugar cane, corn yields have increased significantly over the past 50 years as shown in the following figure. At the same time as yield has increased, the quantity of fertilizer used per tonne produced has declined dramatically. The reductions in fertilizer applied per tonne could be due to the development of new corn varieties, or increases in precision farming practices.

Figure 8-13 Changes in Corn Productivity



Source: USDA

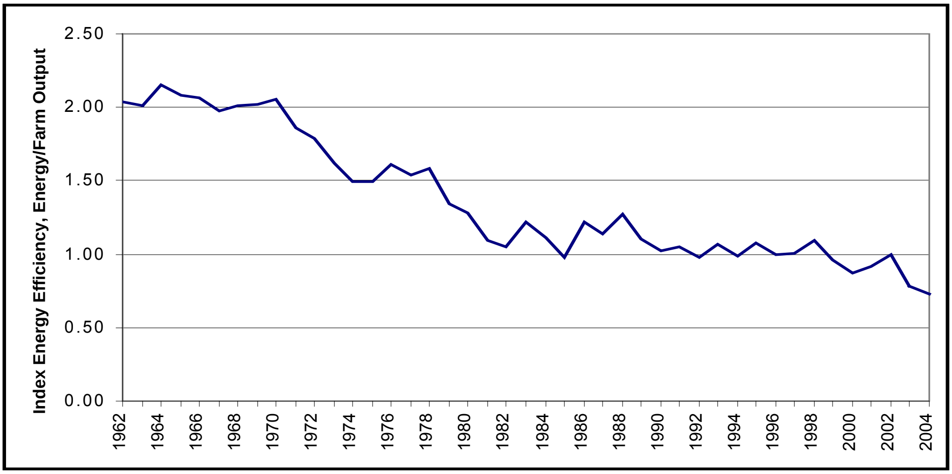
Figure 8-14 Corn Phosphorus (P) and Potassium (K) Fertilizer Rates



Source: USDA

Information on direct field energy use for corn production is difficult to obtain. The following figure shows the US Agriculture Energy Efficiency Index over the past 50 years, showing more than a 50% improvement in energy efficiency.

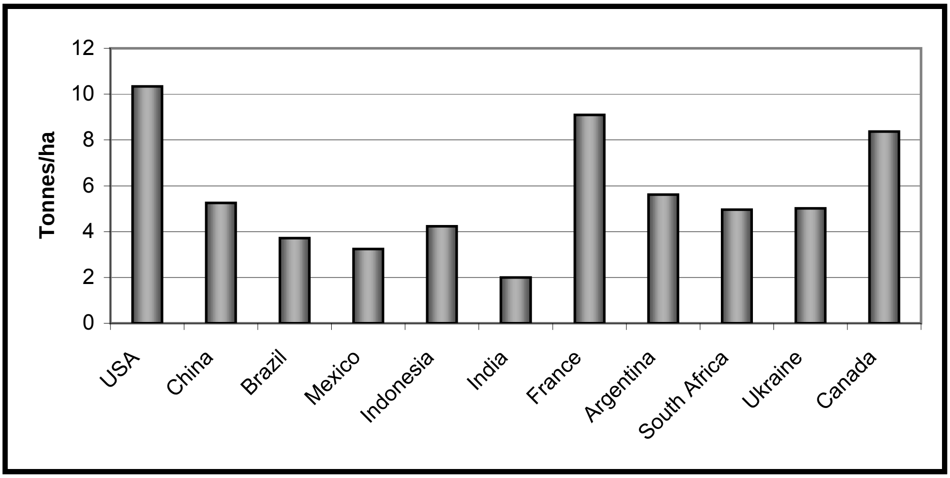
Figure 8-15 Agriculture Energy Efficiency Index - US



Source: USDA

US information for corn production must be used with care when applied to other regions, as there is great variability in the corn yield between growing areas. In the following figure, the 2009 corn yield is shown for the ten largest producing regions in the world. The countries are again arranged in order of production, with the US being the largest, to Canada being the tenth largest.

Figure 8-16 Regional Corn Yield

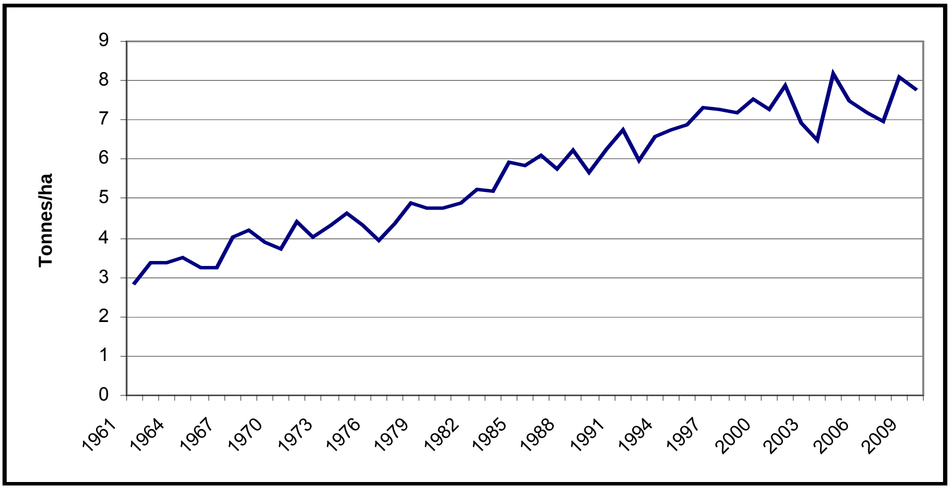


Source:FAO

8.3.6.3 Wheat

Like most crops, wheat yields have also increased significantly over the past 60 years. The following figure is the wheat yield for Germany, showing an increase of 167% during that period. It is therefore important to use the most recent data available when undertaking a wheat based LCA.

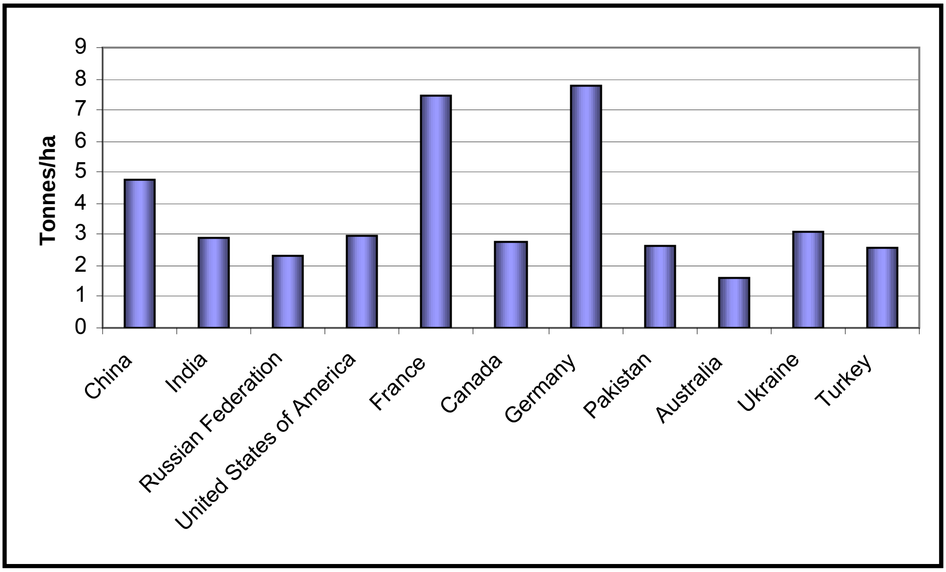
Figure 8-17 Wheat Yield - Germany



Source:FAO

The yield of wheat in the different regions is also very variable. This is shown in the following figure, which shows the wheat yields in the top ten wheat producing regions of the world. The yield in many countries is limited by moisture but that is generally not the case in France and Germany. The countries are again arranged in order of total production.

Figure 8-18 Regional Wheat Yields

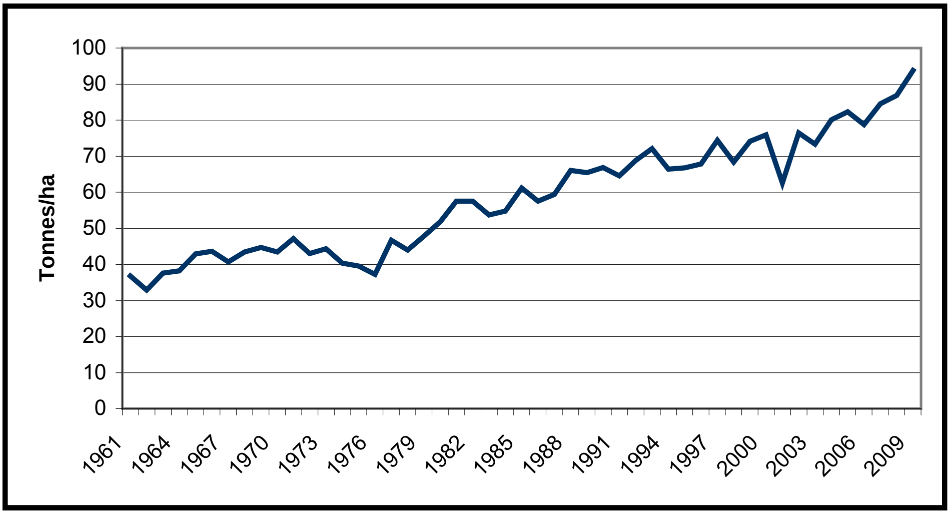


Source:FAO

8.3.6.4 Sugar Beets

Sugar beet yields in France have increased by more than 125% over the past 50 years as shown in the following figure.

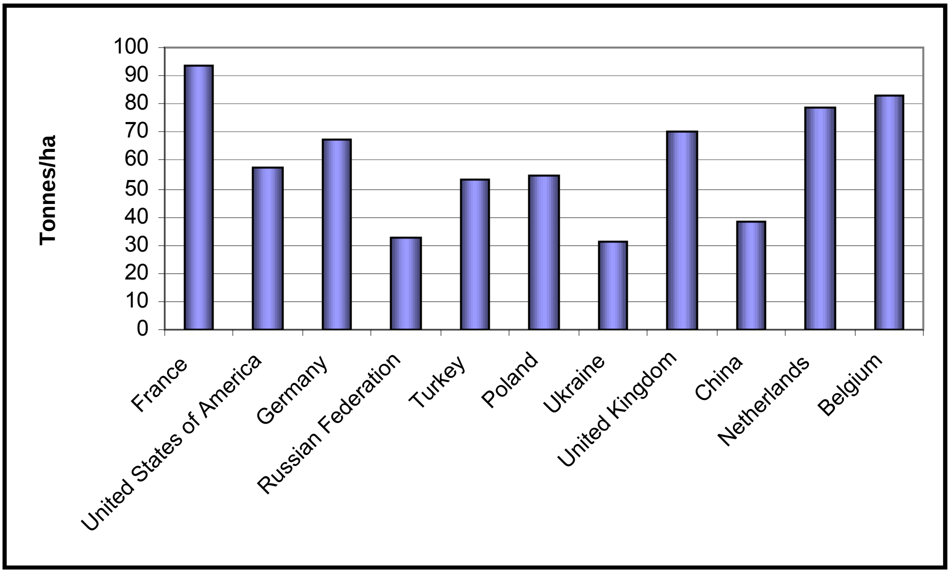
Figure 8-19 Sugar Beet Yield - France



Source:FAO

There is also a wide variation in the yield achieved by the top ten producers in the world as shown in the following figure. There is a range of more than 60 t/ha between France and the Ukraine.

Figure 8-20 Sugar Beet Yield – Top Ten Producers



Source:FAO

8.3.6.5 Lignocellulosics

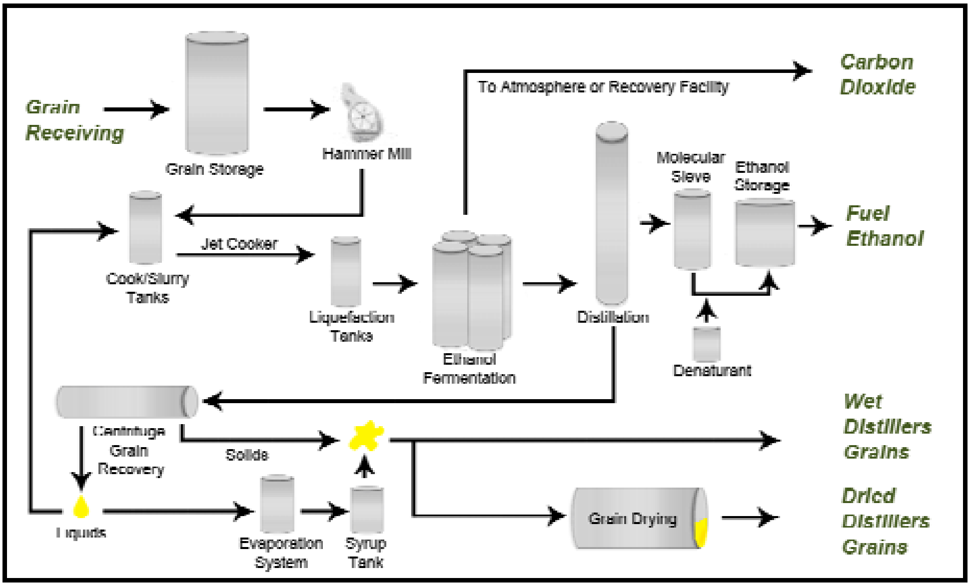
Lignocellulosic feedstocks for ethanol production might be residues, or they might be purpose grown feedstock such as switchgrass, miscanthus, or short rotation forestry. Each feedstock will have a different emissions profile.

In most cases, there is little experience with growing these materials for ethanol production and the data availability and quality is quite low. This can have a significant impact on the results that are produced.

8.4 ETHANOL PRODUCTION

The typical process for a dry mill ethanol plant is shown in the following figure. GHG emissions are a function of the fossil energy used, the power purchased and to a lesser degree the input of process chemicals.

Figure 8-21 Ethanol Production Process



8.4.1 System Boundaries

The system boundaries are relatively well defined for ethanol systems. Almost all analyses exclude the emissions associated with plant construction but include all of the emissions from the point at which the feedstock is delivered to the point where the products leave the plant. Most LCA models do not account for the process chemicals in their analysis. This is not a significant issue for starch and sugar ethanol facilities, but it can be an issue for lignocellulosic processes.

8.4.2 Allocation

Ethanol plants generally produce more than just ethanol. Depending on the feedstock there could be surplus electric power generated, or high protein animal feed distillers grains could be produced. This introduces the issue of how to allocate the emissions between ethanol and the co-product(s).

As noted earlier, it is preferable to avoid allocation altogether by using the displacement method or system expansion. Not all fuel ethanol systems follow this advice; some use allocation by energy content and others use allocation by mass. Other options are available as well, such as allocation by economic value of the products. In the following table the difference between the three primary approaches is shown. In the mass and energy allocation cases the emissions allocated to the co-products are shown as a separate item for comparison to the displacement approach. Alternative presentations of the data could reduce the emissions in fuel production rather than showing a credit for the co-product. These results are for corn ethanol produced in the United States.

Table 8-6 Impact of Allocation Method on GHG Emissions

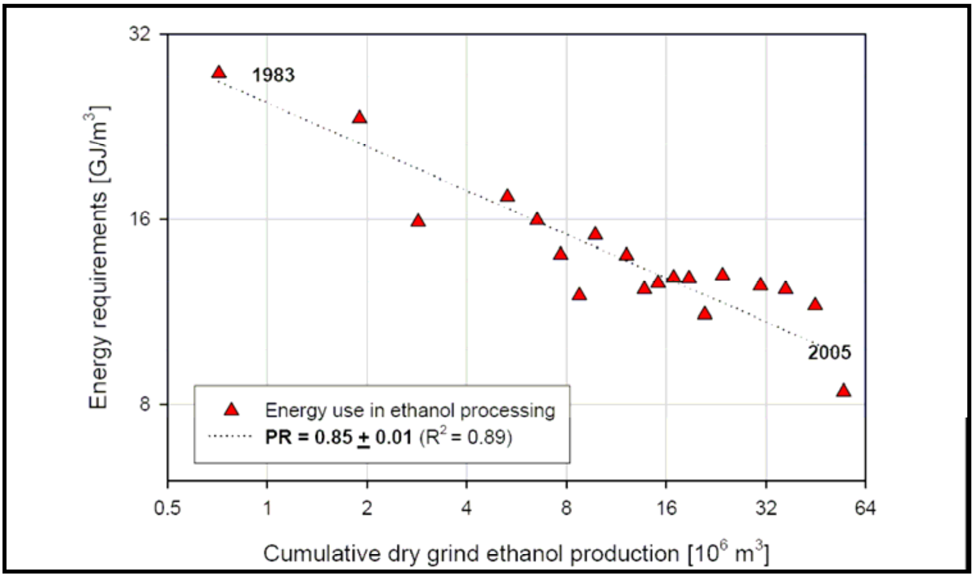
	g CO_2eq/GJ (HHV)		
	Displacement	Mass	Energy
Fuel dispensing	583	583	583
Fuel distribution and storage	880	880	880
Fuel production	37,108	37,108	37,108
Feedstock transmission	1,407	1,407	1,407
Feedstock recovery	5,350	5,350	5,350
Feedstock Upgrading	0	0	0
Land-use changes, cultivation	19,833	19,833	19,833
Fertilizer manufacture	7,663	7,663	7,663
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-14,532	-34,645	-25,558
Total	58,291	38,179	47,266

The highest emissions result from using the displacement approach and the lowest with the energy allocation method. These relative values will vary between fuel pathways. It is apparent that the choice of allocation procedure can have a significant impact on the results.

8.4.3 Temporal Issues

The efficiency of dry mill ethanol plants has increased at a rapid rate over the past three decades. This is shown in the following figure (Hettinga, 2007). The energy use in ethanol dry mills has declined by 65% over the past three decades. It is very important, therefore, that current data is used in ethanol LCA analyses.

Figure 8-22 US Corn Ethanol Energy Use



8.4.4 Regional Issues

There can be regional issues with respect to ethanol LCA results. Some of the energy that is used in ethanol plants is in the form of electricity and the carbon intensity of the electric power consumed can have an impact on the results. Electric power consumption of 0.25 kWh/litre of ethanol corresponds to 12,000 g CO_2eq/GJ when coal powered electricity is used. This represents about 15% of the unallocated emissions. This is a fairly significant quantity and has about the same impact as using energy allocation rather than the displacement method for the co-product allocation method.

Other regional factors are not directly related to the plant, but the feedstock could change from one region to another. Energy requirements at an ethanol plant are a function of the feedstock, as the quantity of ethanol and DDG produced varies with feedstock composition. Wheat ethanol plants do not have the same energy requirements or GHG emissions profile as a corn ethanol plant.

8.4.5 Data Quality

Data quality on ethanol plant energy requirements varies from region to region. Some high quality, statistically sound data has been published for US plants recently (Mueller, 2010). Aggregated data is also available for Canada (Cheminfo, 2009).

Good quality data for other parts of the world is more problematic. The most recent public data for Brazil is from 2005/2006 (Macedo et al, 2008) and some other regions have no data available publicly.

8.4.6 Conversion Technology

There is some variation in the energy efficiency of starch and sugar ethanol plants between process developers, but the differences are not usually that large.

There are significant variations in the various technologies that are being developed for cellulosic ethanol. The uncertainty due to the process variances is also compounded by the lack of actual operating data for these plants. Any LCA on cellulosic ethanol must be considered as prospective until such time as plants are actually operating.

Energy requirements could vary depending on whether the co-products are produced wet or dry.

8.4.7 Process Fuels

Ethanol plants generally use process steam, but the carbon intensity of the steam is a function of the fuel that is used to produce it. In Brazil, bagasse is used to produce steam and, as it is biomass, the carbon intensity of the steam is low. In the United States most plants are fuelled by natural gas, but there are some using coal and a few using biomass. For a given plant energy efficiency, each of these plants will have different carbon intensities.

Biomass fuel plants will have the lowest GHG emissions, followed by natural gas, and then coal. Some coal fired plants could have emissions similar to natural gas if they are co-generation plants and also generate all of their own electricity. The following table shows the impact of process fuel type of a US corn ethanol plant. All plants have the same energy efficiency.

Table 8-7 Impact of Process Fuel on GHG Emissions

	g CO_2eq/GJ (HHV)		
	Natural Gas	Coal	Biomass
Fuel dispensing	583	583	583
Fuel distribution and storage	880	880	880
Fuel production	34,684	46,805	15,167
Feedstock transmission	1,407	1,407	1,696
Feedstock recovery	5,350	5,350	7,907
Feedstock Upgrading	0	0	0
Land-use changes, cultivation	19,833	19,833	19,833
Fertilizer manufacture	7,663	7,663	7,663
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-14,532	-14,532	-15,038
Total	55,867	67,988	38,690

The biomass in the table is corn stover so the higher feedstock recovery and transmission emissions reflect the extra mass removed from the field and shipped to the plant. The emissions from the coal fired plant are twice those of the biomass plant.

8.4.8 Co-products

Beyond the issue of how co-products are treated, different plants can produce different co-products and the co-products can sometimes be used in different ways, resulting in different displaced emissions.

A recent USDA report determined how DDG was being used in the diets of different animals and found that the displacement ratios were all quite different. Their findings are summarized in the following table.

Table 8-8 DDGS Displacement Ratios

	Beef	Dairy	Hogs	Poultry	Total
	Kg displaced/kg DDGS				
Corn	1.20	0.73	0.70	0.61	1.00
Soy Meal	0.00	0.63	0.30	0.44	0.21
Total	1.20	1.36	1.00	1.05	1.22

The displacement benefits would therefore be a function of the type of animal that consumes the material, which can change from region to region. Overall differences in the co-product credit could therefore be expected even when studies use the same allocation methods.

Some ethanol plants capture the carbon dioxide from the fermenters for use in various industrial processes. Since this gas is essentially 100% CO_2, the energy required to collected and compress it is much lower than from other sources. A credit could be applied for this practice.

8.5 SUMMARY

A large number of factors have been identified that can cause variation in the calculated life cycle emissions for the production of ethanol. It is generally accepted that the emissions will be different for different feedstocks but the impact of other regional, temporal, allocation, and process issues are less well understood and accepted. The key findings from this review are:

1. For important inputs like nitrogen fertilizer, there can be large variations in GHG emissions by type of nitrogen fertilizer and, for a given type, there are regional differences in plant efficiencies.
2. There are a wide range of emission factors used to determine N_2O emissions from the application of nitrogen fertilizers. Some variation is expected due to climate and soil conditions, but there are also

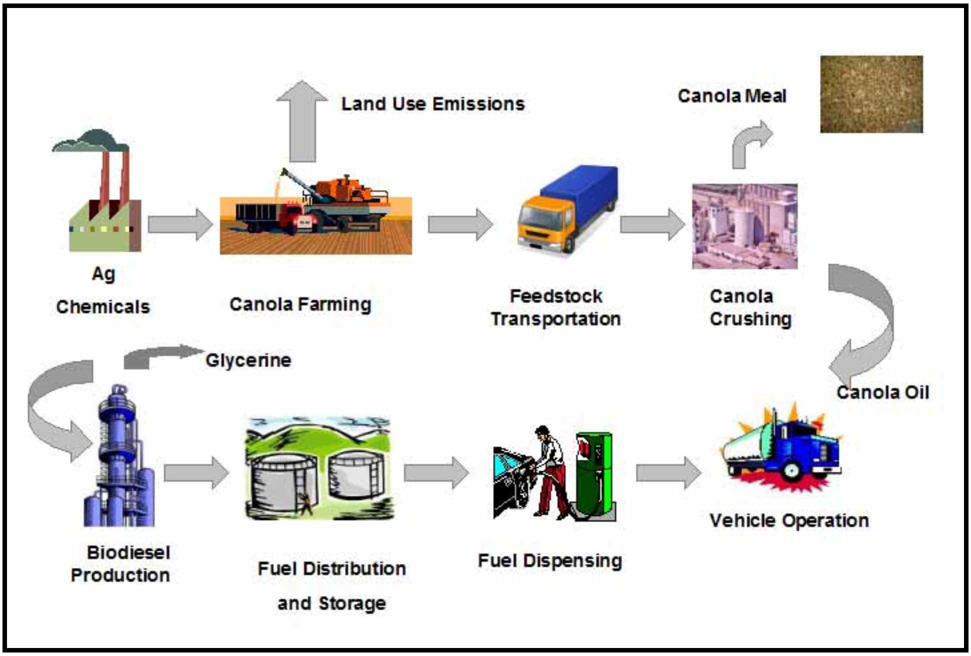
variations in the methodologies used by various governments to develop their National GHG Inventories.

3. Biomass feedstock practices are changing rapidly, resulting in increased yields and reduced fertilizer requirements for most feedstocks.
4. There is significant variation in the yields achieved for the same feedstock in one region to another, even just considering the top producing regions of the world.
5. In some regions soil carbon is increasing as a result of changing management practices and not all models and studies account for this emission sink. In others, soil carbon is decreasing due to changing land management and is an emission source.
6. Ethanol plant technology has improved considerably over the past several decades; high quality, current data are required to accurately assess the emissions from these plants.
7. The method used to allocate feedstock and plant emissions can have a significant impact on the reported emission results. Not all models or studies consider the ISO guidelines for undertaking LCA work.
8. The carbon intensity of the electric power consumed by ethanol plants, and the process fuel used, have a large impact on the life cycle results. These can be expected to vary from one region to another.

9. BIODIESEL

Biodiesel is the second largest volume biofuel currently being used in the world today. The largest producers and markets are found in Europe. There are many different feedstocks that can be used to make biodiesel, with the three largest ones being rapeseed/canola, soybeans, and palm. The basic biodiesel life cycle is shown in the following figure.

Figure 9-1 Biodiesel Life Cycle



Biodiesel LCAs have all of the same issues with respect to agricultural inputs and land use emissions as ethanol systems do, so that information is not repeated here.

9.1 CROP PRODUCTION

All crops require fertilizers, pesticides, and energy for implements for the preparation of the land, planting, growth and harvesting of the crop. All of these activities create either direct (occurring at the site) and/or indirect (remote from the site) GHG emissions. The specific requirements vary from crop to crop.

Rapeseed or canola has the highest nitrogen fertilizer requirements per tonne of biomass produced of all of the biofuel feedstocks, whereas soybean fix their own nitrogen and have no or very little additional nitrogen requirement, so a very wide range of nitrogen inputs can be found for biodiesel feedstocks.

9.1.1 System Boundaries

The most common system boundary issue with crop production is the inclusion or exclusion of the energy embedded in farm machinery. The overall impact is relatively small; in GHGenius the impact is 0.05 to 1.75% of the production emissions for the ethanol feedstocks.

9.1.2 Allocation

The quantity of biodiesel feedstock produced per hectare is generally lower than that for ethanol feedstocks (with the exception of palm). The use of crop residues from rapeseed and soy is not as large an allocation issue as it is with ethanol feedstocks.

9.1.3 Temporal Issues

Biodiesel feedstocks have the same general temporal issues as the ethanol feedstocks. Farm tractors energy efficiency is improving, and farming practices are becoming more sophisticated in many parts of the world.

Each of the feedstocks is showing significant yield growth over time, and those that have good fertilizer consumption data are showing increased utilization efficiency. LCA must use the most recent data available if accurate results are to be obtained.

9.1.4 Regional Issues

Agricultural practices vary widely from region to region. Soil and climatic conditions play a large role in the variation but the adoption of new technologies such as no till agriculture and precision farming are also important. The adoption of new technologies is partly a social issue and thus it should be expected that different regions adopt the technologies at different rates.

There is a significant variation in crop yields for each of the primary biodiesel feedstocks and this can be expected to influence regional LCA results.

9.1.5 Data Quality

Data quality is an issue for crop production, especially good time series related to fuel consumption. Producers generally do have good quality information on fuel purchased, but since they typically grow multiple crops, the allocation of fuel consumption to individual crops is often an issue.

Information on fertilizer and pesticide application rates is usually of higher quality, since producers do keep good records of the quantities applied by field (and thus by crop). This data is not always readily available in the public domain.

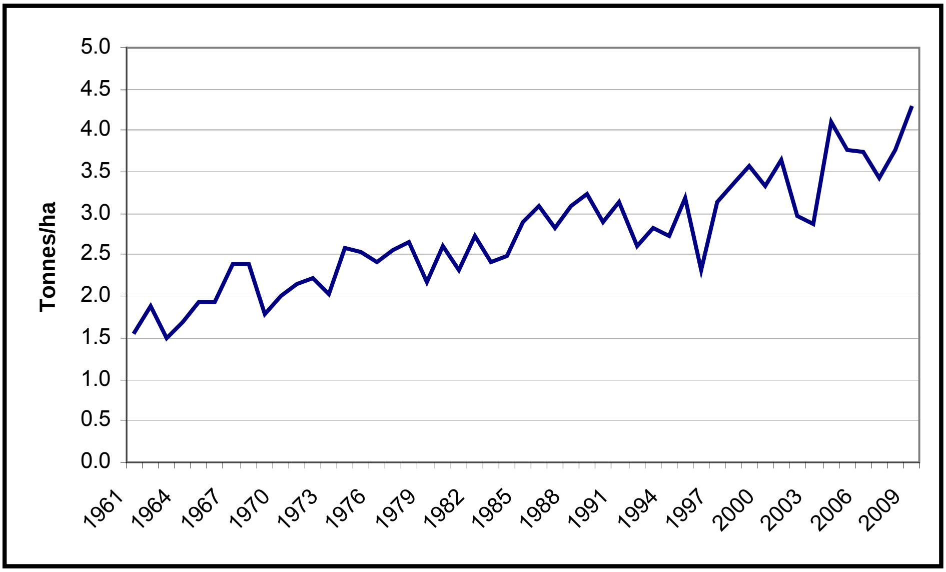
9.1.6 Specific Crop Information

Some of the issues with the three top biodiesel feedstocks are discussed in the following sections. The data shown supports the theme of significantly improved efficiency leading to lower GHG emissions over time, with large regional differences, as was seen for ethanol feedstocks.

9.1.6.1 Rapeseed

Rapeseed is the dominant feedstock used in Europe for biodiesel production. Like most feedstocks the yield has increased significantly over the past 50 years as shown in the following figure, which is based on data for Germany. Yields have almost tripled over this period.

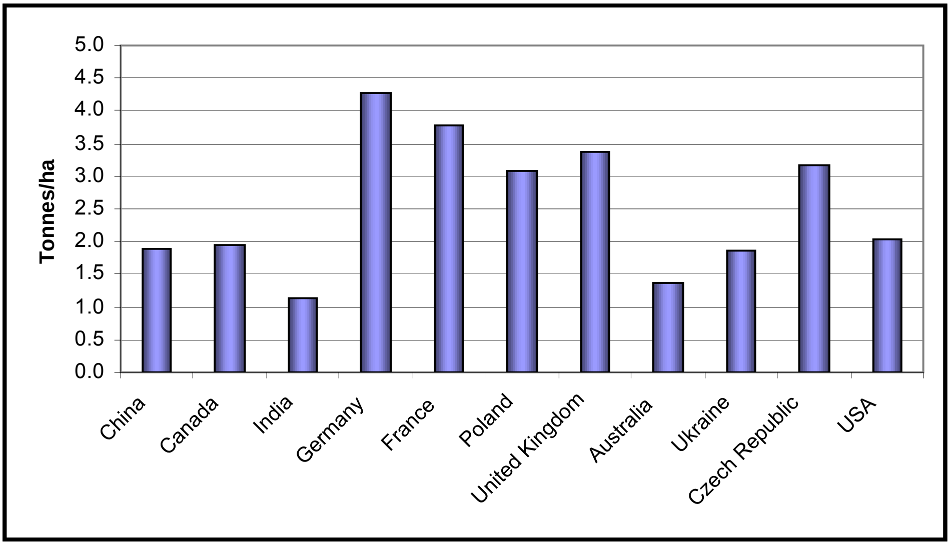
Figure 9-2 Rapeseed Yield Germany



Source:FAO

There is also a significant variation in yield amongst the top ten rapeseed producers in the world as shown in the next figure. The yields in Germany are about four times higher than the yields in India. Some of the variation is due to climatic conditions but the variation is also due to the varieties planted and the production practices.

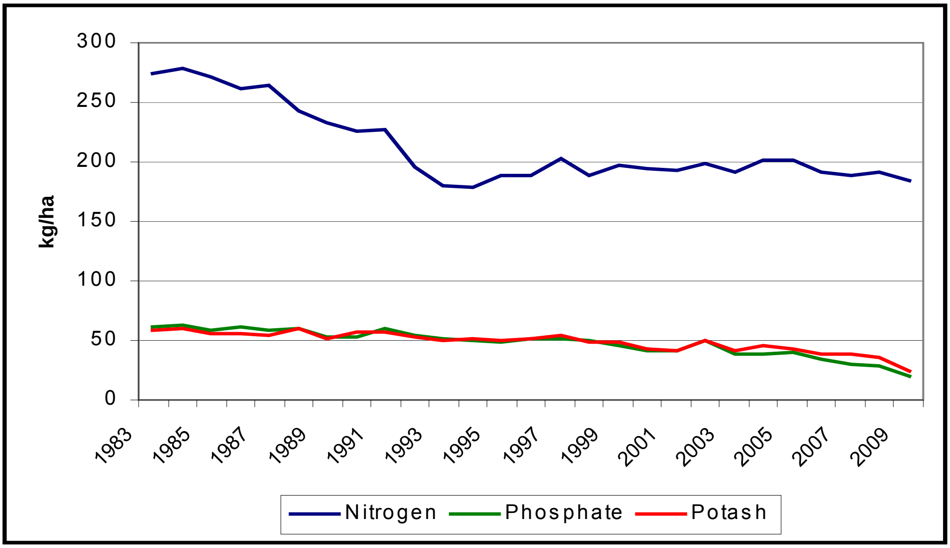
Figure 9-3 Regional Rapeseed Yields



Source:FAO

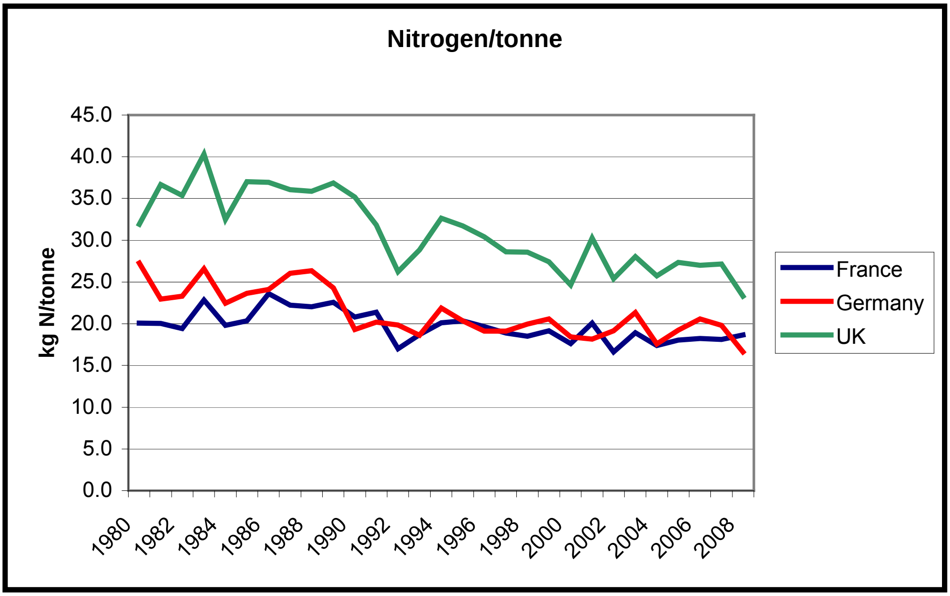
Information on fertilizer trends for rapeseed is difficult to obtain but the UK does report fertilizer use by crop and by year and that information is shown in the following figure (Defra, 2010).

Figure 9-4 UK Fertilizer Trends for Rapeseed



There is also information (see Figure 9-5 below) that shows that fertilizer consumption per tonne of total production of all crops in Europe is declining, even as yields and the area devoted to rapeseed has increased.

Figure 9-5 Nitrogen Trends per Tonne Produced



The use of lime for soil pH control and pesticides are two other important groups of agricultural chemicals used for rapeseed production.

In terms of pesticide application rates, the Moerschner study found 2.9 to 3.3 kg active ingredient/ha were applied. The Unilever study had a mean value of about 10 kg/ha. Both of these values are very high and much higher than the values reported in the UK bi-annual survey. The values in various LCA tools are summarized in the following table.

Table 9-1 Pesticide Application Rates – Rapeseed

Source	Value	Reference
	Kg ai/ha	
JRC	1.23	Multiple German sources
UK Carbon Tool	0.28	British Pesticide Use Survey
Germany default value	1.23	Calculation by IFEU

The information on lime usage in the various LCA tools is summarized in the following table. There is considerable variation between tools.

Table 9-2 Lime Application Rates – Rapeseed

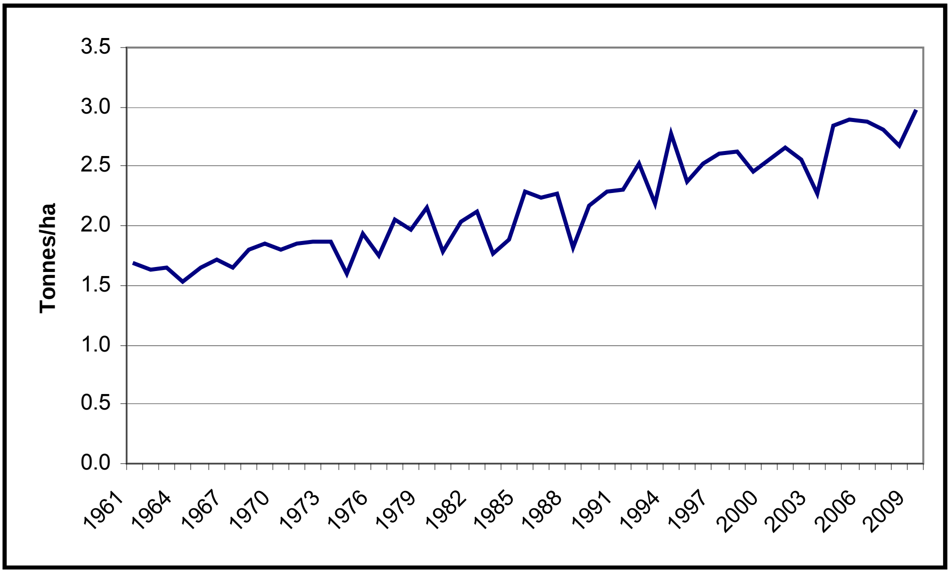
Source	Value kg/ha	Reference
JRC	19	European Fertiliser Manufacturer Association (EFMA), 2008. JRC.
UK Carbon Tool	271	Mortimer et al (2003). From Kaltschmidtt and Reinhardt 1997 (IFEU).
Germany default value	22	Calculation by IFEU

Clearly there are data quality issues for some of the inputs into the rapeseed production systems, but yields are improving and fertilizer use per tonne of production is down. GHG emissions per tonne of rapeseed produced will also be down.

9.1.6.2 Soybeans

Soybeans are grown primarily for their protein content and not for their oil, but they do yield 18 to 20% oil on a mass basis, and soybean oil is an important feedstock for biodiesel production. As for other crops, soybean yields have almost doubled over the past 50 years, as shown in the following figure.

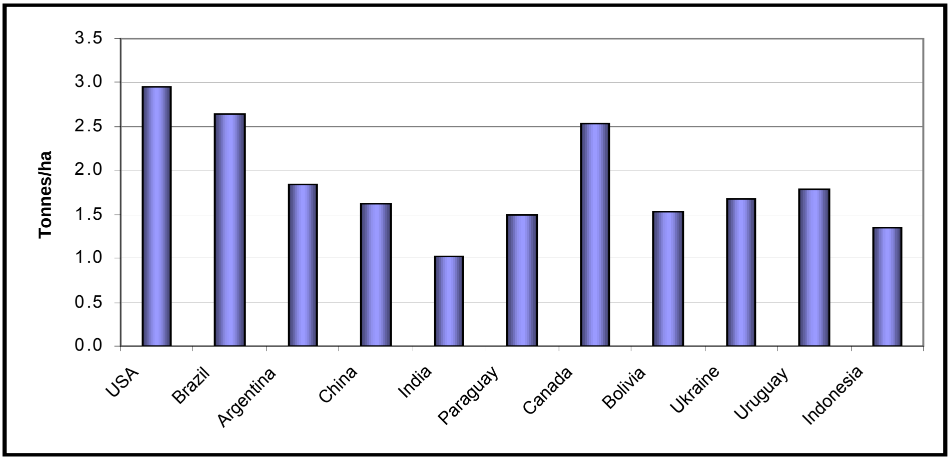
Figure 9-6 US Soybean Yields



Source:FAO

There are significant variations in regional yields as well, as shown in the following figure. Unlike some of the other crops where the variation in yield could be due to the level of nitrogen applied, this is not the case for soybeans, since they fix most of their own nitrogen from the atmosphere.

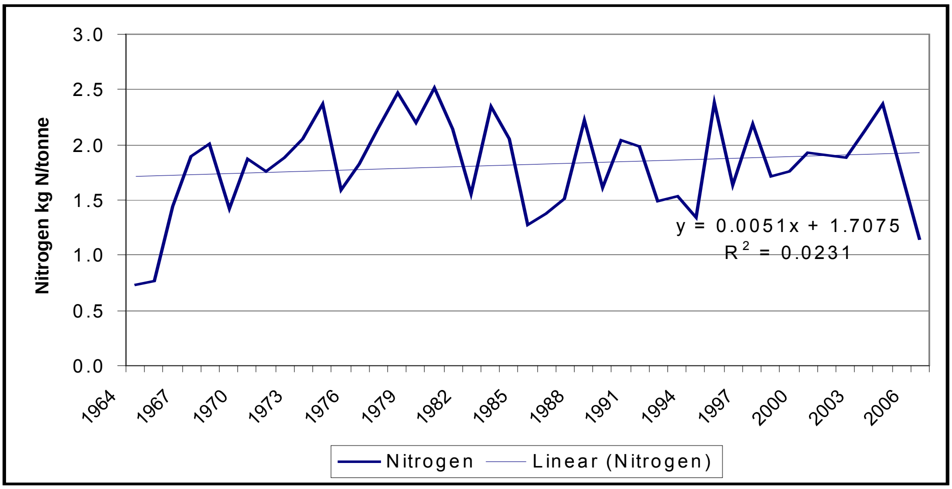
Figure 9-7 Regional Soybean Yields



Source: FAO

The USDA data for fertilizer use for soybeans in the US is shown in the following figures. In theory, soybeans do not require any nitrogen as they fix their own nitrogen from the atmosphere but in practice a small amount of nitrogen fertilizer is used to start the plant. While the trend line shows a small increase over the past 40 years, the most recent data shows no trend.

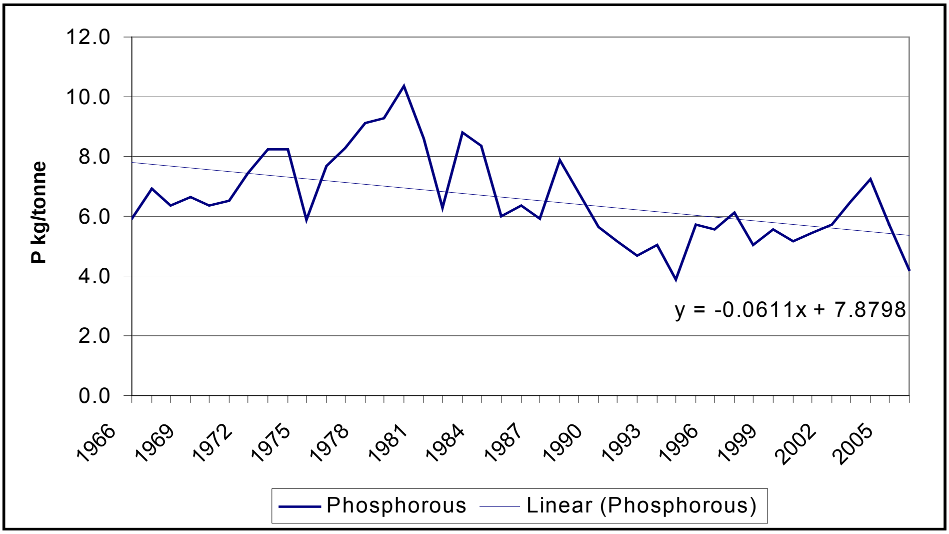
Figure 9-8 Soybean Nitrogen Use



Source: USDA

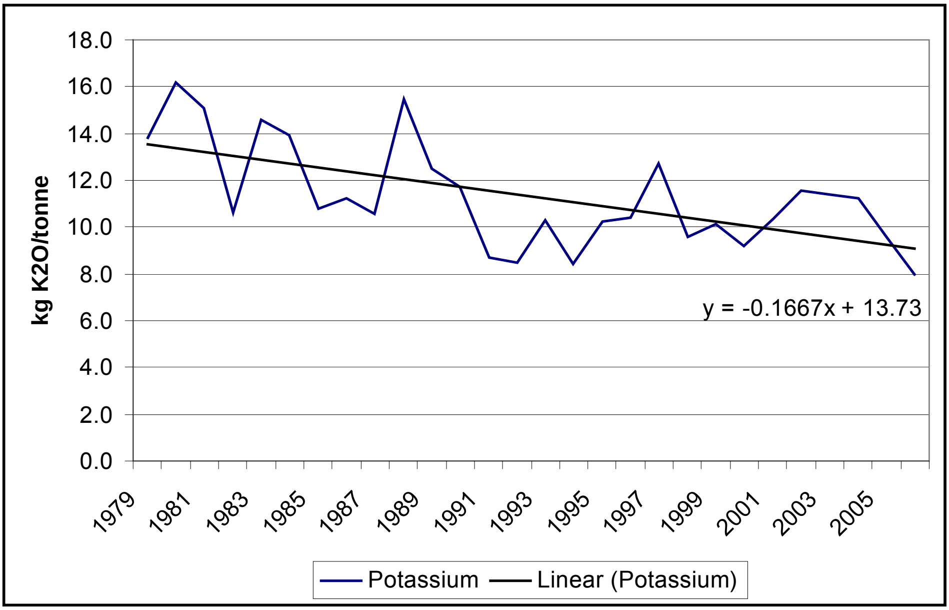
Phosphorous and potassium fertilizer application rates are shown in the following figures. Both data series show a decline in fertilizer application in recent years.

Figure 9-9 Soybean Phosphorus Use



Source: USDA

Figure 9-10 Soybean Potassium Use

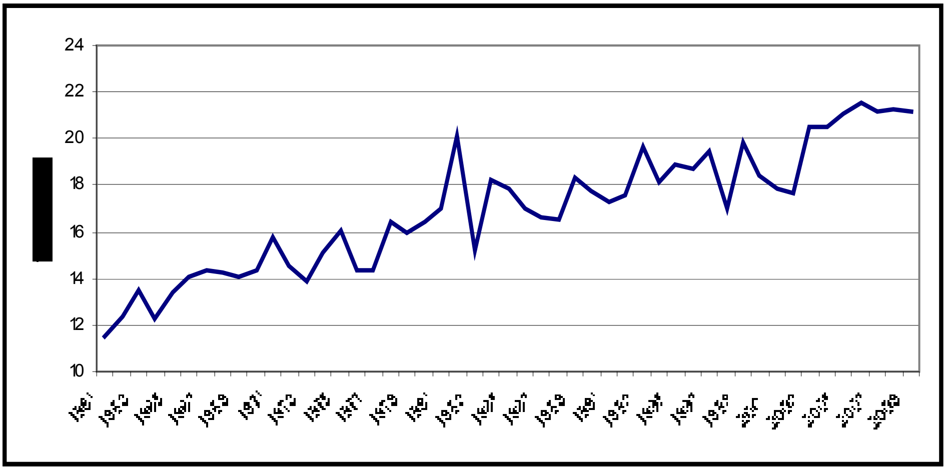


Source: USDA

9.1.6.3 Palm

Palm trees are grown in tropical climates. The fruit produced by the plants has about 20% oil content, with most of the rest of the mass accounted for by moisture. Only a small amount of protein is extracted from the fruit. Palm is a significant source of vegetable oil in the world. Like the other feedstocks considered, the yield of palm has been increasing over the past several decades, as shown below. In Malaysia the yield has doubled in the past 50 years.

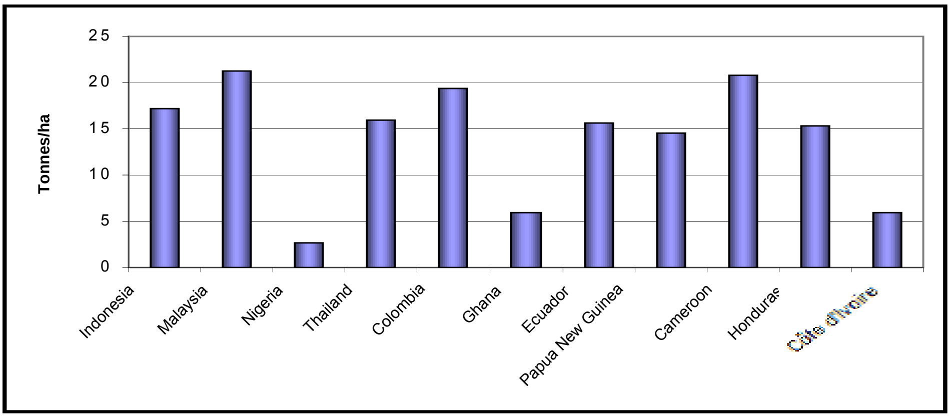
Figure 9-11 Malaysian Palm Yield



Source:FAO

Malaysia and Indonesia are the largest suppliers in the world but palm is produced in a number of other regions as shown in the following figure. There is a large variation on the fruit yield that is obtained in the different countries.

Figure 9-12 Regional Palm Yields

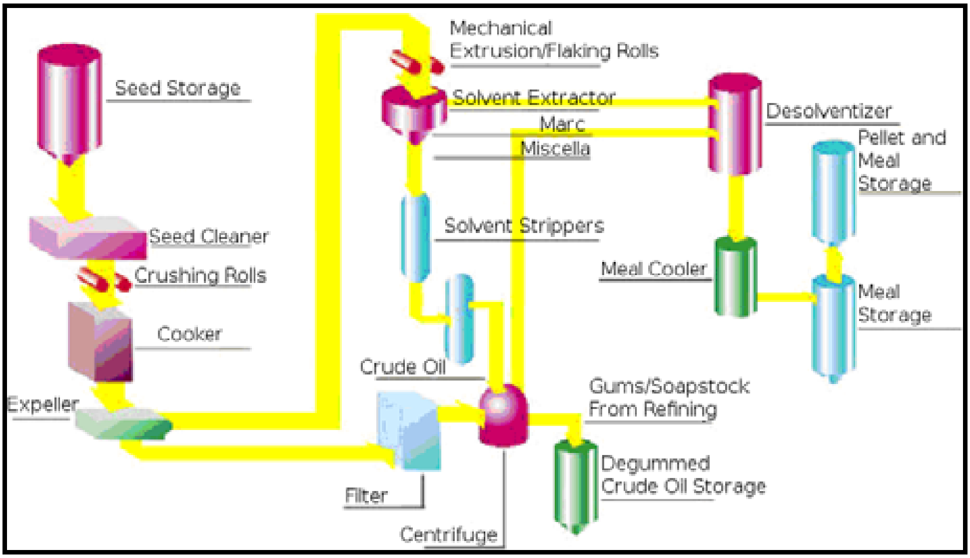


Source:FAO

9.2 OILSEED CRUSHING

Oilseeds must be processed to extract the oil from the protein meals. Each oilseed requires a slightly different processing scheme. The process for rapeseed is shown in the following figure.

Figure 9-13 Rapeseed Crushing Process



While there are some differences between the processes, they all require thermal energy and electric power. They all also require some allocation of the energy and emissions between the oil and meal.

9.2.1 System Boundaries

The system boundaries for oilseed crushing are straightforward and generally consistent between models and studies. Most exclude the emissions associated with plant construction.

Palm fruit processing facilities can have high methane emissions from their waste water treatment systems and these are not always included in models and studies, particularly older ones.

9.2.2 Allocation

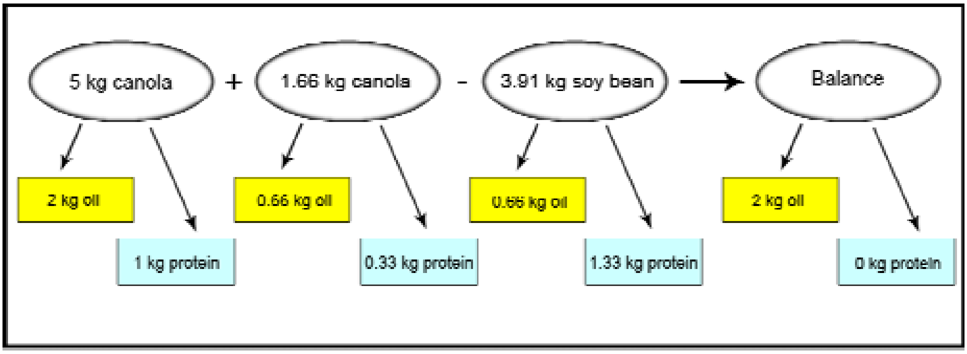
Since the plants produce oil and protein meals there are allocation issues for LCA modellers. Some models and studies have undertaken a system expansion using rapeseed and soybean production to avoid allocation. The concept is described below.

In order to determine how much of the energy and emissions associated with the production and crushing of the oilseeds should be attributed to the oil and how much should be attributed to the protein, a systems expansion can be performed. The objective of this is to identify a combination of production systems that only has a net production of one of the products, either oil or protein. Weidema (1999) performs this system expansion between rapeseed (Canola) and soybeans based on the following assumptions:

- Soybean meal is the marginal protein and rapeseed oil is the marginal oil on the market.
- Rapeseed contains 40% oil and 20% protein in the dry matter and soybeans contain 17% oil and 34% protein.
- Protein and oil from both products are substitutable in the marginal applications.

These assumptions are reasonable considering the supply and demand of protein and oils in the world. The system expansion is shown in the following figure.

Figure 9-14 Protein Meal System Expansion



In this case, 2kg of rape oil is the net production from the processing of 6.66 kg of rapeseed less 3.91 kg of soybeans. An alternative expansion that could be undertaken would find that the production of 5 kg of soybeans less 2.15 kg of rapeseed would yield a net 1.27 kg of protein. Both approaches produce equivalent results for the oil and the meal. The only problem with this method is that the energy requirements for crushing of the beans are not included, but this easily incorporated into the analysis.

Other models and LCA reports that don't include both rapeseed and soybeans generally use either energy allocation or mass allocation for this stage. GHGenius allows users to change the allocation approach. The following table shows the results for US produced soybean oil using GHGenius. It can be seen that the allocation method has a large impact on the results. As identified in the Wang et al. report, this is a specific case where displacement may not be appropriate because the co-product is actually the principle product. However, mass allocation and energy allocation are similarly misleading if the reason for putting in a soybean processing plant is to take advantage of a renewable fuels mandate by generating biodiesel.

Table 9-3 Comparison of Allocation Approaches for Soybean Oil

	Mass Allocation	Energy Allocation	Displacement
	g CO_2eq/GJ Oil		
Fuel dispensing	0	0	0
Fuel distribution and storage	0	0	0
Fuel production	17,299	17,299	17,299
Feedstock transmission	1,811	1,811	1,811
Feedstock recovery	9,487	9,487	9,487
Feedstock Upgrading	0	0	0
Land-use changes, cultivation	41,584	41,584	41,584
Fertilizer manufacture	5,881	5,881	5,881
Gas leaks and flares	0	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-61,489	-51,454	-29,854
Total	14,573	24,609	46,208

9.2.3 Temporal Issues

No time series data for the energy requirements of oilseed crushing are available in the public domain, so it is not possible to determine the temporal impacts in this sector. It is a relatively mature sector so the annual rates of improvement should be small.

9.2.4 Regional Issues

The inputs into the crushing process are electricity and thermal power. The carbon intensity of the electric power utilized will have an impact on the results. In the examples shown in the previous table, electric power accounts for about 6 of the 17.3 g CO_2eq/MJ of emissions at the crushing facility, with the remainder being mostly the natural gas.

Most crushing facilities in the developed world use natural gas for their thermal energy requirements. In the developing world a wider range of fuels from biomass to diesel fuel can be found, and the choice will have an impact on the results.

9.2.5 Data Quality

In some regions, the associations that represent the crushing industry have undertaken and published surveys on energy use in the industry. These are invaluable for undertaking an LCA study. In other regions, such as Europe, similar surveys are not publicly available and there can be a wider range in the estimates of energy used by the industry.

No single source of industry average data has been identified for European rapeseed crushers. Schmidt (2007) reported the following energy requirements based on data from two companies in Europe. The oil yield was 42%. This is shown below.

Table 9-4 European Rapeseed Mill Energy Requirements

	Per tonne of Rape crushed	Per tonne of Oil produced
Electricity Purchased, kWh	49	116
Natural Gas Purchased, GJ steam	0.67	1.59
Total Energy, GJ	0.84	2.00

The values used in some of the LCA tools are summarized in the following table. Other than the German default value, the results are all quite similar. All of the results appear to be for refined rapeseed oil. The yields of oil vary from 39 to 42% in these tools.

Table 9-5 LCA Tools - Rapeseed Mill Energy Requirements

	Electricity, kWh/tonne oil	Natural gas, GJ/tonne oil	Total, GJ/tonne oil
JRC	99	1.95	2.30
UK Carbon Tool	94	1.99	2.32
Dutch Carbon Calculator	89	2.02	2.34
Germany default value	95	3.55	3.89

Looking at soybeans, the National Oilseed Processors Association (NOPA) published an energy survey of their members in 2009. That data is summarized in the following table. The requirements per tonne of oilseeds crushed is in the same range as rapeseed but, when expressed on a per unit of oil produced basis, the energy requirements are higher. The NOPA values are compared to the values used in a number of LCA tools in the following table.

Table 9-6 LCA Tools – Soybean Mill Energy Requirements

	Electricity, kWh/tonne oil	Natural gas, GJ/tonne oil	Total, GJ/tonne oil
NOPA (US)	289	6.29	7.33
JRC	351	6.23	7.49
UK Carbon Tool	410	5.45	6.92
Dutch Carbon Calculator	257	6.08	7.00
Germany Default value	338	6.49	7.71

9.2.6 Conversion Technology

There are cold press technologies that are used in smaller scale facilities. These use little or no thermal energy, but typically use more power to mechanically extract oil from the seed. The oil recovery rate is usually lower than it is with the extraction process described here.

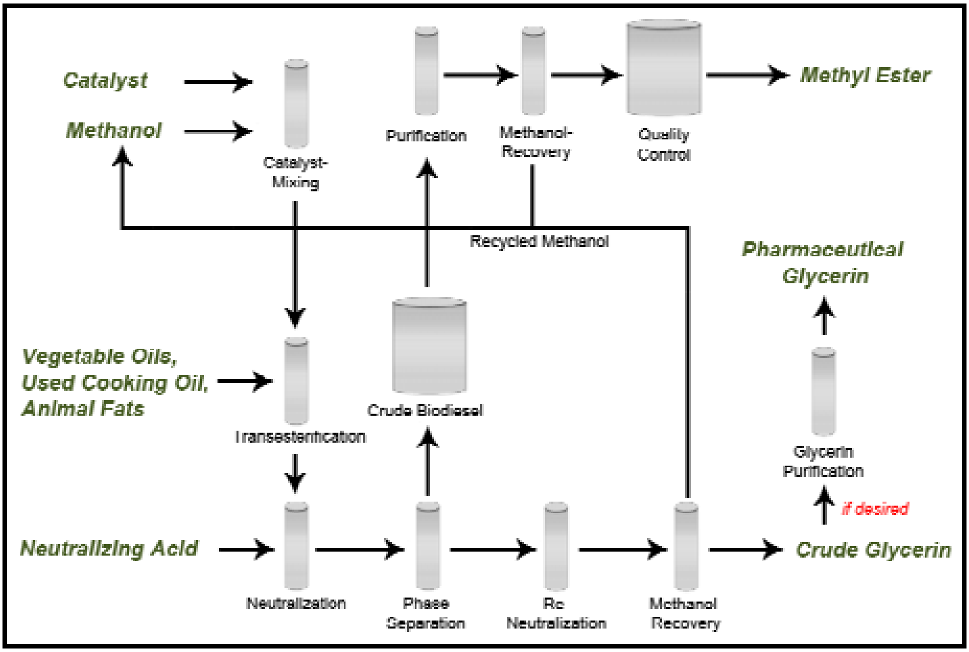
The LCA emissions will vary with this technology. They will obviously be more susceptible to the electric power carbon intensity. The contribution of the cold press technology to the total quantity of oilseeds processed is relatively small.

9.3 BIODIESEL PRODUCTION

Most biodiesel is produced by the same basic chemical reactions. There are variations of this process that are employed by different developers to process different biodiesel feedstocks. Most biodiesel is also produced using methanol but other alcohols can be used, and there have been ethyl esters produced and tested.

The feedstock oil is mixed with methanol and a catalyst to produce a methyl ester (biodiesel) and glycerine. The basic process is shown in the following figure.

Figure 9-15 Biodiesel Production Process



9.3.1 System Boundaries

System boundaries are relatively well defined for biodiesel systems. Almost all analyses exclude the emissions associated with plant construction, but they include all of the emissions from the time that the feedstock is delivered to the plant through to the point where the products are shipped. Most LCA models do not account for process chemicals (other than methanol) in their analysis. This is not a significant issue for the biodiesel sector.

9.3.2 Allocation

Biodiesel production facilities produce glycerine as well as biodiesel so there are some allocation issues. Glycerine is an energy and emission intensive product to make synthetically, and thus if the displacement approach is used and it is assumed that biodiesel glycerine displaces the synthetic product, then a large co-product credit is generated. The number of synthetic glycerine plants in operation around the world has declined since biodiesel production began in the 1990s, but not all biodiesel glycerine is upgraded to synthetic glycerine. For this reason a number of models, studies, and particularly regulatory schemes utilize the mass or energy allocation method for the glycerine.

There is an issue with this approach for glycerine. The methanol that is used in the reaction is usually methanol produced from natural gas, and this fossil carbon must be treated differently than the biogenic carbon from the oilseed. In some studies and models, the oxidation of this fossil carbon is assumed to be part of the biodiesel production process. The problem with this is that this means that the carbon in the glycerine must be biogenic but no credit is given for this fact. When most practitioners do a mass or energy allocation they don't consider the use of the co-product, they effectively truncate the system boundary for the co-product at the point of production. If this glycerine is used for fuel then a biofuel is displacing a fossil fuel and there should be a credit based on the biogenic nature of the glycerine. This would be equal in size to the debit applied to the biodiesel from the inclusion of methanol.

9.3.3 Temporal Issues

No time series data for the energy requirements of biodiesel are available in the public domain, so it is not possible to determine the temporal impacts in this sector. The energy requirements of a biodiesel production facility are relatively small so that annual improvements will also be small.

9.3.4 Regional Issues

The inputs into biodiesel processes are electricity and thermal power. The carbon intensity of the electric power will have an impact on the results. In a high carbon intensity region like the central US, electric power accounts for less than 1 g CO_2eq/MJ of biodiesel production. Regional issues should be limited for the actual biodiesel production process.

9.3.5 Data Quality

Public information on the performance of the biodiesel sector is limited. The US National Biodiesel Board (2009) undertook a survey of US biodiesel producers in 2009 and published the results of their work.

Berghout (2008) attempted to undertake a survey of the mass and energy balances of the European biodiesel industry, but this was not successful as most of the companies approached did not wish to release the information.

The values used in various European LCA tools are summarized in the following table.

Table 9-7 LCA Tools - Biodiesel Energy Requirements

	Electricity, kWh/litre BD	Natural gas, MJ/litre BD	Feedstock, kg/litre BD
JRC	0.026	1.27	0.886
UK Carbon Tool	0.082	1.49	0.925
Dutch Carbon Calculator	0.026	1.33	0.923
Germany Default value	0.040	1.33	0.89
NBB Survey	0.032	0.76	0.88

The energy requirements from the NBB survey are lower than typically used in modelling in Europe, but they represent actual data rather than assumed or unreferenced values.

9.3.6 Conversion Technology

There are a wide variety of process innovations that are used in the biodiesel industry but, with the low level of energy consumed in the processes, the impact that the innovations have on the overall life cycle emissions are low.

9.3.7 Process Fuels

It is possible to use fuels other than natural gas for the production of biodiesel but the quantity consumed is low and the impact of different carbon intensities of the process fuels is quite small.

9.4 SUMMARY

A large number of factors have been identified that can cause variation in the calculated life cycle emissions for the production of biodiesel. It is generally accepted that the emissions will be different for different feedstocks, but the impact of other regional, temporal, allocation, and process issues are less well understood and accepted. Many of the issues are similar to those identified for ethanol. The key findings from this review are:

1. For important inputs like nitrogen fertilizer, there can be large variations in GHG emissions by type of nitrogen fertilizer and, for a given type, there are regional differences in plant efficiencies.
2. There are a wide range of emission factors used to determine N_2O emissions from the application of nitrogen fertilizers. Some variation is expected due to climate and soil conditions but there are also variations in the methodologies used by various governments to develop their National GHG Inventories.
3. Biomass feedstock practices are changing rapidly, with increased yields and reduced fertilizer requirements being significant for most feedstocks.
4. There is significant variation in the yields achieved for the same feedstock in one region to another, even just considering the top producing regions of the world.
5. In some regions soil carbon is increasing as a result of changing management practices and not all models and studies account for this emission sink. In others, soil carbon is decreasing due to changing land management and is an emission source.
6. The method used to allocate feedstock and plant emissions can have a significant impact on the reported emission results. Not all

models or studies consider the ISO guidelines for undertaking LCA work.

7. When allocation by mass or energy is used it is still important to include emission impacts arising from the use of co-products. Many studies do not consider this.

10. INDIRECT IMPACTS

In recent years there has been increased discussion concerning the inclusion of so called indirect effects into life cycle analysis. While there are differing views on what is a direct effect or an indirect effect, the International Standards Organization TC 248 is developing sustainability standards for bioenergy, which may clarify the situation; they have adopted the following working definitions:

> *Direct effects* are those under the direct control of the economic operator and caused by the process being analyzed.
>
> *Indirect effects*: Other effects that may or may not be associated with the process under analysis and that fail to meet the two criteria of direct effects.

The working group on indirect effects has released a draft report and they note that any choice (action or inaction) may have direct and indirect effects that are perceived to be positive or negative from the perspective of a given set of stakeholders in a given place and time.

Direct effects can vary widely and their measurement will depend on the defined system boundaries for analysis. Indirect effects are consequences of interactions and feedbacks in and among complex social, economic and environmental systems. These could result in a broad range of potential impacts that vary in intensity and scale (temporal and spatial) depending on the context specified and the boundaries of analysis. Estimation and attribution of indirect effects depends on assumptions.

The working group has found that the science on indirect effects is nascent and rapidly evolving. This makes it difficult to reach consensus on the state of "current science."

Their conclusion, based on the expertise of, and literature reviewed by, the working group, is that the 'state of science,' in terms of evidence based research, is inconclusive or contradictory regarding indirect effects of bioenergy. The indirect effects of bioenergy may depend, inter alia, on factors related to the management of the sector (including public policy and production), and the local socio-economic and environmental situation of the specific area or group considered. An economic operator should not be held responsible for indirect effects and variables that are outside the operator's control. They also noted that there are indirect effects of other forms of energy such as petroleum.

There is, however, agreement that indirect effects, positive and negative, can occur and should be analyzed based on the definitions above and applicable criteria. Effects should be assessed and documented based on defined system boundaries, baseline data and evidence.

Estimation of indirect effects is dependent upon modeling and the assumptions used therein. At present, models of indirect effects have no ability to assign causality to individual bioenergy operations. Recent modeling has highlighted potential impacts as well as high variability in results though much of the modeling thus far has relied on assumptions that may not be supported by empirical evidence. To date, there has been limited causal analysis to support assumptions underlying the modelling of indirect effects. Further research in this area would benefit the understanding of indirect effects.

Working group members observed that there has been more emphasis on sustainability and indirect effects of bioenergy than on baseline (often fossil fuel) scenarios.

10.1 LAND USE

The indirect effect that has received the most discussion in the past several years is the effect on land use resulting from an expansion of biofuel production. Changing land use patterns can result in emissions of GHG gases. These emissions, usually losses of soil and/or biomass carbon, are usually found some distance from where the actual crop is produced and result from changes in cropping patterns and practices as a result of the crop being used for biofuel production rather than for the traditional use of the crop.

Indirect land use (ILUC) emissions are required to be estimated in the US RFS2 program as part of the life cycle emissions determination. The California Air Resources Board also requires that they be estimated as part of the Low Carbon Fuel Standard being implemented there. In Europe, there are ongoing discussions about the inclusion of an ILUC factor in their Renewable Energy Directive.

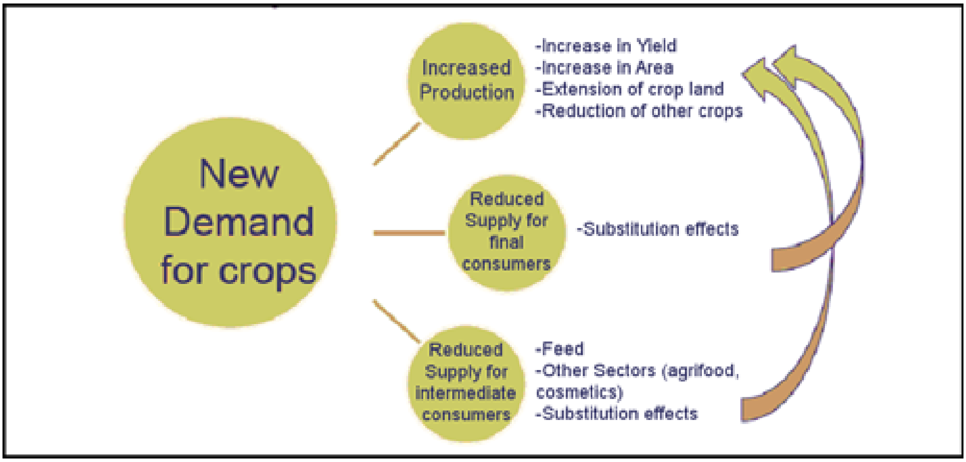
10.1.1 Indirect Land Use Hypothesis

If a new demand for agricultural feedstocks is created through the substitution of biofuels for fossil fuels, this demand must be satisfied one of several ways:

- Intensification of existing production produces more feedstock from the same land base. This can be accomplished through switching varieties to higher yielding crops, better seeds, more fertilizer, increased irrigation, precision farming, more mechanization, or other means.
- New demand generally leads to higher prices. The traditional users of the feedstock may find substitutes that are less expensive, or they may increase the price of their product, which reduces demand.
- Through extensification, the land base is expanded to allow for the production of more feedstock. This expansion could be indirect where the actual feedstock that is produced is used for feed or food and not for the biofuel, and thus this creates indirect land use change.

Graphically, the hypothesis is that an increase in biofuel demand causes an increase in demand for new crops. The world economic system responds as shown in the following figure. There can be a re-allocation of crops from the food and feed markets, yields can increase on existing cropland, or there can be an increase in area cropped.

Figure 10-1 Modelling Hypothesis



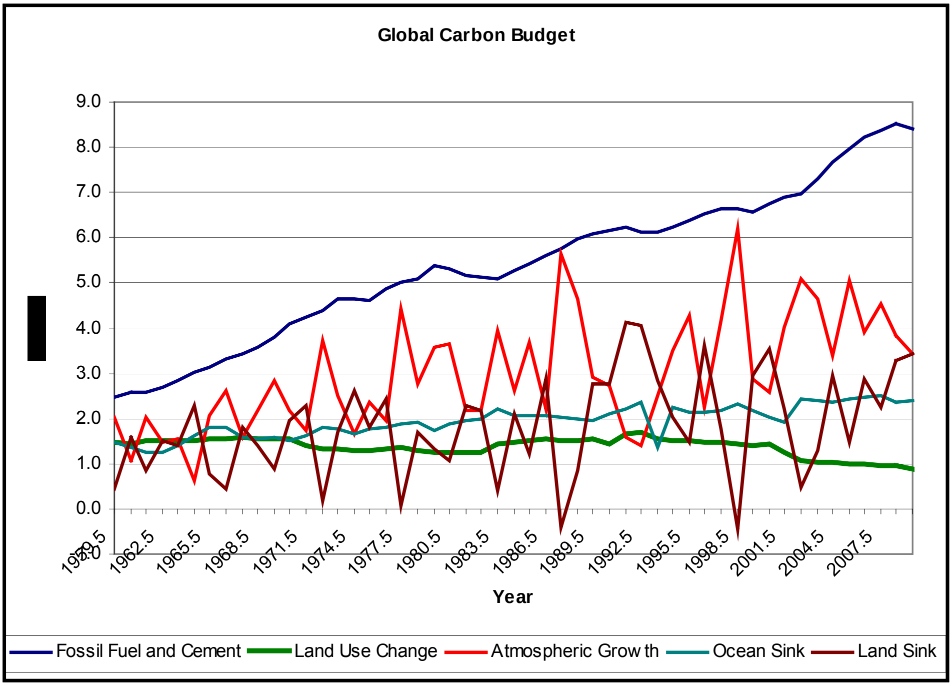
If it is determined that there must be an increase in area cropped, then that new land can come from idle agricultural land, from the pasture portion of agricultural land, from managed forests or, if there is insufficient supply, from unmanaged lands (primary forests, savannahs, etc.). Bringing these new lands into agricultural production may cause a reduction in the carbon stored in the above ground biomass of forests and savannahs, and potentially a reduction of soil carbon content as the soil is disturbed for agriculture.

Land use change is one of the acknowledged sources of carbon in the environment. Land use change emissions are calculated for input into the annual reporting of emissions by countries to the UN Framework Convention on Climate Change (UNFCCC). There are six categories of land use in the IPCC methodology: forestland, grassland, cropland, wetlands, settlements, and other land. Land does move between these categories, and countries make estimates of the GHG emission impacts of those changes in accordance with IPCC methodology.

The UNFCCC only reports the land use emissions for Annex 1 countries but others (Global Carbon Budget) have estimated the total global carbon budget. Friedlingstein et al (2010) updated the data recently and the results are shown in the following figure.

In spite of the increased discussion of deforestation and land use change, this category has actually been decreasing over the past several decades. The land sink category is the residual of the other categories and includes the carbon that is temporarily stored in vegetation.

Figure 10-2 Global Carbon Budget



Source: Friedlingstein et al (2010)

10.1.2 Calculating Indirect Land Use Emissions

The quantification of ILUC emissions can be reduced to answering the following four questions.

1. How does the market respond to the increased demand for biofuel feedstocks? This step needs to determine how the traditional markets respond to higher prices and the availability of biofuel co-products. Out of this determination there will be a projection of how much new feedstock is required.
2. From the quantity of feedstock needed, the land requirements are calculated.
3. Where and what kind of land is converted? Is the land that is converted idle cropland, pasture, managed forests, or unmanaged land, and where is this land?
4. What is the change in carbon stocks on the converted land? This includes the above ground biomass, the soil carbon and could include other emission changes.
5. Over how many years should the one time change in carbon stocks be amortized?

The overall equation for the calculation is

$$(\sum Area * \sum Carbon\ Stock\ Change/ha)/(MJ\ Fuel/year * Years) = ILUC\ gCO_2eq/MJ$$

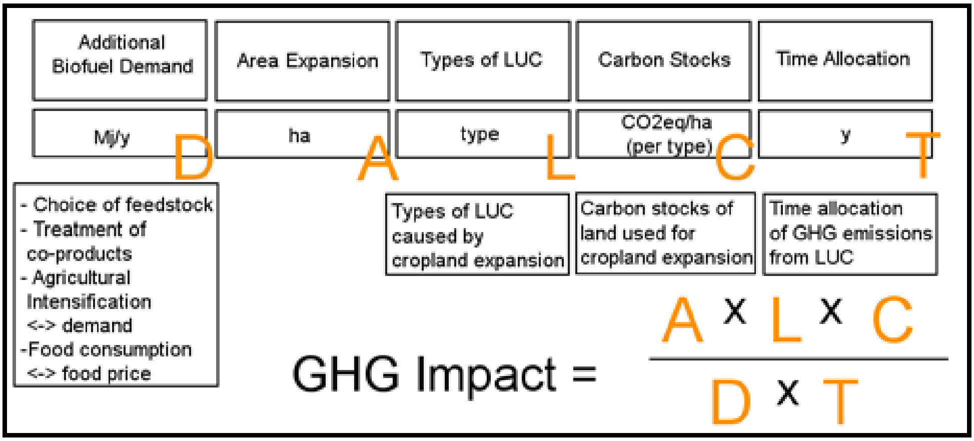
Where:

∑Area=The quantity of land use types in each region or country that is converted to cropland.

∑Carbon Stock Change=The change in carbon stocks in each region or country that is converted to cropland.

The overall calculation is straightforward once all of the data is known but determining the answers to the first two questions is difficult since we need to know what might happen in the future in response to a change today. The calculation steps are shown in the following figure.

Figure 10-3 ILUC Calculations



There have been at least three different modelling approaches proposed for estimating the ILUC emissions from increased biofuels production. Computable General Equilibrium models have been used by the California Air Resources Board and by the European Commission, Partial Equilibrium models have been used by the US EPA, and some groups have proposed causal effect modelling. All three approaches are summarized here.

10.1.3 Computable General Equilibrium Models

Computable general equilibrium (CGE) models are a class of economic models that use actual economic data to estimate how an economy might react to changes in policy, technology or other external factors. A CGE model consists of:

(a) equations describing model variables and

(b) a database (usually very detailed) consistent with the model equations.

The equations often assume cost-minimizing behaviour by producers, average-cost pricing, and household demands based on optimizing behaviour. However, some CGE models may allow for non perfect behaviour, such as:

1. Non-market clearing, especially for labour (unemployment) or for commodities (inventories)
2. Imperfect competition (e.g., monopoly pricing)
3. Demands not influenced by price (e.g., government demands)
4. A range of taxes
5. Externalities, such as pollution

A CGE model database consists of:

1. Tables of transaction values showing, for example, the value of coal used by the iron industry. Usually the database is presented as an input-output table or as a social accounting matrix (SAM). In either case, it covers the whole economy of a country (or even the whole world), and distinguishes a number of sectors, commodities, primary factors and perhaps types of household.
2. Elasticities: dimensionless parameters that capture behavioural response. For example, export demand elasticities specify by how much export volumes might fall if export prices went up. Other elasticities may belong to the Constant Elasticity of Substitution class. Amongst these are Armington elasticities, which show whether products of different countries are close substitutes, and elasticities measuring how easily inputs to production may be substituted for one another. Expenditure elasticities show how household demands respond to income changes.

CGE models are useful whenever one wishes to estimate the effect of changes in one part of the economy upon the rest. For example, a tax on diesel fuel might affect freight costs, the consumer price index (CPI), and hence perhaps wages and employment. They have been used widely to analyse trade policy. More recently, CGE has been a popular way to estimate the economic effects of measures to reduce greenhouse gas emissions.

CGE models always contain more variables than equations—so some variables must be set outside the model. These variables are termed exogenous; the remainder, determined by the model, are called endogenous. The choice of which variables are to be exogenous is called the model closure, and can give rise to controversy. For example, with land use change modelling, some modellers hold food consumption fixed; others allow this to vary. Variables defining technology, consumer tastes, and government instruments (such as tax rates) are usually exogenous.

The structure and assumptions in CGE models almost always lead to linear results. Real world responses where "low hanging fruit" is utilized first, and then more difficult solutions are implemented next, are difficult to model with CGE models. Using these models to derive a precise estimate of the emissions from land use change is probably far beyond their capabilities.

10.1.4 Partial Equilibrium Models

Partial equilibrium (PE) implies that the analysis only considers the effects of a given policy action in the market that is directly affected. That is, the analysis does not account for the economic interactions between the various markets in a given economy. In a general equilibrium model all markets are simultaneously modeled and interact with each other.

The main advantage of the partial equilibrium approach is its minimal data requirement. Generally, the only required data for the trade flows are the trade policy (tariff), and a few elasticity parameters. Another advantage (which follows directly from the minimal data requirement) is that it permits an analysis at a fairly disaggregated (or detailed) level, many times at a level of aggregation that is neither convenient nor possible in the framework of a general equilibrium model. This allows a much more detailed look at the agricultural sector for those models that have been used for ILUC estimations.

The partial equilibrium approach also has a number of disadvantages that have to be kept in mind while conducting any analysis. Since it is only a partial model of the economy, the analysis is only done on a pre-determined number of economic variables. This makes it very sensitive to a few elasticities.

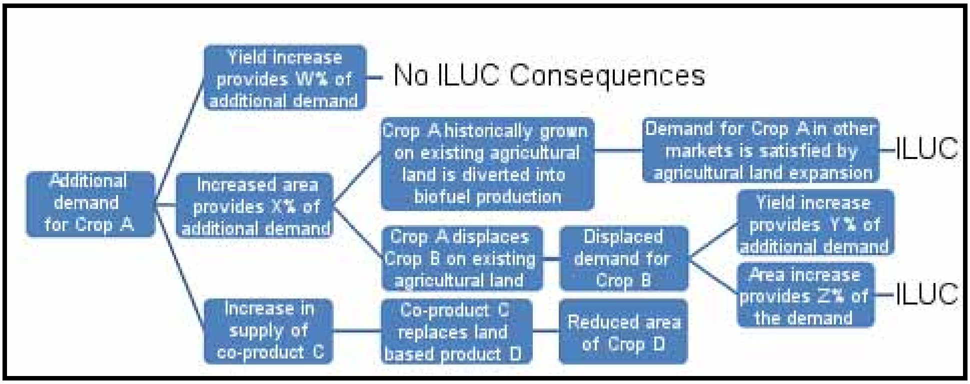
Also, due to their simplicity, partial equilibrium models may miss important interactions and feedbacks between various markets. In particular, the partial equilibrium approach tends to neglect the important inter-sectoral input/output (or upstream/downstream) linkages that are the basis of general equilibrium analyses. They may also miss the existing constraints that apply to the various factors of production (e.g., labour, capital, land) and their movement across sectors.

10.1.5 Descriptive Causal Models

An alternative approach to assessing ILUC is provided by descriptive-causal models. These models use cause and effect logic to describe the behaviour of a given system, based on observations of how the system functions. Crucially, these models provide a more transparent analysis than CGE or PE models, which enables input and review from a broad range of stakeholders. Descriptive-causal models have been promoted as a means to help increase understanding of ILUC and therefore improve economic models, or as a way of deriving fuel chain specific ILUC GHG emission factors ("ILUC factors").

In the following example, the additional demand for crop A is met through two main market responses: an increase in yield associated with no ILUC consequences and an expansion in cultivation area for biofuel production. In the first case, crop A is grown on the same land "as usual" but is diverted from a historical market into biofuel production, thus leading to agricultural land expansion to satisfy the demand for crop A in its historical market. In the other case, the agricultural land expansion reduces cultivation area for crop B, which then has to be produced in some other way. In this example, crop B is now produced through an increase in yields and another area expansion. Each area expansion ultimately leads to ILUC impacts. Furthermore, the increased production of biofuel from crop A leads to the production of co-product C which replaces another land-based product (crop D) and thus "saves" some land.

Figure 10-4 Causal-descriptive Approach to ILUC Quantification



There are relatively few variables in this example but it is obvious that a very good understanding of the agricultural system in many parts of the world is required for this approach to be valid. Typically, information is sought from:

1. Statistical analysis of historical trends is used to quantify the market responses to the additional feedstock demand and estimate business as usual trends.

2. Market analysis is used to gain insights into likely evolution of markets (such as the entrance of new products or the creation of new markets) and to identify product substitutions. When necessary, the projections obtained through extrapolation of historic trends are adapted to take the results of the market analysis into account.

3. Expert input and literature review to provide qualitative validation of the results of the statistical and economic analyses.

4. Variations in parameters from the statistical analysis to reflect different potentially likely ILUC scenarios.

More detailed information on the various models being used to estimate indirect land use emissions is presented in the appendix.

10.2 OTHER INDIRECT IMPACTS

Land use change is not the only potential indirect impact. There are other potential impacts in biofuel and fossil fuels systems. These are briefly discussed below.

10.2.1 Other Indirect Agricultural Impacts

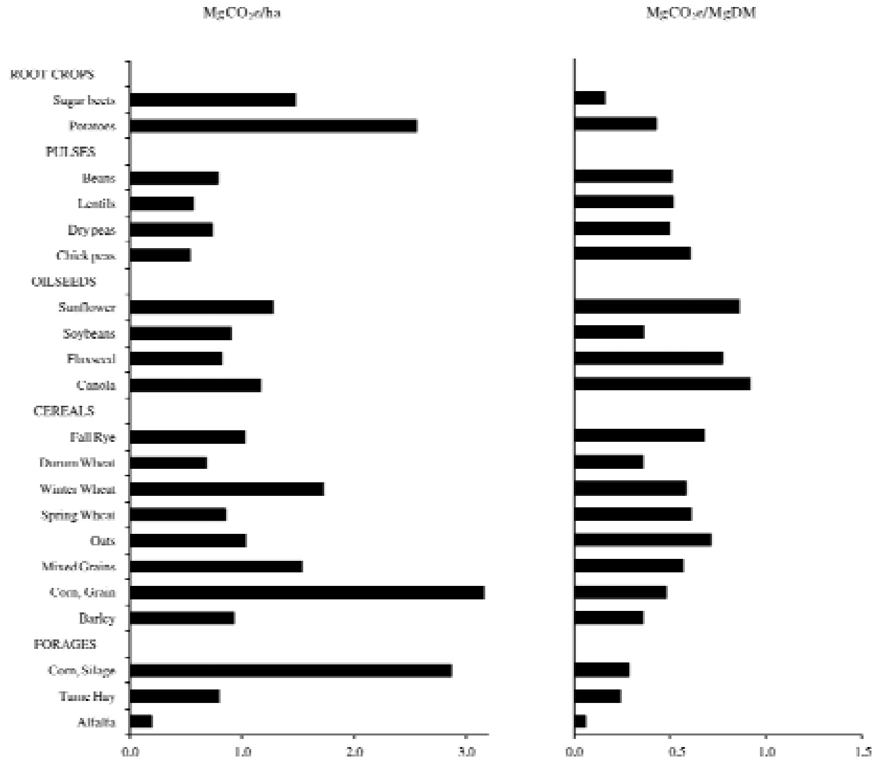
An increase in demand for biofuel feedstocks can have indirect impacts other than land use change that can effect the GHG emissions that are not considered in most models. Some of these are discussed below.

10.2.1.1 Cropping Pattern Changes

The GHG emissions per tonne of biomass and per hectare of crop production varies between crops. Fertilizer requirements are different, energy used to plant and harvest a crop can change and, of coarse, the yield changes.

A recent paper (Dyer et al, 2010) examined this issue for Canada and the results are shown in the following figure. It is expected that similar results (at least directionally) would apply to other locations.

Figure 10-5 GHG Emission Variation Between Crops



GHG emission intensities per unit area and per unit of dry matter (DM) for the 21 most important field crops in Canada during 2006.

The total GHG emissions from cropland therefore depend on the crop mix and field management practices. The assumption that has effectively been made in most ILUC studies, that there are no GHG impacts of cropland remaining cropland, is obviously not correct. The issue is that some of the crop shifting is driven by the availability of co-products, whereas other crop shifting is caused by demand changes resulting from changes in prices. In the direct GHG analysis, one generally already attempts to put a GHG values on those co-products, so there is some overlap between the GHG change from crop shifting and the GHG benefits from the direct analysis of co-products.

10.2.1.2 Changes in Livestock

Agricultural emissions account for about 32% of total anthropogenic emissions. Livestock emissions account for about 42% of these emissions in two major categories:

- Enteric fermentation (~34% of total ag emissions)

- Manure (~8% of total ag emissions) and indirect emissions from manure management are highly variable and substantial.

Changes in livestock population will directly impact both of these livestock emission sources.

In many ILUC models it would appear that the livestock population decreases with the increase in biofuel production. This would result in a reduction in livestock emissions, which are an indirect impact, the same way that new land requirements are an indirect impact.

10.2.1.3 Changes in Rice Production

Rice production also drops in many models with an expanded biofuels scenario. Methane emissions from rice production account for 11% of agricultural emissions (US EPA, 2006). They amount to about 1.05 tonnes of CO_2 eq/tonne of rice. A reduction in rice production in an expanded biofuel scenario would result in lower GHG emissions, an indirect impact. This is not accounted for in most models.

10.2.2 Indirect Impacts - Other Fuel Systems

Indirect effects are not restricted to biofuels, they can also happen in fossil fuel systems. Two of these are discussed here.

10.2.2.1 Transportation Fuel Co-Products

Processing crude oil to produce gasoline and diesel fuel also results in the production of heavy fuel oils, asphalt, coke, and other low value materials. In most LCA work the refining emissions are allocated across all products but this approach is not universally accepted as being correct and it is not aligned with ISO guidance on avoiding allocation.

Some crude oils actually produce very little or no bottom of the barrel products. If a LCA study were done on these crude oils there would be the issue of how to make the two systems equivalent. That is, what would replace the coke and heavy fuel oil if it weren't available? This issue was discussed earlier in the report on the allocation section for crude oil. Another way to look at it is that the production of coke and heavy fuel oil is an indirect effect of producing gasoline and diesel fuel and that the emissions associated with the production and use of those products should be quantified as an indirect effect. Depending on the crude oil and the alternative fuel used these indirect emissions could range from a few g CO_2eq/MJ up to 10 or 15 g CO_2eq/MJ.

10.2.3 Military Support

Some argue that much of the US Military expenditure is a direct result of the US reliance on imported oil. If there weren't that reliance, the military expenditures would be reduced, as would the military GHG emissions. Liska and Perrin (2010) argue that the GHG emissions from US military activity in the Persian Gulf could range fro 8.1 to 18.2 g CO_2eq/MJ, depending on the LCA methodology applied.

The subject of the cost of imported oil from the Middle East has been study by others but not from the perspective of GHG emissions. Delucchi and Murphy (2008) estimated that spending on defence of the Persian Gulf is in fact related to US interests in the region, which are mainly but not entirely oil interests. Their best estimate of this relationship translates to \$0.005–\$0.05 per litre of all gasoline and diesel fuel used by motor vehicles. The high end of this range is comparable with Liska estimate.

The determination of the carbon emissions from this indirect impact is as difficult to resolve as the indirect land use issue.

10.3 SUMMARY

In the past several years the issue of the indirect impacts of expanded biofuel production has received considerable attention in the policy and academic communities. A significant number of modelling projects have been undertaken to try and quantify the land use change impacts and the resulting GHG emissions from the changes.

There are significant issues with the quality of the modelling efforts, a fact acknowledged by many of the modellers. Some of the major uncertainties are:

1. Determining an accurate inventory of cropland throughout the world. Most models don't include cropland that is temporarily idle in their calculations.
2. Determining which kind of land is converted is a problem for many models. Most do not include the cost of land conversion and thus overestimate the conversion of forest land to cropland.
3. Most models have difficulty dealing with co-products. They try to determine the effect of co-products on land requirements just through the price of the products. They are not capable of doing this based on the functional value of the co-products (i.e. their protein or energy contents).
4. There are indirect impacts for biofuels that are not calculated in many of the models. Some of these could reduce the ILUC impact.
5. There are indirect effects of other fuels. Some estimates for fossil fuels have been in the same range as some of the biofuel estimates.

11. SPECIFIC REGIONAL ISSUES

A number of member countries of the IEA AMF funded this work either through cash or in kind contributions (or both in some cases). The countries making in kind contributions were invited to provide a short summary of the state of LCA modelling in their country. They were specifically asked to address the following questions.

1. A description of the state of LCA modelling in your country:
   - what approaches are being used currently for LCA and why?
2. What are the main challenges in improving LCA analysis capacity?
   -e.g., availability of data from particular processes and industries? Which ones?
3. How are the results of LCA work used in your country?
4. What are the main fuel pathways of interest in your country?

The responses received from the countries are provided below with minor editing.

11.1 AUSTRIA

In Austria there is a long tradition of performing life cycle assessment. In particular, as noted earlier, Austria was strongly involved in developing the LCA methodology for biomass and bioenergy system by leading the IEA Bioenergy Task on “Greenhouse gas balance of biomass and bioenergy systems” since 1997.

In Austria there are a handful of institutions that perform life cycle assessments for alternative fuels (e.g. JOANNEUM RESEARCH, Umweltbundesamt). Based on a decision in the 1990s made by Austrian stakeholders from research, industry and governmental bodies an Austrian data set for the GEMIS LCA software was developed. This Austrian GEMIS data is regularly updated with new data. The Umweltbundesamt is responsible for the updating and distribution of the Austrian GEMIS data set. So most of the LCA made in Austria use the GEMIS Model. The model offers all the necessary flexibility to adapt the model to the LCA The model offers all the necessary flexibility to adapt the model to the LCA methodology applied, e.g. setting of system boundaries, handling of by-products, reference system.

Since the development and the implementation of the greenhouse gas methodology of the European Directive on Renewable Energy (RED), this methodology is applied for the transportation biofuel production plants in Austria.

Beside this, in Austria there is a strong expertise in modelling the carbon dynamics in agriculture, forestry and land use management, where direct and indirect land use aspects are analysed and assessed for different biomass management and use options in various life cycle considerations.

Due to the long LCA tradition in Austria there has been a continuous process of improving LCA analyses in the past. Currently the main challenges are in gathering actual data in the following areas:

- Cultivation of agricultural raw materials for transportation biofuels;
- Modelling of emissions from the application of digested material from biomethane production in agriculture;
- Modelling of carbon stocks and flows with different land use management strategies (Figure 11-1);
- Inclusion of emissions from indirect land use change;
- Production of biodiesel, bioethanol and biomethane;
- Modelling of CH_4, N_2O and NH_3 emissions in agriculture e.g. manure storage and application;
- Production of 2nd generation biofuels mainly synthetic biofuels (e.g. Fischer-Tropsch, synthetic natural gas - SNG) via gasification of wood and straw and bioethanol from wood, straw and sulphite spent liquors;
- Production of renewable electricity and hydrogen;
- Listing of the new electricity generation plants installed and planned in Austria;
- Production of (hybrid) electric and fuel cell vehicles (Figure 11-2) and
- Development of concepts of using algae for biofuel production.

Figure 11-1 Modelling Carbon Stocks

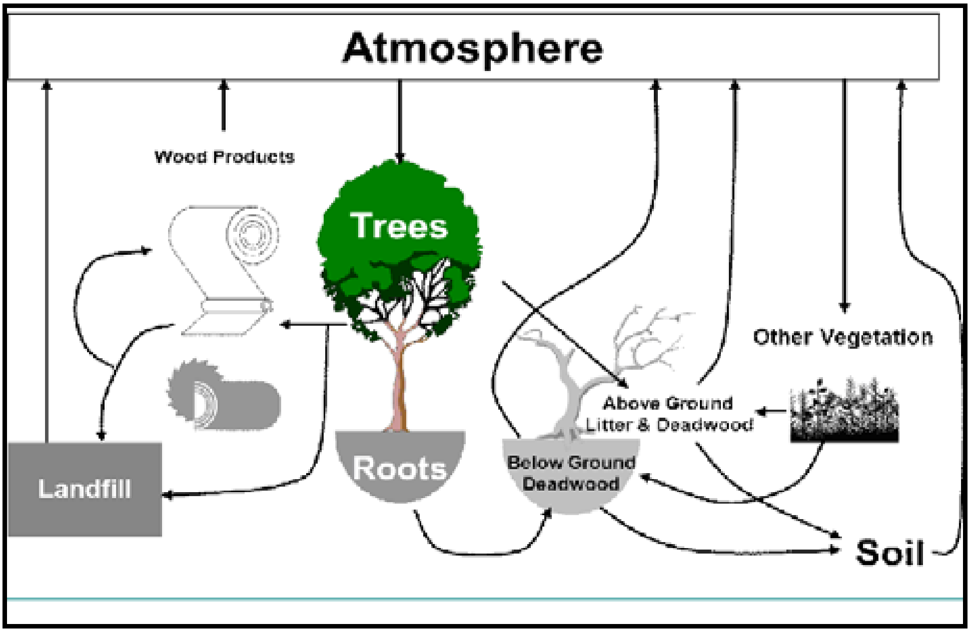
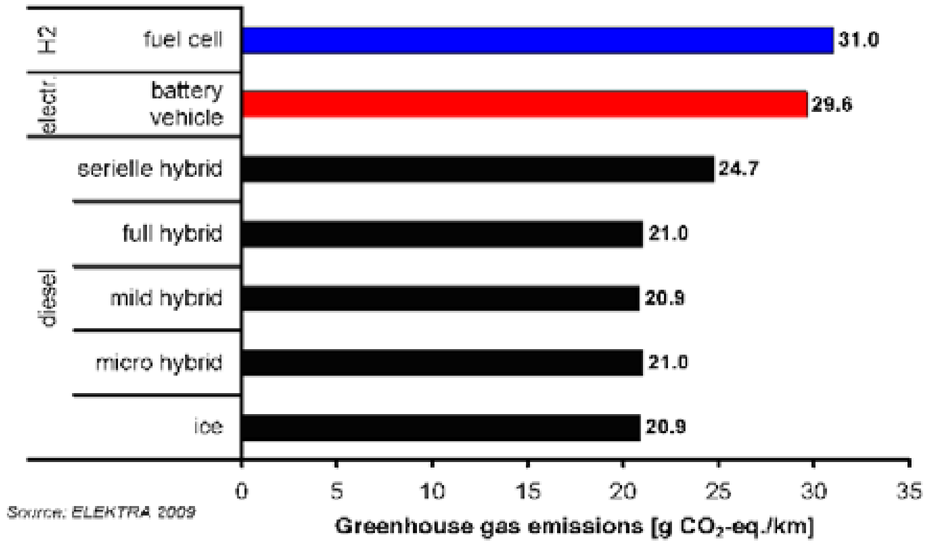


Figure 11-2 FCV LCA Results



Source: Elektra 2009

There are many data available to make the necessary calculations, according to the RED, for biofuel production in Austria. However, of course, most of these data are confidential as they refer to existing industrial plants. For today's alternative propulsion system and future developments there are many data available for different combinations of fuels, propulsions systems and type of vehicle (e.g. passenger car, bus, trucks)

In addition to databases, the LCA methodology is being further developed in the following specific areas:

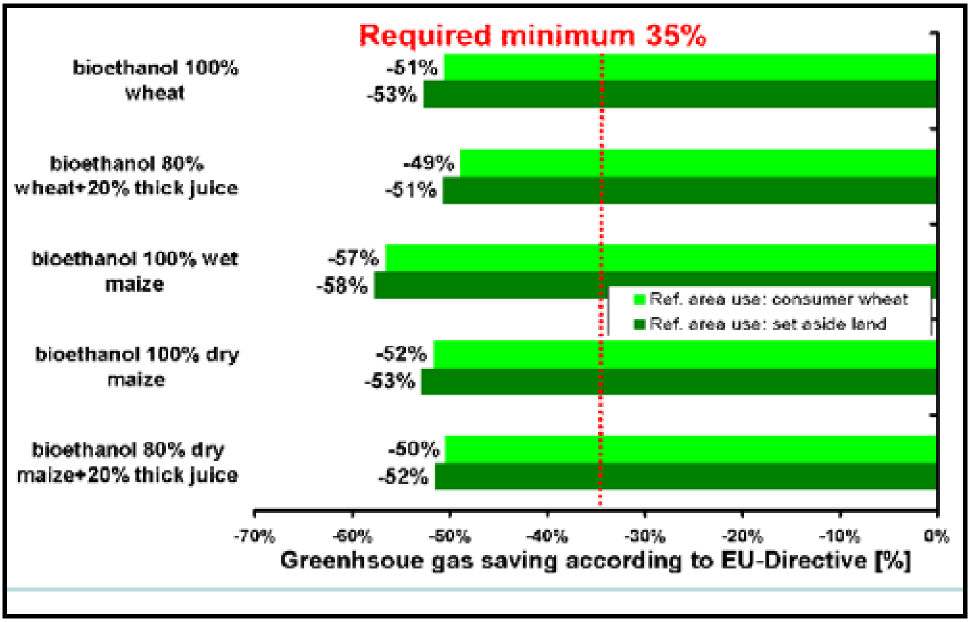
- Integration of carbon dynamics in LCA
- Aspects of indirect land use
- Reference use of biomass based residues; and
- LCA applications for biorefineries.

In Austria, all relevant activities and projects stimulated by industry, policy or research in the area of alternative motor fuels need an environmental assessment to demonstrate that they provide benefits rather than harm the environment. It also accepted that LCA is the best scientific methodology to assess the environmental impacts. So the LCA methodology is widely accepted for these applications and also for investment decisions e.g. new public fleets, renewable hydrogen for oil refining, product development of hydrogen vehicles, rolling out infrastructure for e-mobility.

The following section highlights some of LCA uses for alternative motor fuels specifically, biofuels, electricity and hydrogen:

Biofuels: The current main use of LCA results in Austria is in the biofuel industry due to the necessity of the RED. This covers mainly biodiesel and bioethanol. For biofuels made from lignocellulosic raw materials the LCA results are mainly used for policy decisions to focus research on the most promising 2nd generation biofuels. There is a growing interest in algae as a source of transportation biofuels. Currently a study is going on to identify the most promising options in Austria, e.g. there is a strong industrial interest in the production of biodiesel made from algae oil. The following figure shows the results from the analysis of some bioethanol options at an Austrian plant.

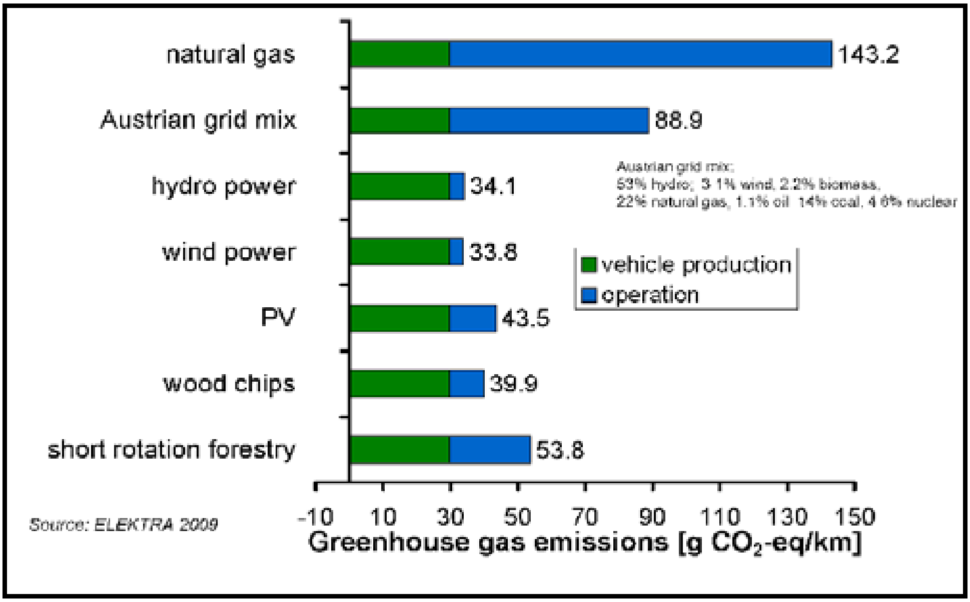
Figure 11-3 LCA GHG Emission results for Austrian Bioethanol



Source: Jungmeier et al. 2008

Electric vehicles: Due to the current challenges of introducing electric vehicles, LCA results are used for policy decision for the further implementation of electric vehicles and development of the necessary infrastructure. Key interest is the possibility to produce additional renewable electricity for e-mobility and the environmental impacts from the production and disposal of batteries. Some examples of LCA results for battery electric cars are shown in the following figure, where the main influence of the type of electricity generation is evident beside a significant contribution from the vehicle production.

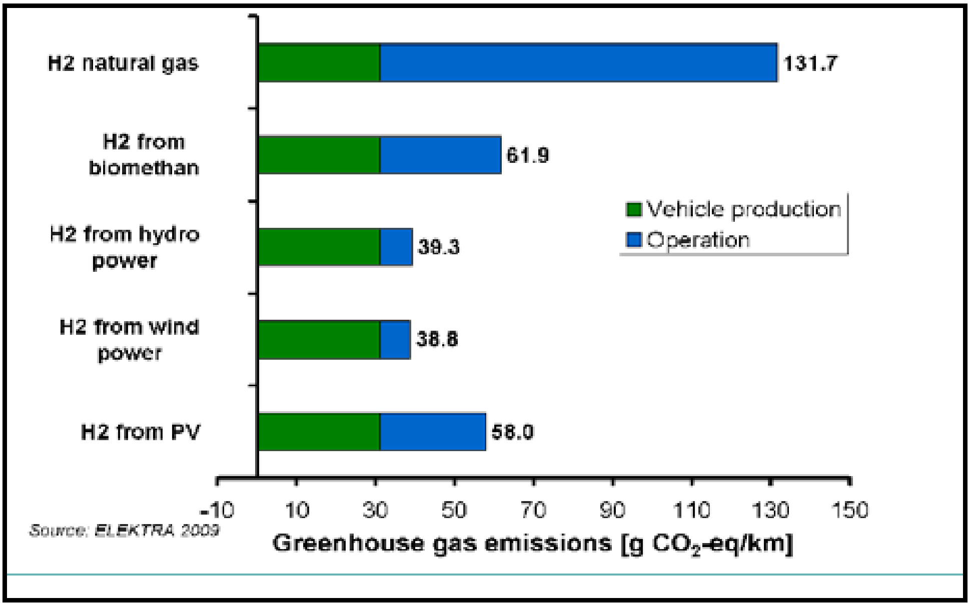
Figure 11-4 EV LCA Results



Source: Elektra 2009

Hydrogen: The LCA of hydrogen as a transportation fuel is mainly of interest for policy and industrial decisions to implement demonstration activities. There is a strong interest in hydrogen fork lifts, for which the LCA results from hydrogen are essential. Main challenge for hydrogen LCA is that the production of hydrogen is sustainable (e.g. hydrogen made via decentralized steam reforming of biomethane) and that the energy for hydrogen cannot be used in a more environmentally friendly manner (e.g. biomethane as biofuel for fork lifts). Some LCA results are shown in the following figure, where it becomes clear that the production of the fuel cell-vehicle might significantly contribute to the greenhouse gas emissions. In addition there is a strong interest from the oil refining industry in Austria to substitute the natural-gas derived hydrogen required for the desulphurisation of diesel by hydrogen made by gasification from wood. This seems currently one of the most promising options for renewable hydrogen production and use in Austria. LCA results from hydrogen are also relevant for the electrolytic production of hydrogen from renewable electricity, where also the by-products from electrolyses (oxygen and heat) are used. This increases the environmental benefits of the hydrogen substantially.

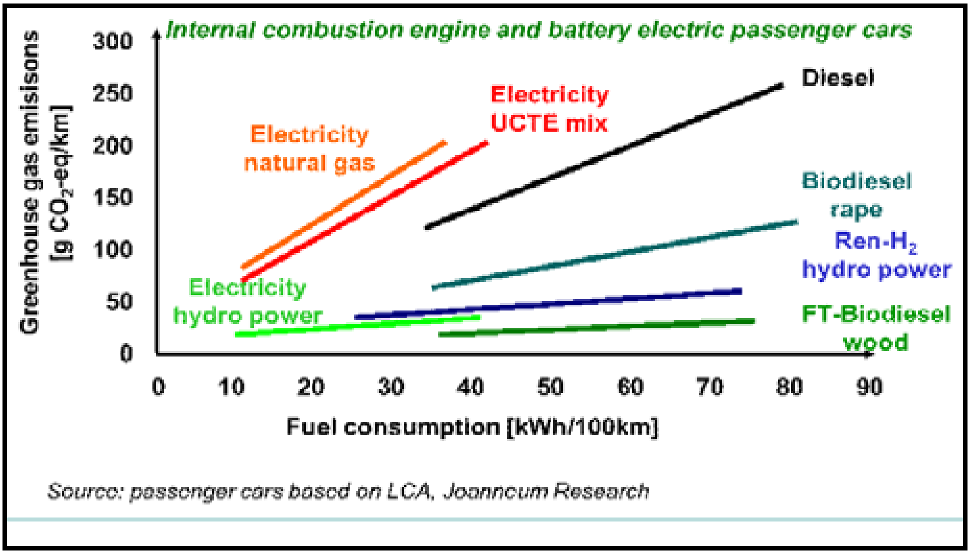
Figure 11-5 Hydrogen Production Options



Source: Elektra 2009

Summing up: one of the main goals of LCA for alternative motor fuels in Austria is to show and communicate the main influences on the environmental impacts e.g. type of raw material, influence of vehicle production, fuel consumption, to identify under which conditions is a significant environmental improvement possible. An example is shown in then following figure, where the influence of the fuel consumption on the greenhouse gas emissions of different alternative motor fuels is shown.

Figure 11-6 Impact of Fuel Consumption on GHG Emissions

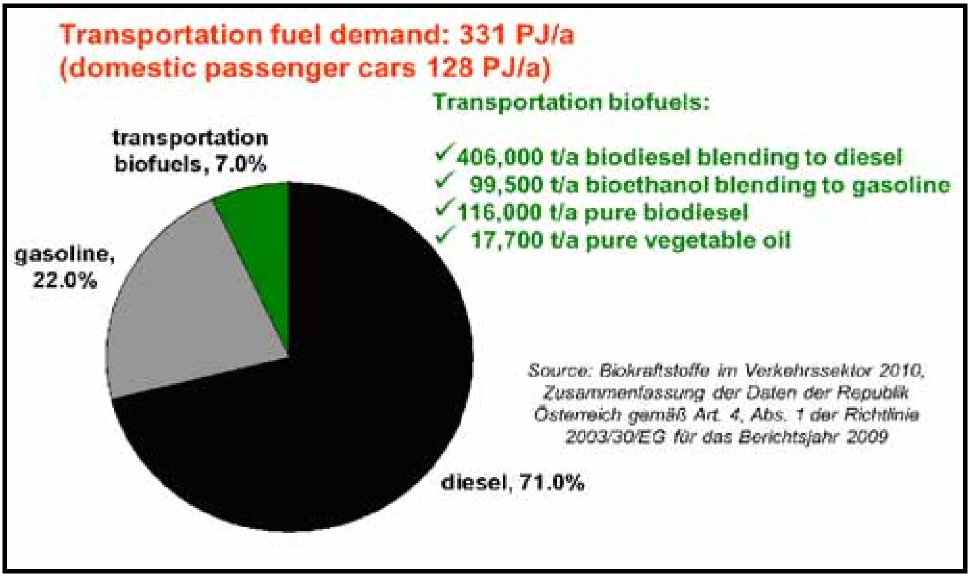


Source: Jungmeier et al. 2010

Austria has a long tradition of using biomass for heat and electricity, which is now expanded also to transportation biofuels. Today the commercial production of bioethanol and biodiesel is established.

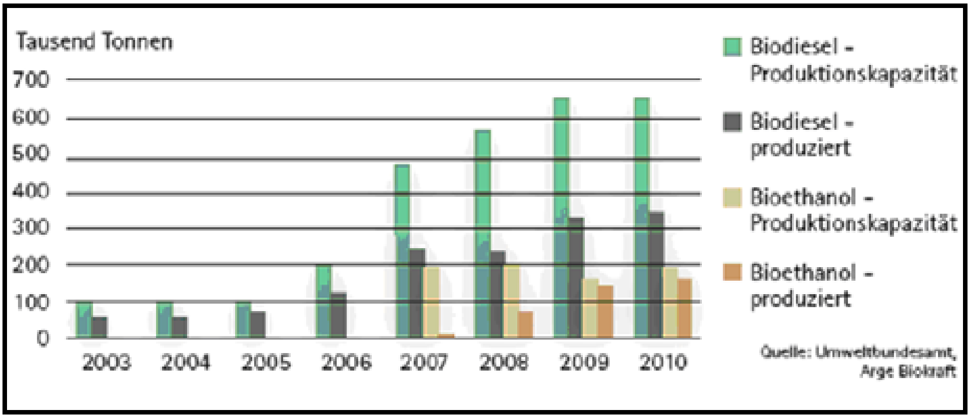
In Austria, the transportation sector requires about 350 PJ/a, or approximately 35% of the total final energy demand in Austria. Of this, the current use of biofuels is 7% of the fuel consumption in transportation sector as shown below'

Figure 11-7 Austrian Transportation Fuel Demand



The development of the Austrian transportation biofuel production over the last seven years is shown in the following figure.

Figure 11-8 Biofuel Production Growth

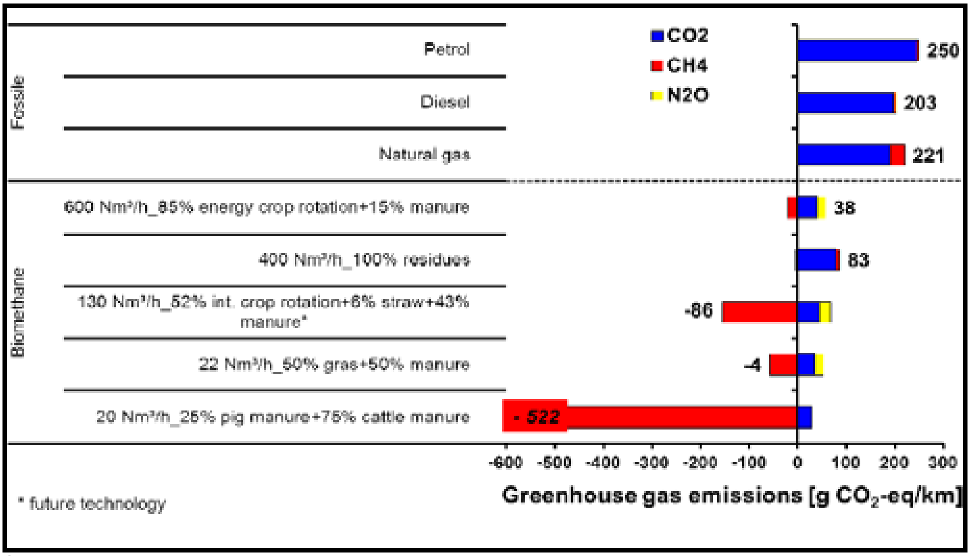


The production strongly increased in the period 2005 to 2008. In 2010, there are 14 biodiesel production facilities, which have a production capacity of around 650,500 t/a. The actual biodiesel production in 2010 was 336,700 tons. Biodiesel is mainly made from (used) vegetable oils and animal fats. Biodiesel has been produced industrially since 1990s.

In Austria, bioethanol has been added to petrol since 1 October 2007. Before 2008, bioethanol was not produced domestically. In this year, the bioethanol plant in Pischelsdorf opened. It has an annual production capacity of nearly 200,000 t, so the total national demand for bioethanol can be satisfied.

Many demonstration activities are on-going to produce biomethane and use it as a transportation biofuel (also in mixture with natural gas). The LCA results show, that the environmental effects strongly depend on the type of raw material used as input for the biogas production. An example of the life cycle based greenhouse gas emissions is shown below.

Figure 11-9 Biomethane LCA Results



Source: Pucker et al. 2011

Second generation biofuels are of strong interest for pilot and demonstration activities, where a strong focus is on the production of synthetic biofuels mainly FT-fuels and synthetic natural gas (SNG) via gasification of wood (and straw). Due to the decentralised availability of wood and straw these activities focus on the so called “polygeneration”, where transportation biofuels, electricity and heat are coproduced with very high overall efficiency. There is a demonstration plant in Austria for the production of SNG via steam gasification and methanisation with a capacity of 1 MW SNG output. There is also a pilot plant for the production of FT-biofuels with a production capacity of about 1 barrel (metric units) per month. The life cycle based effects of FT-biofuel depends on the type of feedstock used and the type and amount of useful by-products mainly heat and electricity.

The bioethanol activities are concentrated on a pilot testing of bioethanol from straw and the integration of bioethanol production from wood in the pulp and paper industry, where also bioethanol can be produced from sulphite spent liqueur. All other biofuels are of little interest e.g. DME, methanol, as they cannot be blended with gasoline and diesel or natural gas, and hence require totally new infrastructure.

One relatively new national research focus is the assessment of the possibilities to cultivate algae to produce transportation biofuels. Currently extensive LCA work is carried out to identify under which frame work conditions biofuels from algae might contribute to a sustainable development by substituting fossil fuels and “conventional” biofuels, e.g. biodiesel from rape seed oil versus biodiesel from algae.

11.2 CANADA

The GHGenius model is the most widely used model in Canada. The GHGenius model has been developed for Natural Resources Canada over the past eleven years. It is based on the 1998 version of Dr. Mark Delucchi’s Life Cycle Emissions Model (LEM). GHGenius is capable of analyzing the energy balance and emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels.

The model is continually being developed and improved with typically 3 - 4 updates being released per year. Updates include new fuel production pathways, updated data as new information is always being released into the public domain, refinement to pathways to better reflect actual processes, and improved functionality. Model users suggest about one half of the changes with the remained being suggested by Natural Resources Canada.

The model has regional data for Canada, the United States, and Mexico. It also has national data for India. It has the capacity to be expanded to included other countries.

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. Includes energy and emissions associated with the transportation infrastructure construction and maintenance (trucks, trains, ships, pipelines, etc.)
- Feedstock Production and Recovery

  Direct and indirect emissions from recovery and processing of the raw feedstock, including fugitive emissions from storage, handling, upstream processing prior to transmission, and mining.
- 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.

GHGenius produces a wide range of outputs designed to meet the needs of the users. The specific output data includes:

- CO_2-equivalent emissions (in g/km or g/unit fuel) by stage of fuelcycle and for vehicle manufacture, for the feedstock/fuel/vehicle combinations identified above,
- Summary of % change in life cycle g/km emissions from alternative-fuel vehicles, relative to conventional gasoline LDV's or diesel HDV's,
- Emissions (in g/km) by individual pollutant for each stage of the fuelcycle for each feedstock/fuel,
- Emissions from EV's, by region,
- CO_2-equivalent emissions (in g/unit of fuel) by stage of fuelcycle and for vehicle manufacture, for the feedstock/fuel/vehicle combinations identified above,
- CO_2-equivalent emissions (in g/GJ) (HHV or LHV) for each stage of the upstream fuelcycle for each feedstock/fuel,

- Emissions (in g/GJ) (HHV or LHV) by individual pollutant for each stage of the upstream fuelcycle for each feedstock/fuel,
- kJ's of process and end-use energy per kilometre of travel by stage of life cycle, for different feedstock/fuel/vehicle combinations,
- kJ's of fossil process and end-use energy per kilometre of travel by stage of life cycle, for different feedstock/fuel/vehicle combinations,
- Breakdown of energy use by type of energy (e.g., diesel fuel, natural gas, propane), stage of life cycle, and feedstock/fuel combination,
- Emissions from electricity use: CO_2-equivalent emissions (in g/GJ and g/kWh delivered) for different sources of electricity generation,
- Emissions from use of heating fuels: CO_2-equivalent emissions (in g/GJ-heat-delivered) for natural gas, LPG, electricity, biodiesel and fuel oil;
- The cost effectiveness of GHG's reduced for each of the vehicle/fuel combinations in the model.

GHGenius has two tools to enable the user to undertake more complex scenario investigations.

There is a Sensitivity Solver, which allows the user to vary any input cell over a range and determine the impact on any output cell in the model. The results are also automatically graphed.

The second tool is a built in Monte Carlo simulation tool. Up to five input cells can be varied according to user selected distributions and values and the impact on up to 18 output cells can be determined. The results can also be presented graphically.

At the Federal Government level, GHGenius has been used to inform public policy on the emissions from various fuel production pathways but it is not used for regulatory purposes.

Two Provinces in Canada, British Columbia and Alberta, have started to use GHGenius for regulatory purposes. British Columbia has introduced a low carbon fuel standard, which calls for a 10% reduction in GHG emissions from the production and use of transportation fuels by the 2020. GHGenius has been used to develop the default values for a number of the fossil fuels and biofuel providers must use GHGenius to determine their individual carbon intensities for compliance purposes.

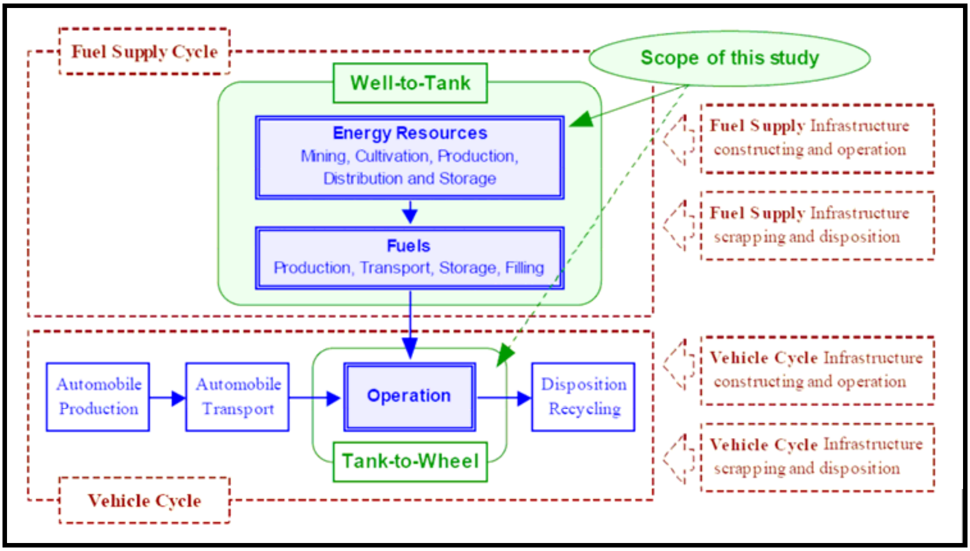
Alberta has introduced a renewable fuel standard, which calls for 5% renewables in gasoline and 2% renewables in diesel. The renewable fuel must achieve at least a 25% reduction in GHG emissions compared to the fossil reference fuel. GHGenius is used to determine the reference fuel GHG emissions and whether or not the biofuel meets the required emission reduction threshold.

11.3 JAPAN

Toyota Motor Corporation and Mizuho Information & Research Institute, Inc. published a report "Well-to-Wheel Analysis of Greenhouse Gas Emissions of Automotive Fuels in the Japanese Context - Well-to-Tank Report" in 2004. An excerpt from this report has been translated into English.

This study focused on estimating well-to-tank energy consumption, greenhouse gas (GHG) emissions and the energy efficiency of current and near-future automotive fuels in Japan. The results of this study were subsequently combined with data related to tank-to-wheel studies previously conducted by TMC, and a case study showing well-to-wheel GHG emissions under fixed conditions, calculated using sedan-type vehicles. The scope of the study is shown in the following figure.

Figure 11-10 Scope of Japanese WTW Study

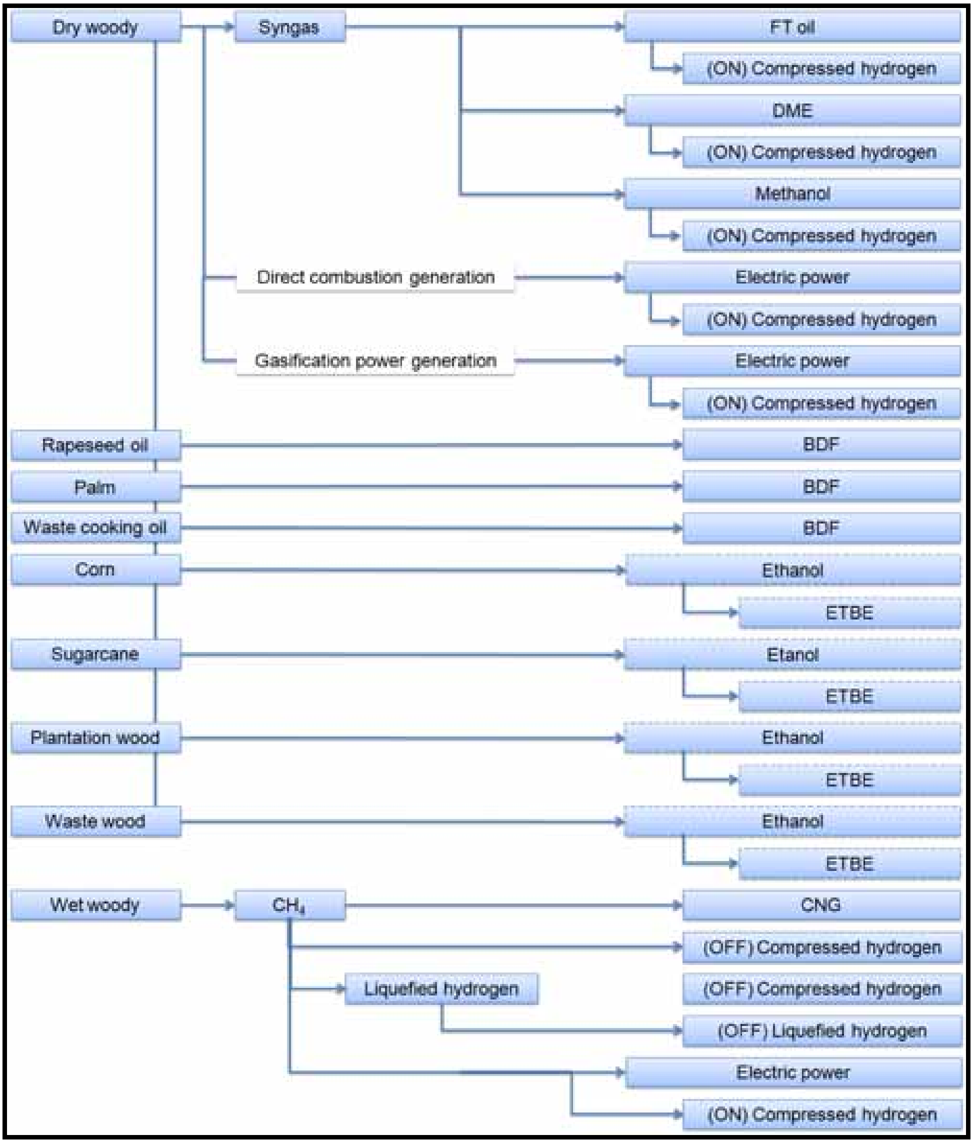


The 76 fuel pathways considered, broken down into six categories, were:

1) 21 petroleum-based fuels,
2) 20 natural gas-based fuels,
3) eight coal-based fuels,
4) 19 biomass resource-related fuels (three bio-diesel fuels, 10 dry biomass-based fuels and six wet biomass-based fuels),
5) power grid mix (Japan average) and
6) hydrogen production through electrolysis (six byproduct hydrogen pathways).

As an example of the pathways studied the 19 biomass pathways are shown in the following figure.

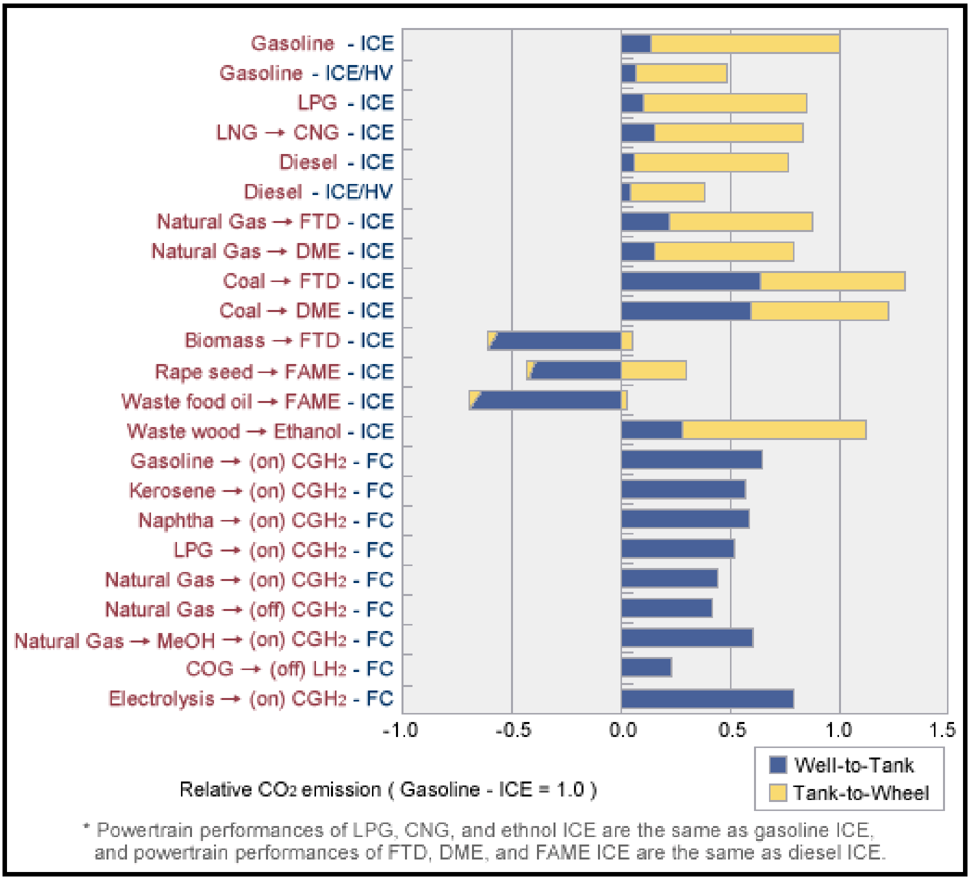
Figure 11-11 Biomass Pathways Studied



No fixed timeframe was set for the data collected, with efforts focused on understanding and organizing existing data. Additionally, in order to ensure data impartiality, efforts were made to improve credibility by seeking varied advice, ranging from third-party evaluations by an Advisory Committee to obtaining calculation methods from the data sources. Moreover, where data used in calculation had a broad range, the range is indicated through minimum to maximum values.

For well-to-wheel studies, and in concurrence with previous research for the Japanese 10-15 test cycle (example of calculations are made in this study), which is mainly a comparatively low-speed run, significantly superior results were obtained for hybrid-electric vehicles (gasoline, diesel) in relation to GHG emissions. For synthetic fuels, such as Fischer-Tropsch diesel oil, dimethyl ether (DME) and hydrogen, large variations in well-to-tank GHG emissions were apparent depending on the primary energy used as feedstock, and it is clear that an important aspect of future considerations will be the production of fuels through low GHG emission pathways. Regarding hydrogen, during transition, hydrogen derived from fossil fuels, such as natural gas, has also shown results similar to that of hybrid electric vehicles, and depending on trends in CO_2 capture and storage, possibilities of further reductions in GHG emissions with these pathways are conceivable. In addition, fuels derived from biomass resources have comparatively low GHG emission values, and future utilization is anticipated. The typical results are shown in the following figure.

Figure 11-12 Typical Results Japan WTW Study



The authors concluded that the credibility and applicability of calculations in this study depends greatly on calculation preconditions, such as implemented load distribution methods and quality of data. In reality, some fuels, such as petroleum products, city gas, liquefied petroleum gas (LPG) and electricity, are already in industrial use, while biomass resources, synthetic fuels, hydrogen and so on, are still in the early stages of technological development. In addition, even where calculation results of this study are based on actual values, “there is a high degree of uncertainty concerning future technological innovation, market size, new laws and regulations and such” and thus many problems exist concerning the simple comparison of these fuels.

With respect to allocation issues between main products and co-products/ byproducts, although this study was conducted under the premise that, in principle, byproducts will be disposed of, the usage of certain byproducts has been considered in prior studies, although the possibility of realizing this usage is unclear (load distribution considerations). Also, regarding the system boundaries of the system, the environmental load from the production process of byproduct hydrogen feedstock, such as coke-oven gas (COG), was not taken into consideration during this study.

The authors concluded that for these reasons, the calculation results of this study are not unlike preliminary approximations, and in order to contribute further to the initial objectives, the consistency of preconditions and the accuracy of data used in calculations must be improved, and the credibility of the results must be enhanced.

It was concluded that well-to-wheel analysis results will be an important factor in the selection of future technologies and fuels. However, the technologies and fuels that will be implemented in the future will not be determined by this factor alone. This is because a variety of other factors such as cost, infrastructure and completeness of the technology and its supply potential and usability will also be taken into consideration. In the future, it will be necessary to seek out optimum vehicle/fuel combinations according to energy circumstances, available infrastructure and regulations that apply in each country or region.

11.4 THAILAND

LCA has been around in Thailand for almost 15 years, though its application to fuel chain analysis is more recent. Process analysis has largely been used for conducting LCA of transportation fuels; with organizations from the government, industry and academia playing the key role. Calculations are done either on spreadsheets or commercial LCA software; there is no dedicated software for LCA of transportation fuels in Thailand. LCAs have been conducted for the conventional fossil fuels used in transportation including gasoline, diesel, liquefied petroleum gas and natural gas as well as agro-based fuels (biofuels) such as ethanol from cassava and sugarcane molasses and biodiesel from palm oil, used cooking oil and jatropha oil. Second generation biofuels are still in the research and development stage and hence, not yet covered in the LCA studies except as scenarios in studies on first generation biofuels. The attributional approach has largely been used for quantifying the potential environmental impacts though some studies analyzing the impact of governmental targets for biofuels have also considered the consequential approach. The entire life cycle starting from resource (crude oil and gas) extraction up to final use is considered for fossil fuels. For biofuels, the life cycle includes land use change, cultivation and processing up to final use. Recent studies have also looked at aspects of indirect land use change.

The national life cycle inventory database development over the past several years has resulted in the availability of much of the background data especially for oil & gas exploration & production, gas separation, oil refining and transportation. LCA projects initiated by the industry of course have the advantage of easier access to data from the commissioning companies and their suppliers; however, this data is usually deemed confidential and not publicly available. For studies that are carried out by research institutes, data accessibility, especially for sensitive information on energy use within the companies are difficult to obtain and estimates have to be made, at times, based on literature. This is especially true for new technologies where the companies have more serious confidentiality concerns. In many cases, energy measurements are not made for individual processes or products within a facility; rather energy use is metered for an entire facility, which is producing multiple products and has many unit processes. Data on manufacture of certain chemicals is also sometimes from international databases. When studying biofuels, calculations for land use change usually rely on the default values from the Intergovernmental Panel on Climate Change (IPCC) as local data on soil carbon stocks, etc. are not yet available. Also, data collection on cultivation requires much effort due to the presence of small-holder farmers for many of the fuel feedstocks; the farmers may not be keeping systematic records of inputs and outputs.

LCA has not officially been adopted at a policy level by the government. However, the importance of life cycle thinking is recognized and incorporated, for example, in the Thai ecolabel and green purchasing programs. Clean Development Mechanism (CDM) projects of course utilize the life cycle concept. More recently, the carbon footprint label considers the life cycle greenhouse gas emissions from product cycles. The Ministry of Energy has been promoting the use of alternative fuels for several years and there have been quantitative targets and roadmaps for achieving these. LCA is accepted as a standard assessment tool for transportation fuels. Over the last decade, the acceptance of LCA by the government and industry has increased dramatically.

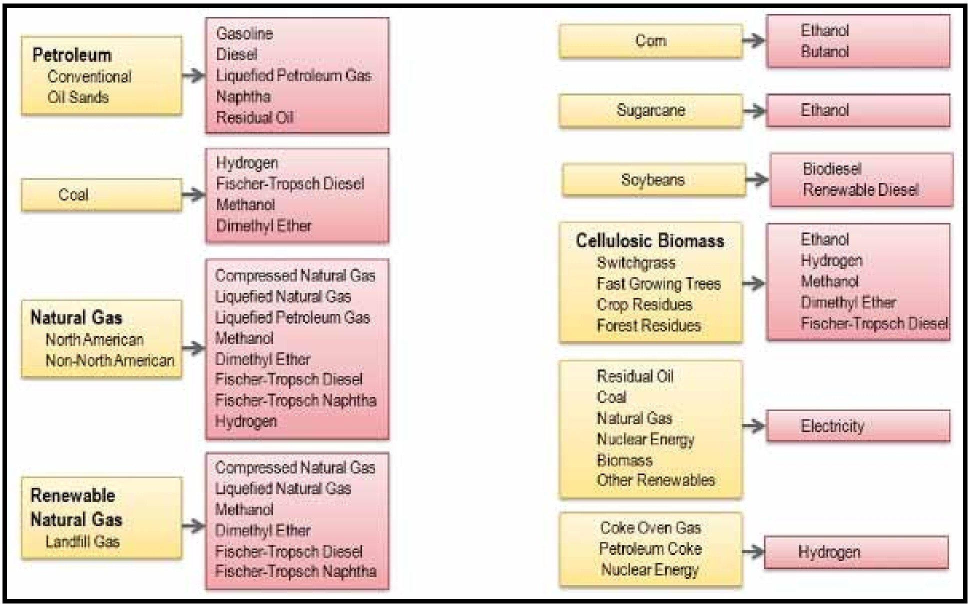
In Thailand, the main fuel pathways of interest have traditionally been diesel and gasoline. Natural gas for vehicles and liquefied petroleum gas have been promoted by the government and are now much in use. Biofuel blends of ethanol with gasoline and biodiesel with diesel have been mandated in the Ministry of Energy's Alternative Energy Development Plan and are thus of interest. Currently the biofuels in use are the so-called first generation ones and the pathways correspond to those; fermentation of sugar and starch-based feedstocks for ethanol production and transesterification of plant oils to biodiesel. However, second generation biofuels from lignocellulosic conversion are also being considered. Advanced biofuels such as bio-DME and algal biodiesel are also being considered.

11.5 UNITED STATES

In the United States many organizations—governmental, academic, industrial—have developed LCA tools for conducting analyses of fuel and vehicle pathways of interest to these organizations, reporting and interpreting their results in the open technical literature. Whilst the overall quality of data input to these tools conforms to accepted norms, not all methods employ the same pathway elements for each fuel and both accounting and discounting methods can differ across models and platforms. The U.S. Department of Energy has adopted the GREET (Greenhouse-gas, Regulated Emissions and Energy use in Transportation) model as its recommended procedure. GREET is designed to minimize bias in structuring pathways and to provide a fully compatible basis of comparison amongst fuels with respect to (a) input energy (by type/source) required per unit of energy output and (b) the resulting environmental residuals. GREET began as an ALCA method, but is in the process of evolving into a CLCA tool with the ability to examine the effects of various input-output assumptions on such factors as land use, water demand, and technology shifts. A description of the latest version of this model is available at http://greet.es.anl.gov/files/greet_1_2011_memo. The new version (GREET 1_2011) may be downloaded from the GREET site.

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

Figure 11-13 GREET Pathways



Recent enhancements to the model include new pathways for producing (a) bio-oil from algae, palm, rapeseed, jatropha and camelina; (b) renewable gasoline and diesel from pyrolysis of cellulosic biomass; (c) shale gas from contemporary hydro-fracking methods; (d) renewable natural gas from anaerobic digestion and conventional manure management; and (e) jet fuel. New analysis options account for energy use and emissions associated with the construction of petroleum and natural gas wells, and excavation and operation of coal mines; and for plant and equipment composition and onsite construction activities of three geothermal power plant technologies. Also, petroleum recovery and refining estimates and farming assumptions for corn stover, forest residue, switchgrass, sugarcane, and soybeans have been updated.

Whilst GREET maintains more than 100 fuel production pathways, there remain pathways of interest to some institutions that have yet to be included. For some of the missing pathways, needed or desired data cannot be obtained easily (e.g., renewable natural gas production from waste water, food waste, and cellulosic biomass). Moreover, fuel production processes developed recently or realized only at pilot or demonstration scales may not provide information sufficient to develop pathways in GREET. Example pathways of this type include algae production from sugar, hydrothermal liquefaction, and renewable gasoline production by fermentation of cellulosic biomass.

Even for existing fuel pathways in GREET, some data or process definitions may be questionable due to lack of information. For example, methane leakage during gas well completion and work-overs depends highly on ultimate recovery estimates with large uncertainty and highly variable or unofficial emission factors. Other examples of questionable process data include methane venting into tailing ponds for surface mining of oil sands, coal mining and cleaning process parameters, cellulosic ethanol production parameters, emissions from land use change, and power generation by integrated gasification from combined cycle of coal and biomass. Moreover, some upstream inputs, such as farming parameters for palm, rapeseed, jatropha, and camelina, are obtained from non-U.S. sources and therefore may not be applicable for U.S. case studies.

GREET is certainly not unique in lacking fully reliable input parameters for some pathways, for it is a reasonable generalization that weaknesses of all such tools in use in the US are concentrated along pathways of very limited interest to domestic fuel producers and policy analysts.

LCA has not been adopted as an official policy tool by national or state governments in the USA, but has become more influential as a heuristic, guiding investment decisions by large industries and venture capitalists, especially decisions focused on renewable and "clean" energy. LCA is not specifically credited as the substantive foundation of strategic incentives such as the tax credits now in place for specific fuels and energy technologies (e.g., wind, solar, biogas, ethanol and trans-esterified oils). Nonetheless, the formalized computation of (a) fuel cycle-related net residuals, (b) energy output to input ratios, and (c) reduction in demand for conventional petroleum product for such fuels and technologies has clearly informed the structure of those incentives. Moreover, the increasing ease of application and transparency of LCA tools now available opened up exploration of an ever-expanding palette of exploitable energy pathways that have attracted investor interest.

Without question the distribution of the USA's production and consumption of alternative transportation fuels across the current spectrum of options is driven by the impact on the market for bio-fuels of the mandates encoded in the Energy Policy Act of 2005 (PL 109-58) and the Energy Independence and Security Act of 2007 (PL 110-140). The Renewable Fuels Association reports that domestic production of fuel ethanol has climbed from 3.4 billion gallons (US) in 2004 to 13.23 billion gallons in 2010, whilst production of bio-diesel (which is gradually being supplanted by "renewable diesel" and other refinery-based products) peaked at 691 million gallons in 2008, declining to 315 million gallons last year. Total US consumption of fuel ethanol, including imports, grew from 4.06 billion gallons (≈325 petajoules) in 2005 to 11.04 billion gallons (≈885 petajoules) in 2009. By contrast, consumption of natural gas as a road and off-road transportation fuel, long viewed as a cost-competitive rival to petroleum (especially so since the recent development of coal and shale bed methane reserves), has risen only from 23 bcf (≈26 petajoules) in 2005 to 33 bcf (≈37 petajoules) in 2010 (EIA *Annual Energy Review 2010*). There is still broad public perception of natural gas as an option less safe and convenient for personal vehicles than liquid fuel, although gas has made major inroads in commercial and industrial fleet fuelling. Another fuel used widely in transportation, LPG (or propane), has remained relatively stable at slightly under 30 petajoules consumed per year (the vast majority of propane production goes to space and industrial heating demand). The impact of recent modest growth in the market for electric and plug-in hybrid vehicles has not in itself prompted a discernible shift in feedstock fuels for electricity generation, and it is not anticipated that even continued steady growth in that market will have such an effect for many years.

12. DISCUSSION AND CONCLUSIONS

The purpose of this work was to improve the understanding of the concept of life cycle analysis of transportation fuels and some of its pertinent issues among non-technical people, senior managers, and policy makers. This work should provide some guidance to nations considering LCA-based policies and to people who are affected by existing or in-development policies.

There is no question that LCA work is complex and highly dependent on having detailed data on many different processes, both natural and anthropogenic. It should also be apparent that for any given production system there is no one correct answer for that systems carbon intensity. People produce the same product, whether that product is electricity, gasoline or diesel fuel, or biofuels, in different ways in different parts of the world.

As there is a myriad of potential analysis tools and methodologies available to evaluate the environmental performance of products over their life cycle, there have been a lot of difficulties associated with assessing results from different studies on the life cycle performance of transportation fuels. Naturally, the question of which result is correct is often raised. The question that should be asked, however, is not which result is correct, but instead "why are the results different?". It is possible that a number of models analyzing the same fuel in different countries can give different results and all still be correct based on the data available. This project has focused on putting LCA modelling into context, while highlighting the importance of understanding modelling methods, using a three tiered approach:

1. It provided a general overview of Life Cycle Analysis principles (ISO methodologies, multiple approaches, etc.).
2. It characterized LCA specific sensitivities (such as scope and system boundaries, data sources, geo-physical differences, etc.) for a number of transportation fuels.
3. And, where appropriate and feasible, it put sensitivities into context using specific examples.

When LCA is used to make environmental claims disclosed to the public about the performance of a product or service system as compared to alternatives (a "comparative assertion"), the ISO 14044 standard requires that a more rigorous process be followed in preparing the LCA. Some additional requirements for "comparative assertions" include:

- **Data Quality** - A high quality of data must be used in a LCA for comparative assertions. This includes addressing the following data elements:
    - time-related coverage (comparable time effects: duration, diurnal, seasonal, etc.);
    - geographical coverage (comparable geography: weather, terrain, systems, etc.);

- technology coverage (comparable technical effects: product life cycle systems);
- data precision (e.g. number of decimal places);
- completeness (similar product system "reach", scope of life cycle stages);
- data representativeness (does modeled data truly reflect actual performance?); and
- methodology consistency and reproducibility (standard measurement tests, etc.).

- **Peer Review** - The LCA must be peer reviewed by an expert panel in accordance with the "critical review process" as outlined in ISO 14040. A review by a single internal expert or external expert is not permitted for a "comparative assertion".

- **Impact Assessment** - An impact assessment is required that uses category indicators that are sufficiently comprehensive, internationally accepted, scientifically and technically valid, and environmentally relevant. Weighting must not be used.

- **Comparable Systems** - The LCA comparison must be performed on systems using the same functional unit and equivalent methodological considerations, such as performance, system boundaries, data quality, allocation procedures, decision rules on evaluating inputs and outputs, and impact assessment. Any differences between systems regarding these parameters must be identified.

This list of requirements for a rigorous LCA provides insight into the primary drivers of why different studies can arrive at different results. The primary drivers include:

1. The data relates to different time periods. All systems change over time, either due to technological learning, or changing environmental conditions. Data from two different time periods, while being correct in both cases, can be different.
2. The same activity can be done differently into two different regions. This can be due to different technologies being employed or different environmental conditions. Again, two different data sets can have significant differences while both being correct.
3. It can sometimes be difficult to obtain the data required to undertake and LCA. The required information may not be in the public domain, or it may be secondary data (information that has been published by a party different from the party that collected the data). This data may have been processed (averaged, units changed, etc.) and some of the original conditions pertaining to the data are no longer reported. Sometimes secondary data is collected from two sources (e.g., one reporting total emissions and another reporting production) in order to develop

emission factors (emissions per unit of production). Issues can arise if the two sources have different boundaries.

4. Data might not always be truly representative of normal conditions. It might just represent the performance when a production system is operating and exclude the emissions during start-up and/or shut down. Alternatively it could include a period that had unusual production problems. This additional' clarifying information is not always presented with the data.
5. Finally, there are some cases where different methodology is used. For example, the allocation of emissions to the multiple products that can be produced in the same system can have a significant impact on the results.

In the following table the main issues for the analyses of the different pathways have been ranked on a scale of 1-5, with 1 being not significant and 5 being very significant. The issue of indirect effects are excluded from the rankings.

Table 12-1 Comparison of Issues in Various Fuel Systems

	System Boundaries	Data Temporal Issues	Regional Practices	Data Availability	Representative Data	Methodology
Electricity	1	1	5	2	2	2
Crude Oil Production	3	5	5	4	4	2
Gasoline and Diesel Fuel Refining	1	3	3	3	3	4
Natural Gas	3	3	3	4	4	4
Biofuel Feedstock Production	2	4	5	4	4	4
Ethanol Production	1	4	3	3	3	5
Biodiesel Production	1	4	3	3	4	5

It is apparent from the table that different fuel pathways have different sensitivities to the important issues. The simpler pathways, like electricity, are driven by one important issue, what is the production system in that specific region. Other pathways, like biofuels, can have a number of important issues that influence the results.

12.1 ADVICE TO POLICY MAKERS

While the concept of employing LCA to evaluate fuel options is simple and straightforward, the act of putting the concept into practice is complex and fraught with issues.

Policy makers need to understand the limitations inherent in carrying out LCA work for transportation fuel systems. For many systems, even those that have been employed for a 100 years, there is a lack of sound data on the performance of those systems.

Comparisons between systems should ideally be made using the same tool, so that differences caused by system boundaries, allocation processes, and temporal issues can be minimized (although probably not eliminated). Comparing the results for fuel pathway 1 from tool A to those of fuel system 2 from tool B introduces significant uncertainty into the results. There is also the question of the scale of system changes. LCA will give more reliable estimates when it is used to examine small changes in transportation fuel pathways than when used to estimate large scale changes that replace current pathways with completely new pathways.

Some LCA tools have been developed recently primarily for regulatory purposes. These tools may deviate from ISO principles in order to facilitate simplicity and ease of use. In a regulatory environment, simplicity and ease of use are worthy objectives and in most cases there is nothing inherently wrong with this approach, particularly for assessing relative performance. However, the results of these tools should not be confused with, or compared to, the results that are obtained from a more complex and rigorous ISO compliant LCA.

It should be reiterated that an LCA will not determine which product is the most cost effective or works best. No LCA can identify optima in the manner of, say, a linear program. This would still be true even if all inputs were specified with complete accuracy and precision because no result would yield a simultaneous optimum for all outputs.

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14. APPENDIX 1- INDIRECT LAND USE

In this appendix more detailed description of some of the models being used to estimate indirect land use emissions and some of the issues with the models are discussed.

14.1 GTAP

GTAP (Global Trade Analysis Project) is a global network of researchers and policy makers conducting quantitative analysis of international policy issues. GTAP's goal is to improve the quality of quantitative analysis of global economic issues within an economy-wide framework. GTAP offers a variety of products, including: data, models, and resources for multi-region, applied general equilibrium analysis of global economic issues. The GTAP model is used in California and the GTAP database serves as the foundation of the MIRAGE model described next.

The standard GTAP Model is a multiregion, multisector, computable general equilibrium model, with perfect competition and constant returns to scale. It allows for the explicit treatment of international trade and transport margins. Bilateral trade is handled via the Armington assumption.

The GTAP Model also gives users a wide range of closure options, including unemployment, tax revenue replacement and fixed trade balance closures, and a selection of partial equilibrium closures (which facilitate comparison of results to studies based on partial equilibrium assumptions).

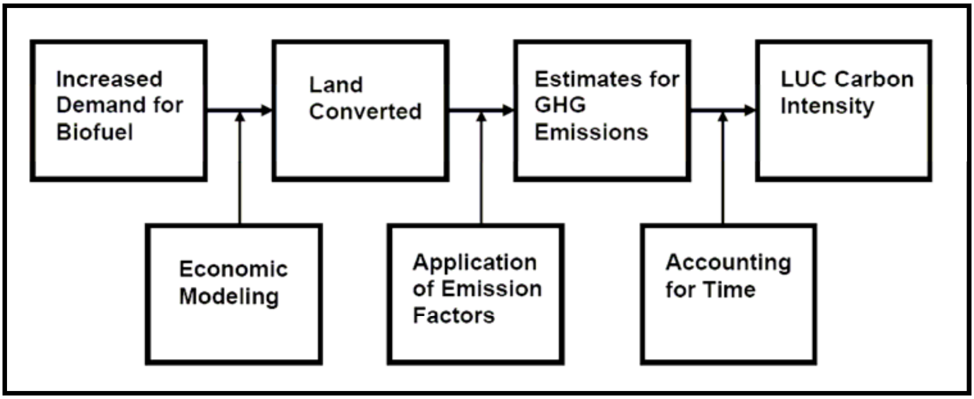
There are many versions of the GTAP model (GTAP-E, GTAP-Bio, GTAP-AEZ) as researchers in the GTAP network develop their own versions for specific purposes. The versions that have been used for California's LCFS work have focussed on biofuel developments. Land use data has been added to the model, and the latest versions have more land use and land cover types, and revised elasticity factors with respect to cropland expansion.

14.1.1 CARB LCFS

The California Air Resources Board (CARB) has used the GTAP CGE model for their work in estimating the indirect land use emissions for corn and sugar cane ethanol and soybean biodiesel. Their first model results were published in 2008 and those results have continued to be refined. They have published results for three fuels (corn ethanol, soybean biodiesel, and sugar cane ethanol) and have another round of modelling underway with a more recent version of the GTAP model.

The process that CARB applies is shown in the following figure. The GTAP model is used for the economic modelling and then a number of adjustments are done outside of the model to determine the emissions per unit of fuel.

Figure 14-1 CARB Modelling Process



CARB has typically run a number of economic modelling scenarios with different elasticity values and then averaged the results. The selected variables for the scenarios are;

- Crop Yield Elasticity, varies from 0.2 to 0.4. This adjusts the crop yield on existing land in response to higher prices. The factors are relatively low.
- Elasticity of Harvested Acreage Response. One value of 0.5 is used. This is a measure of how easily the land can switch from one crop to another.
- Elasticity of Land Transformation across Cropland, Pasture and Forestry. Varies from 0.1 to 0.3. This elasticity expresses the extent to which expansion into forestland and pastureland occurs due to increased demand for agricultural land.
- Elasticity of Crop Yields with Respect to Area Expansion. Varies from 0.5 to 0.75. This is the yield on new cropland as a fraction of the yield on old cropland.

14.1.1.1 CARB Results 2009

The current results that CARB is using are summarized in the following table. The high, low and average value is shown.

Table 14-1 CARB ILUC Results

	Low	High	Selected Value
	CO_2eq/MJ g		
Corn Ethanol	18	44	30
Sugar Cane Ethanol	32	57	46
Soybean Biodiesel	40	87	62

14.1.1.2 CARB Expert Working Group

In 2010 CARB established an Expert Working Group to review the ILUC modelling that they had done using GTAP. There were nine sub-groups established to look at the following aspects of the modelling work:

- Elasticity Values subgroup
- Land Cover Types subgroup
- Emission Factors subgroup
- Co-Product Credits subgroup
- Time Accounting subgroup
- Food Consumption subgroup
- Uncertainty in LUC Estimates subgroup
- Indirect Effects of Other Fuels subgroup
- Comparative and Alternative Modeling Approaches subgroup

Each group prepared a report with findings and recommendations. The reports are all available at the EWG website[20]. The findings of some of the groups were significant and addressing the shortcomings discovered could significantly reduce the reported emissions.

Elasticity Values

This group considered the three primary elasticity factors: crop yield elasticity, yield with respect to area expansion and the elasticity with respect to land transformation (the CET function). Their recommendations were:

1. Keep the central value of the yield elasticity with respect to price at 0.25 if only one value can be used for all crops and all countries. If this elasticity can be varied, then it should be increased for crops-country combinations that can be double-cropped and it should be decreased for combinations that cannot.
2. CARB should adopt the version of GTAP that varies the value of yield with respect to area expansion by region as used in the 2010 version of GTAP. Babcock and Carriquiry (2010) found no support for the hypothesis that the yield of newly converted land is less than the yield of existing soybean land in Brazil. UNICA (2009) calculates the ratio between yields in new and old cropland in Brazil as between 0.9 and 1.05. And new analysis of U.S. data conducted as part of this expert workgroup found that counties that expanded cultivated land in response to higher crop prices beginning in 2007

[20] http://www.arb.ca.gov/fuels/lcfs/workgroups/ewg/expertworkgroup.htm

had, on average across crops, about the same yield as existing cropland. This empirical evidence strongly suggests that setting this parameter value at the upper limit of the current range of values (0.75) would dramatically underestimate crop yields on new land. The Tyner et al (2010) method uses a bioprocess-based biogeochemistry model (the Terrestrial Ecosystem Model - TEM), which is well documented and has been used in peer-reviewed studies about the patterns of land carbon dynamics across the globe considering multiple factors such as CO_2 fertilization, climate change and variability, land-use change, and ozone pollution. The Tyner et al approach results in yields on new land brought into production that are much closer to yields on existing land. Hence, the Tyner et al method is much more consistent with the (limited) empirical data than what was used in the initial CARB GTAP runs.

3. There is very little real world evidence to indicate what the CET values should be. A paper by Babcock and Carriquiry (2010) that looked at the GTAP modelling of biodiesel explains the issue in some detail. The issue is complex but the conclusions were that pasture land should be at least 30 times more responsive to crop prices than forest land in a five year horizon rather than the assumption in the GTAP model that these two land categories have the same responsiveness.

   It should also be intuitively obvious that it is more difficult to convert forest land to crops as there are significantly more activities required to clear a forest and prepare the land for planting compared to preparing pasture land. This high "capital cost" of preparing forest land is essentially ignored when the CET values for pasture and forest land are set to the same value.

The second and third recommendations have the potential to significantly reduce the ILUC emissions. Changing the yield on new land will reduce the land required by 35% to 50%, with a similar reduction in GHG emissions. Changing the function of the CET parameter will not change the quantity of land required but it will change the type of land, moving from the high carbon stock forest land to the less carbon intensive pasture. The expected change from this parameter is again in the region of 35% to 50% and these two factors are cumulative, that is the combined reduction is expected to be 55% to 75% of the current values.

Land Cover Types

GTAP has three types of land in it: cropland, pasture and forest. This is generally inadequate to model the agricultural and forestry sectors. There are lands that are included in these three categories that should be accessible by the model but are not (idle land, fallow land, conservation reserve program land (CRP), cropland pasture) and other unmanaged land such as primary forests and savannahs. This group made a number of recommendations including;

1. Address issues of marginal and underutilized lands within cropland, livestock and unmanaged land categories.
2. Consider adding a separate marginal land pool.
3. Estimate the proportion of total cropland that is idle/fallow/abandoned for each region.
4. Consider methods to account for pasture intensification and price responses in Brazil.
5. Adopt and, where appropriate, modify the TEM approach used by Tyner et al 2010 for estimating agro-ecological zones (AEZ)-specific yields for new land pools brought into agriculture.
6. Evaluate alternative approaches to calculating yields on new agricultural lands based on statistical analysis of climate and management factors using updated datasets from Monfreda et al 2008.
7. Investigate methods to improve CET function / land allocation that will account for regional differences and move beyond applying data for the U.S. to all regions.

Several of these recommendations are similar to the recommendations from the elasticity group and serve to reinforce the need to update certain aspects of the model.

Emission Factors

This group considered the change in carbon stocks on the land that is converted and the role of other changes in GHG emissions from land use change. The recommendations included;

1. Both forest carbon stock and soil carbon stocks should be available for each region and AEZ within the region. The values used by CARB are higher than those found in national Inventory reports and other "official" estimates. This increases the ILUC values compared to what they should be.
2. Include the Harvested Wood Products pool in the ILUC analysis to better reflect the timing of emissions. This would lower emissions from forested areas.
3. Consider a broader range of significant indirect emissions from land use changes such as, but not limited to, those related to livestock and rice production.

Co-Products

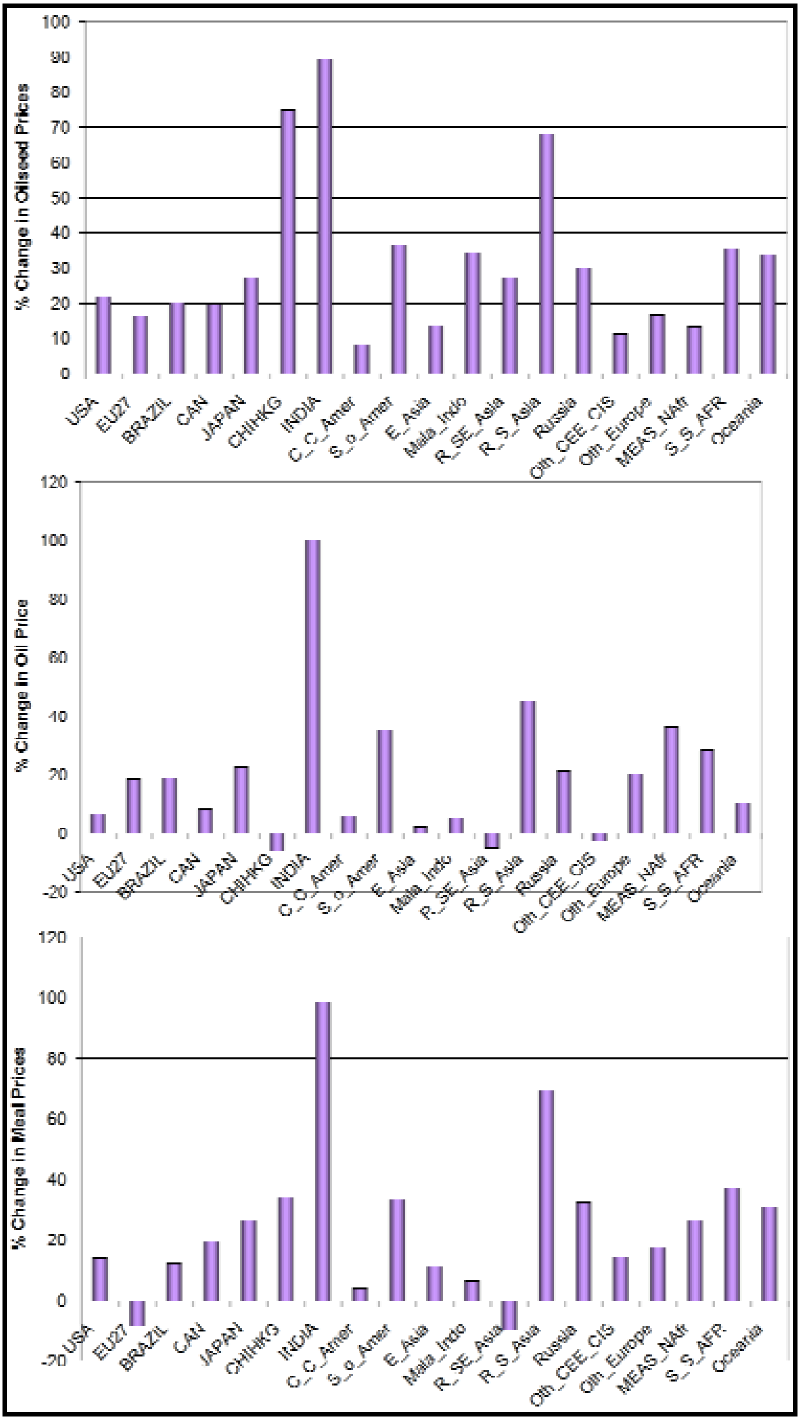
The Co-products group studied the issue of how to model co-products within the GTAP framework and what are the actual displacement ratios for corn DDG in the United States. A consensus was not reached on what the appropriate displacement factors are for the United States. They clearly vary by region and by species. In addition, there are issues of how these displacement factors could be modelled in an economic model like GTAP.

There was certainly some evidence that GTAP underestimates the displacement of DDGS for protein meals and that has a negative impact on the quantity of land that is needed to supply the additional biofuel demand.

A new version of the GTAP model was released in July 2010 (Tyner et al, 2010) and this model produced results for ethanol of about 15 g CO_2eq/MJ, about half of the earlier value that California achieved. There were a number of changes to the model including updating the database to 2006 from 2001, increasing the yield on new land, and the first attempt to include CRP and cropland pasture areas into the available land database, and better estimates of carbon stocks. It does not address the CET function, co-products, nor the full availability of idle land.

One of the problems with modelling soybean biodiesel in GTAP has been that the price response of the three components of the soybean crushing industry (seed, oil, and meal) has been inconsistent between the different regions (see section 10 for a description of the GTAP regions). All three components are traded internationally and tend to move in unison in different regions. As shown in the following figure, this not happening with the GTAP model and it is indicative of problems with the model. Furthermore, the impact on the profitability of the crushing sector is huge in some regions. Seed prices in “CHIHKG” increase by 75%, but the oil price goes down by 5% and the meal prices goes up by 35%. The crushing sector profitability is goes negative and this would never happen in the real world.

Figure 14-2 Price Response of Increasing Soy Biodiesel



14.1.1.3 CARB Results 2011

CARB funded work in 2001 to address some of the issues that were identified by the Expert Working group. The work included segregation of soybeans from oilseeds, the use of the TEM model to predict yield on new land, and update to the 2004 GTAP database, revised carbon stock inventories by AEZ and revised emission factors for land use change by AEZ and country. The preliminary results of the work were released in October 2011. The revised numbers are compared to the original values in the following table.

Table 14-2 CARB ILUC Results - 2011

	2009	2011	Change
	CO_2eq/MJ g		
Corn Ethanol	30	20	-33%
Sugar Cane Ethanol	46	21	-54%
Soybean Biodiesel	62	25	-60%

It is expected that other EWG recommended changes could also significantly reduce the estimates.

14.2 MIRAGE MODEL

The MIRAGE model is a CGE model originally developed at CEPII (The French Centre for Research and Studies on the World Economy) for trade policy analysis. It was extensively modified at IFPRI in order to address the potential economic and environmental impact of biofuels policies. The key adaptations to the standard model are the integration of two main biofuels sectors (ethanol and biodiesel) and biofuel feedstock sectors, improved modeling of the energy sector, the modeling of co-products and the modeling of fertilizer use. The land use module, which includes the decomposition of land into different land uses, and the quantification of the environmental impact of direct and indirect land use change (ILUC), was introduced in the model at the Agro-Ecological Zone (AEZ) level, allowing for infra-national modeling. This feature is particularly valuable for large countries where production patterns and land availability are quite heterogeneous. The overall architecture of the model has been modified to allow for various sensitivity analyses, as well as for the computation of marginal ILUC under specific assumptions.

The MIRAGE model relies on the Global Trade Analysis Project (GTAP) database for global, economy wide data. The GTAP database combines domestic input-output matrices, which provide details on the intersectoral linkages within each region, and international datasets on macroeconomic aggregates, bilateral trade, protection, and energy. IFPRI started from the latest available database, GTAP 7, which describes global economic activity for the

2004 reference year in an aggregation of 113 regions and 57 sectors (Narayanan and Walmsley, 2008). The database was then modified to accommodate the sectoral changes made to the MIRAGE model.

Twenty-three new sectors were carved out of the GTAP sector aggregates -- the liquid biofuels sectors (an ethanol sector with four feed-stock specific sectors, and a biodiesel sector), major feedstock sectors (maize, rapeseed, soybeans, sunflower, palm fruit and the related oils), co- and by- products of distilling and crushing activities, the fertilizer sector, and the transport fuels sector. IFPRI developed an original and specific procedure aiming at providing a database that is consistent in both values and quantities. They make the following claims:

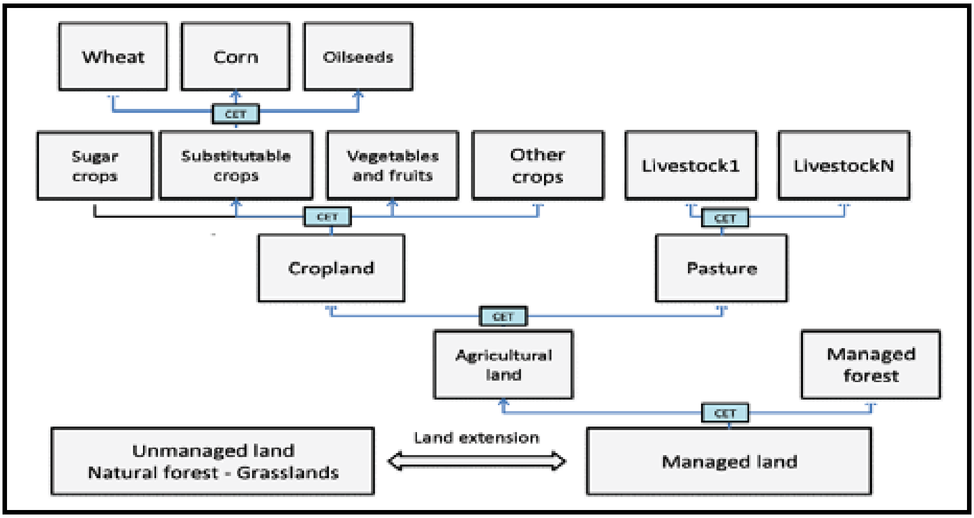
1. Agricultural production value and volume are targeted to match the UN Food and Agriculture Organization (FAO) statistics. A world price matrix for homogenous commodities was constructed in order to be consistent with international price distortions (transportation costs, tariffs, and export taxes or subsidies);
2. Production technology for new crops is inherited from the parent GTAP sector and the new sectors are deducted from the parent ones;
3. Vegetal oil sectors are built with a bottom-up approach based on crushing equations. Value and volume of both oils and meals are consistent with the prices matrix, the physical yields, and the input quantities;
4. Biofuels sectors are built with a bottom-up approach to respect the production costs, input requirements, production volume, and, for the different type of ethanols, the different byproducts. Finally, rates of profits are computed based on the difference between production costs, subsidies and output prices;
5. For steps 2, 3 and 4, the value of inputs is deducted from the relevant sectors (Other Food, Vegetal Oils, Chemical products, Fuel) in the original social accounting matrix (SAM), allowing resources and uses to be extracted from different sectors if needed (mapping n to n).
6. At each stage, consumption data are adjusted to be consistent with production and trade flows.

This level of disaggregation is unique to MIRAGE and is an improvement over the GTAP model, which suffers from a lack of detail in many sectors. There is no evidence in the available documentation that this work has been peer reviewed and checked.

The authors correctly acknowledge the importance of this effort and the need to tie price substitution effects (it is an economic model) to physical effects, but little evidence is presented to demonstrate that the model is functioning correctly.

The land market schematic used in MIRAGE is shown in the following figure. This is an important figure in the modelling and while the concept is generally correct, it has been misapplied by the modellers through their choice of land data used, and elasticity factors chosen.

Figure 14-3 Land Markets



Source: IFPRI

14.2.1 EU Renewable Energy Directive (RED)

The European Commission has utilized a number of models in their investigation of the ILUC impacts of biofuels. The MIRAGE model has been used for multiple studies for the EU and so it is the one that is described here.

14.2.1.1 IFPRI Results

The results from the March 2010 and March 2011 modelling studies done for the EU are shown in the following table. The authors suggest that in the 2011 work all feedstocks benefit from higher yields assumed in the baseline case, and that less land is required because the land is more productive. The second major change that the authors report is the increased mobility of land among crops. Wheat and maize areas actually contract as the result of increased demand for oilseeds and significant displacement of wheat and maize from the livestock sector. There were also changes to the co-product methodology in the 2011 work.

Table 14-3 Crop Specific Land Use Change Coefficients

	March 2010 Report	2011 Report
	g CO_2/MJ	
Sugar Beet Ethanol	16.1	6.6
Sugar Cane Ethanol	17.8	13.4
Maize Ethanol	54.1	10.3
Wheat Ethanol	37.2	14.4
Palm Biodiesel	46.4	54.3
Rapeseed Biodiesel	53.0	53.8
Soybean Biodiesel	74.5	55.8
Sunflower Biodiesel	59.8	51.8

The 2011 results for ethanol are very low but the biodiesel results are higher and are in line with some of the other modelling efforts.

14.2.1.2 MIRAGE Results Review

Understanding what has not been modelled is as important as what has been modelled.

1. No restrictions have been placed on land expansion. The RED requires certification that the feedstocks used for ethanol production come from land that was in production prior to Jan 1, 2008 or, if from new land, land that has low carbon stocks. While this does not eliminate the leakage issue (old land used for fuel and new land used for feed and food) it will have some impact on land expansion.
2. No changes in the rates of improvement of technology are assumed. The 2020 baseline is developed from the 2008 case using business as usual assumptions with respect to historic rates of change.

The indirect land use modelling undertaken by IFPRI has a large number of problems and the result is that the ILUC emissions are greatly overestimated. While the MIRAGE modelling effort has a number of unique factors and could be considered an improvement over other similar models, such as GTAP, not all of these unique features are utilized in the work undertaken for the European Commission. In addition, the model has a significant number of shortcomings that seriously impact the reported results.

Land Database

The cropland inventory database that has been added to the MIRAGE model is missing all of the cropland that is used to produce forages for livestock feed and all of the cropland that is temporarily idle. These two sub categories of cropland amount to about 400 to 500 million hectares. This land is available for increased crop production and some of it is currently creating GHG emissions without producing a crop. The land demands that are calculated by MIRAGE for the increased EU biofuel demand range from 1.74 to 1.87 million hectares, a small fraction (less than one half of one percent) of the land that is available.

The land to produce fodders has apparently been added to the inventory of pastureland but this approach has two problems. The first is that land that is already in annual production and owned by a producer is much more likely to be converted to a biofuel crop than land that is still natural pasture. This land may not be owned by a crop producer and it needs some work to convert it to land that is suitable for annual production. The second is that land that is already in production has reached an equilibrium in soil carbon and the conversion from fodder to biofuel feedstock would not create any land use emissions. Including this land as pasture overstates the land use change emissions.

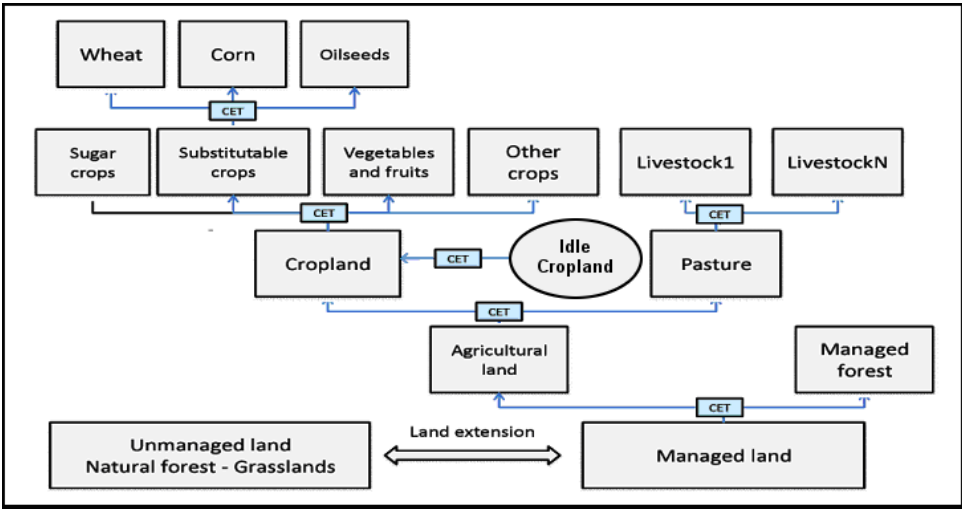
The land inventory for the world is compared in the following table. There are significant differences in the databases including important crops for biofuels. The world crop area harvested in MIRAGE is significantly lower than that reported by the FAO. Fallow land is estimated by Seibert et al (2010) to be as high as 400 million ha.

Table 14-4 Land Inventory Comparison World- 2008

Crop	MIRAGE	FAO	Difference
	1,000 ha		
Maize	112,730	160,814	48,084
OthCrop	178,346	282,645	104,299
OthOilSds	255,651	16,466	-239,185
Palm	8,582	14,702	6,120
Rapeseed	19,020	30,659	11,639
Rice	97,527	157,739	60,212
Soybeans	61,896	96,480	34,584
Sugar_cb	17,921	28,620	10,699
Sunflower	46,308	25,031	-21,277
VegFruits	168,365	242,363	73,998
Wheat	154,220	242,531	88,311
Hay & Fodders	0	166,980	166,980
Fallow	0	0	0
Total Principal crops	1,121,566	1,465,030	343,464

Addressing the missing land issue is more than just adding new data to the model, as it needs to be added as a new land category with its own CET function as shown in the following figure. It is most likely that if this were done and the appropriate CET function was used, the ILUC emissions for the EU biofuels mandate would drop to very close to zero.

Figure 14-4 Modified Land Markets for MIRAGE



In addition, the land data that is in the model appears to significantly underestimate the land devoted to the major biofuels crops. This will underestimate the impact of intensification. Finally, the model currently has no way of modelling double cropping, an important management practice in many parts of the world. 150 million hectares of cropland are double cropped and there is evidence that this area is very responsive to price signals, at least in some parts of the world.

Oilseed Crushing Sector

There are important issues with the way that the model deals with the oilseed crushing sector and the livestock industry. First, it is not clear how the livestock sector can be modelled accurately without including the production of forages in crops produced. Replacing forages with oilseed meals would be one possible response to an increase in meal availability. Secondly, the description of the crushing sector implies that it is considered as part of the biodiesel sector, yet it existed as a very large part of the agriculture value-added sector long before biodiesel existed. The change in the price of oilseeds and the crush products, oil and meal, indicate that the profitability of this sector disappears as demand for the products increase. This scenario is not possible in the real world. The model is structured so that oilseed meals can’t be traded on their own, but only through the livestock sector, and this is partially the reason for the incorrect results for the crushing industry. What is happening with the model is that an increase in demand for oil results in the increased production of meal. Rather than let that meal be traded to another country where it might replace the production of some agricultural commodity, it increases the livestock sector so that all of the meal is consumed and then lets the resulting meat be traded between countries. The net result of all of this is that the meals probably don’t receive the proper credit in terms of displacing other agricultural crops and this leads to higher demands for additional land.

Co-Products

The model is reported to have better handling of co-products but there is little evidence that these are adequately modelled. There are issues with the quantities of DDGS produced from wheat and maize. Very little oilseed meal is displaced by DDGS in contrast to the substitution ratios that can be found for European practices. Displacing oilseed meals from livestock rations is expected to produce significant land use benefits as the yield of wheat and maize is much higher than the oilseeds, and thus more land is made available if oilseed demand is reduced than if wheat or maize consumption is reduced.

Elasticity Factors

There are other issues with the model and the assumptions that have been made and these lead to either higher estimates of land converted to cropland or higher emissions from the converted land.

There are significant issues with the elasticity factors used in the MIRAGE model. The elasticity factors related to crop displacement and substitution should be the strongest of the elasticity factors used in the model since they are at the core of how the model has been traditionally used. While this is probably still the case for the response of consumers to different meat prices and vegetable oil prices, the response of the livestock sector to different feedstock availability and prices is not clear.

It appears that the livestock model is not modelled adequately. Forages, an important component in the diets, are not specifically included in the model or the land database created. Thus, co-products cannot substitute for these feed components.

Being an econometric model, there is no way for the model to balance diets for protein and energy, it just balances for lowest cost based on the elasticity factors between different co-products that are chosen by the modellers.

Less than 1% of the new supply for ethanol feedstock is produced through intensification efforts on existing land. A relatively low elasticity factor has been applied to these effects. Higher elasticity factors were recommended by the EWG in California.

The elasticity factor for the yield of crops on expanded land is an assumption chosen by the modellers. Based on the data that is available and the results of other more sophisticated models, the values chosen are too low by 25% to 50%. This directly impacts the GHG emissions attributed to the biofuels, so this one assumption alone increases the ILUC factors by 25% to 50% over what they should be.

An even larger issue are the assumptions made with respect to the CET function values. The modellers have used the same value for pasture land and managed forests, whereas in reality the available data indicates that there should be a difference of 20 to 30 times between the values. This error increases the quantity of forest land converted by more than an order of magnitude and this increases the ILUC factor by 30% to 50% in the case of the scenarios modelled by IFPRI.

These errors are additive. The combined impact of just the improper elasticity with respect to land expansion and the CET function is that the real values should be 25% to 50% of the values reported in the report. The improvement of the modelling of co-products would be expected to provide additional reductions in the reported values.

Other Issues

The reported soil carbon losses appear to be high and could not be duplicated or reconciled with the information that is reported.

The above ground biomass loss makes no provision for natural mortality of the forests and thus overstates the above ground carbon losses.

The peatland impacts are new to the 2011 report and are a major reason why the biodiesel emissions are as high as they are. Depending on the feedstock, these emissions account for 20% to 60% of the total emissions, as shown in the following table. There is a great deal of uncertainty in these emissions, both due to the emission rate and the area impacted. Several recent papers indicate that the emission rate used in the IFPRI report is overstated and could be reduced between 30% and 60%.

Table 14-5 Peatland Impacts

Feedstock	Total ILUC Factor	Peat Portion	% Peat Portion
	g CO_2eq/MJ		
Sugar Beet Ethanol	6.6	2	30
Sugar Cane Ethanol	13.4	0	0
Maize Ethanol	10.3	1	10
Wheat Ethanol	14.4	2	14
Palm	54.3	33	60
Soybean	55.8	16	28
Sunflower	51.8	10	19
Rapeseed	53.8	15	28

The 20 year amortization period chosen for the calculation of the emissions is arbitrary. A 30 year (also arbitrary) period has been used both by the US EPA and the California Air Resources Board (CARB). One problem with both the 20 and 30 year time periods is that all of the rest of the GHG emissions are calculated based on 100 year GWPs. If they were calculated using 20 or 30 year GWPs, the baseline emissions for petroleum fuels would all be higher.

Finally, the individual ILUC factors deliver results that are 11.5% higher than the result from the combined shock. This finding is consistent with the analysis of other work in this area undertaken by the US EPA and CARB. Artificially constraining the response to a single commodity limits the ability to choose the best options. In the following table the individual factors and their shares are summed and compared to the combined shock of 38.4 g CO_2eq/MJ.

Table 14-6 Individual Impacts

Fuel	ILUC Factor	Fraction of Total Shock (%)	Contribution to total
	g CO_2eq/MJ		g CO_2eq/MJ
Ethanol Sugar Beet	6.6	5	0.3
Ethanol Sugar Cane	13.4	13	1.7
Ethanol Maize	10.3	4	0.4
Ethanol Wheat	14.4	6	0.9
Palm Oil	54.3	17	9.2
Rapeseed Oil	53.8	41	22.1
Soybean Oil	55.8	11	6.1
Sunflower Oil	51.8	4	2.1
Total			42.8

14.3 PARTIAL EQUILIBRIUM MODELS

The US EPA has used partial equilibrium models in their ILUC work. Their modelling results are discussed below.

14.3.1 US EPA RFS2

The US EPA utilized two PE models for their work, FASOM (for domestic land use changes) and FAPRI (for international land use changes). These models were used in combination with GREET and other models in a detailed and complex modelling framework as shown in the following figures.

Figure 14-5 EPA ILUC Modelling Schematic

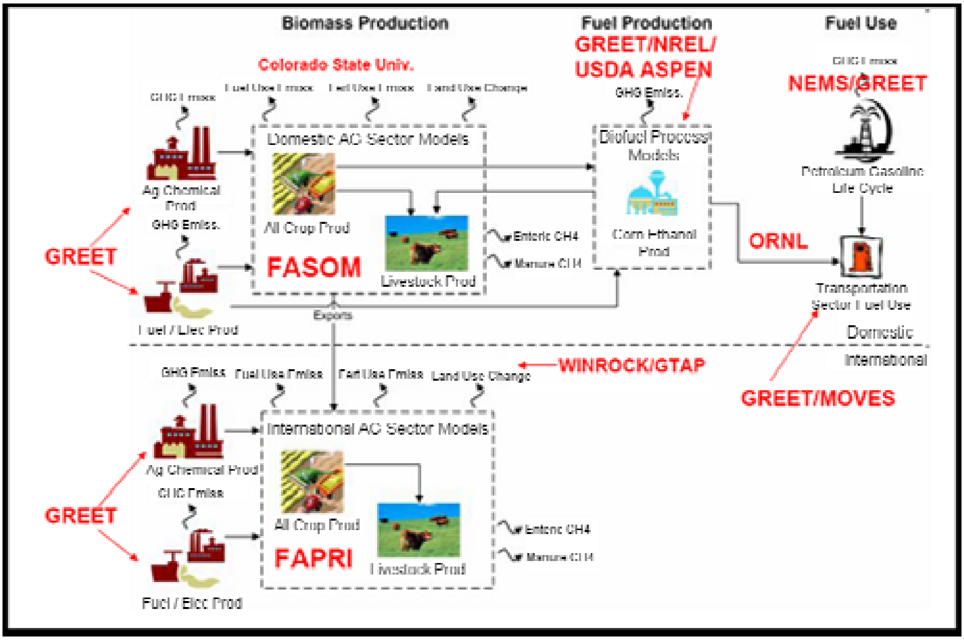
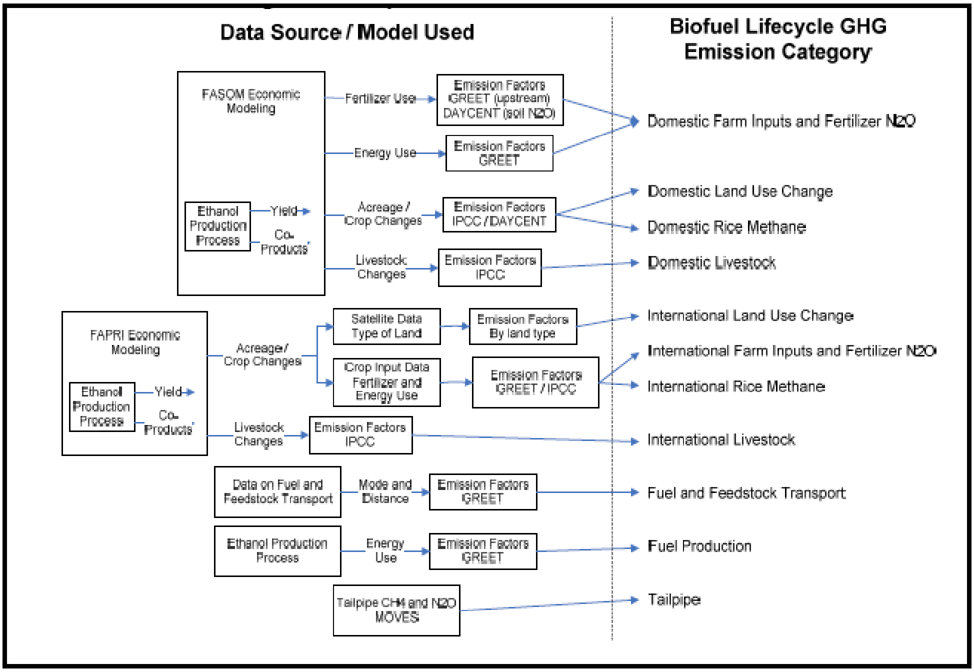


Figure 14-6 System Boundaries and Models Used



The Forest and Agricultural Sector Optimization Model (FASOM) is a dynamic, nonlinear programming model of the forest and agricultural sectors in the United States. The FASOM model initially was developed to evaluate welfare and market impacts of alternative policies for sequestering carbon in trees but also has been applied to a wider range of forest and agricultural sector policy scenarios. The model depicts the allocation of land, over time, to competing activities in both the forest and agricultural sectors. It can calculate the GHG emission impact of crop shifting, livestock production, and other indirect effects beyond land use change, offering advantages over other models. However, the model is a black box, making it difficult to verify the calculations.

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

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

The FAPRI-CARD agricultural modeling system is a set of multi-market, partial-equilibrium, and non-spatial econometric models. The models cover all major temperate crops, sugar, biofuels, dairy, and livestock and meat products for all major producing and consuming countries and are calibrated on the most recently available data. They have been used extensively for generating 10- to 15-year baseline projections for agricultural markets and for policy analysis based on the baseline projections. Data on supply and utilization for the commodities are obtained primarily from the United States Department of Agriculture (USDA) PSD Online and the Food and Agriculture Organization of the United Nations (FAO) FAOSTAT, and macroeconomic historical data and projections are obtained from the International Financial Statistics (IFS) of the International Monetary Fund and IHS Global Insight, respectively.

Table 14-7 FAPRI Inputs and Outputs

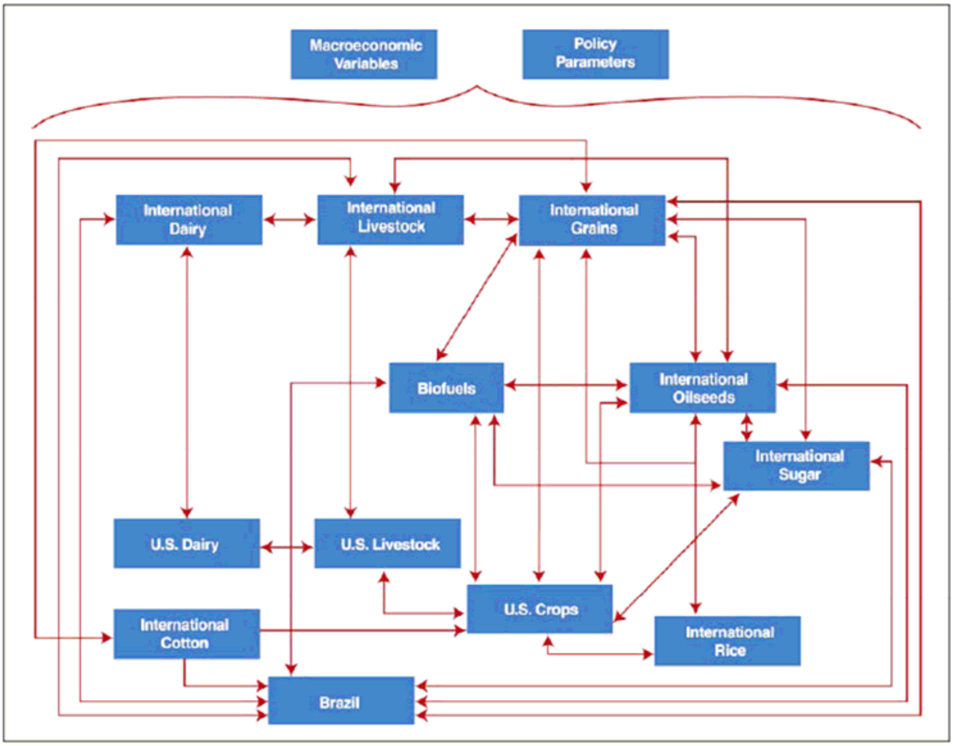
Exogenous Inputs	Population, GDP, GDP deflator, Exchange rate, Population, Policy variables
Historical Data (Inputs)	Production, Consumption, Exports, Imports, Ending stocks, Domestic prices, World prices
Commodities	
Grains	Corn, Wheat, Sorghum, Barley
Oilseeds	Soybeans, Rapeseed, Sunflower
Livestock products	Beef, Poultry, Pork
Dairy	Milk, Cheese, Butter
Sugar	
Ethanol/Biodiesel	
Major Countries/Regions	
North America	United States, Canada, Mexico
South America	Brazil, Argentina, etc.*
Asia	China, Japan, India, Indonesia, Malaysia, etc.*
Africa	South Africa, Egypt, etc.*
European Union	
Australia, New Zealand	
Middle East	
Output by Commodity and Country	World prices, Domestic prices, Production, Consumption, Net trade, Stocks, Area harvested, Yield

* A total of 53 countries are included.

The commodity models capture the biological, technical, and economic relationships among key variables within a particular commodity and across commodities. They are based on historical data analysis, current academic research, and a reliance on accepted economic, agronomic, and biological relationships in agricultural production and markets. Agricultural and trade policies in each country are included in the model to the extent that they affect the supply and demand decisions of the economic agents. Examples of these include taxes on exports and imports, tariffs, tariff rate quotas, export subsidies, intervention prices, set-aside rates, and biofuel mandates. Macroeconomic variables, such as GDP, population, and exchange rates, are exogenous variables that drive the projections of the model.

The models specify behavioural equations for production, use, stocks, and trade between countries/regions. The crop supply side is the product of area harvested and yields, wherein the former is determined by a system of land allocation based on the relative expected profitability of competing enterprises (e.g., corn and soybeans) and the latter is driven by an exogenous trend yield as well as intensification and extensification effects. In general, the demand side of the model is categorized into food, feed, and industrial demand, whereby one aspect of industrial demand is the demand from the biofuel sector for feedstocks. Food demand is primarily driven by macroeconomic assumptions such as income and population, while feed demand is driven by the livestock, poultry, and dairy sectors. Industrial demand is determined by the crude oil price assumption as well as by existing government policies such as the U.S. Energy Independence and Security Act (EISA) of 2007 and the Renewable Energy Directive of the European Union. The meat supply side is a combination of investment decisions on the breeding herd and output decisions on slaughter. The animal inventory is the main driver of the feed grain and oilseed meals demand.

Figure 14-7 FAPRI Model Interactions



* The arrows represent trade, prices and physical flows.

The FAPRI model does not determine what kind of land is converted that was estimated by the EPA based on the historical land use change patterns. Its strength is in the level of disaggregation of the agricultural sector. To determine the historical land use change, the EPA relied on MODIS satellite imagery analysis.

Determining land use change from satellite imagery is an evolving science. There are significant issues that have been identified with the EPA analysis. Lywood (2009b) compared the EPA MODIS analysis for Europe with FAO data and found very large differences as shown in the following table.

Table 14-8 EPA MODIS and FAO Land Use Change Data

	MODIS	FAO			
Change in Cropland Area, 2001-2004	17.6%	-1.0%			
Land Type Converted	Forest	Grassland	Mixed	Savanna	Shrub
MODIS	14.8%	8.6%	45.0%	20.0%	11.7%

There is also information on the MODIS results for the US but all of the other countries that have information reported were developing countries were "land based" data is not available. The comparison of the US EPA MODIS analysis with USDA data is shown in the following table.

Table 14-9 EPA MODIS and USDA Land Use Change Data

	MODIS	USDA			
Change in Cropland Area, 2001-2004	5.2%	-1.0%			
Land Type Converted	Forest	Grassland	Mixed	Savanna	Shrub
MODIS	3.4%	28.5%	53.5%	9.8%	4.8%

The MODIS analyses would appear to overestimate land use change with respect to cropland. This overestimation leads to higher estimates for ILUC emissions than the actual data would support and leads to a high degree of uncertainty with respect to the calculated emissions.

14.3.1.1 EPA Modelling Results

The EPA amortized land use change emissions over a 30 year period. The estimates of the type of land converted in each country and the change in carbon stocks was derived from the database developed by Winrock International for the EPA.

The EPA initially published results for three fuels, corn and sugar cane ethanol, and soybean biodiesel. They subsequently published results for canola biodiesel. It is difficult to isolate the indirect land use emissions from the EPA results. The results include indirect emission changes in the livestock sector from crop switching, and from changes in rice production. Land use was held constant in the US so we can look at international land use emissions. These are summarized in the following table.

Table 14-10 EPA RFS2 Results

Fuel Chain	International Land Use	Other	Total Life CycleLife Cycle Emissions
	CO_2eq/MJ g		
Corn Ethanol	30	47	77
Sugar Cane Ethanol	4	43	47
Soybean Biodiesel	40	0	40
Canola Biodiesel	29	16	45

The EPA results were quite interesting in that some of the other results were surprising. The emissions for soybean biodiesel, excluding the international land use emissions were essentially zero. The co-product credit for the soybean meal and the glycerine offset all of the other emission sources. The other emissions for corn ethanol were lower than many other US analyses and lower than the GHGenius results, again indicating that the co-product credit was higher than that found in many models. On the other hand, the emissions for sugar cane ethanol and canola biodiesel were higher than found in GHGenius. There were some anomalies in the canola biodiesel results that still have not been explained by the EPA and if these were corrected it is likely that the results would be quite close to those in GHGenius.

14.3.1.2 Analysis of EPA Results

Since the four pathways analyzed all passed the required thresholds for inclusion in the RFS2 program there has not been as much published independent analysis of the final results as there has been about some of the other modelling efforts. There is certainly some concern about the Winrock data and whether it captures just the land conversion due to agriculture or if it captures all land use change drivers and thus overestimates the quantity of forest land converted to agriculture.

There has been concern raised (RFA, 2010) that the weighted sum of the individual ILUC factors does not equal the ILUC factor that is obtained from shocking the models for all biofuels simultaneously. These results are for the combined domestic soil carbon changes and the International land use changes.

Table 14-11 Individual vs. Combined Shocks

	Based on Control Case (combined shock)	Based on "Only" Cases (individual feedstock shocks)	% Difference
	CO_2eq/MJ g		
Soybean Biodiesel	7.9	32.2	-76%
Corn Ethanol	10.8	28.4	-62%
Sugarcane Ethanol	2.7	4.7	-43%

In some respects, these results shouldn't be surprising, in that any restraining of a model should reduce the options compared to an unrestrained model.

While the corn ethanol results are close to those currently used by CARB, there are significant differences in how they are arrived at. The results from the two modelling systems are compared in the following table.

Table 14-12 Comparison of CARB and EPA Results

	CARB	EPA
Corn Ethanol		
ILUC, g CO_2eq/MJ	30	30
Land Converted, acres/1000 usg	0.73	0.85
Soybean Biodiesel		
ILUC, g CO_2eq/MJ	62	40
Land Converted, acres/1000 usg	0.95	3.8
Sugar Cane Ethanol		
ILUC, g CO_2eq/MJ	46	4
Land Converted, acres/1000 usg	1.35	0.66

The CGE models have thousands of elasticity factors so there are many possible reasons for the differences in the results. Some of the differences are due to different carbon stock changes on the converted land. The CARB values are higher than those of the EPA. This could account for some of the differences. The different land requirements per unit of fuel will be impacted by different assumptions on co-product values, different demand impacts, and different substitution rates between feedstocks. There will be different types of land converted with the EPA assuming that future conversion will be similar to historical patterns and the CARB values a function of the economic rent on the land and their assumed elasticity values.

14.4 DESCRIPTIVE CAUSAL MODELS

Another approach to estimating ILUC emissions has been the development of descriptive causal models such as the ones developed by E4 Tech.

14.4.1 E4Tech Modelling

The UK Department for Transport commissioned E4tech (2010) to develop fuel chain specific ILUC factors using a descriptive-causal approach for the following fuel chains: bioethanol from wheat and sugarcane, biodiesel from palm oil, rapeseed oil and soybean oil. An objective of the project was to demonstrate the validity of the approach.

Assessing the magnitude of the market responses to an increase in the demand for a biofuel feedstock requires working out a relationship between the change in demand and the different responses. The principal responses E4tech were interested in were to understand ILUC impacts and how yields and agricultural areas vary and what product substitutions occur as the result of changes in demand for crops under the biofuels projection.

CGE and PE models use price changes and elasticity factors to determine these responses. The E4tech work took a different approach. They decided to analyse the market responses through direct demand-based relationships for yields based on historic trends and through product properties and market analysis for product substitution. However, they also used expert opinion to understand if extrapolations of historic trends are realistic based on their understanding of the particular markets studied. Also, prices are implicitly considered by using projections based on historical trends and expert opinion to understand deviation from historic trends, for example, which country is likely to be the marginal exporter of a particular commodity in 2020. The experts' views on how markets are likely to evolve in the future have also played a role in deciding which alternative future scenarios should be studied.

The next step in the estimation of ILUC is to determine the type of land that is converted to crop production and to assess the change in carbon stocks on that land.

As part of the calculation of ILUC impacts for the RFS 2, Winrock International used MODIS satellite data to estimate the different amount of land converted to cropland and pasture land in recent years in different world regions. The data provides estimates of proportions of different land types converted to cropland/pasture in different world regions, over a 6-year period (2001-7), based on satellite images taken at 500 m resolution. Winrock also carried out data validation by comparing satellite classifications with actual land types observed on the ground and through aircraft surveys and other satellite data. E4tech decided to use the Winrock information to determine the type of land and the carbon stocks on that land.

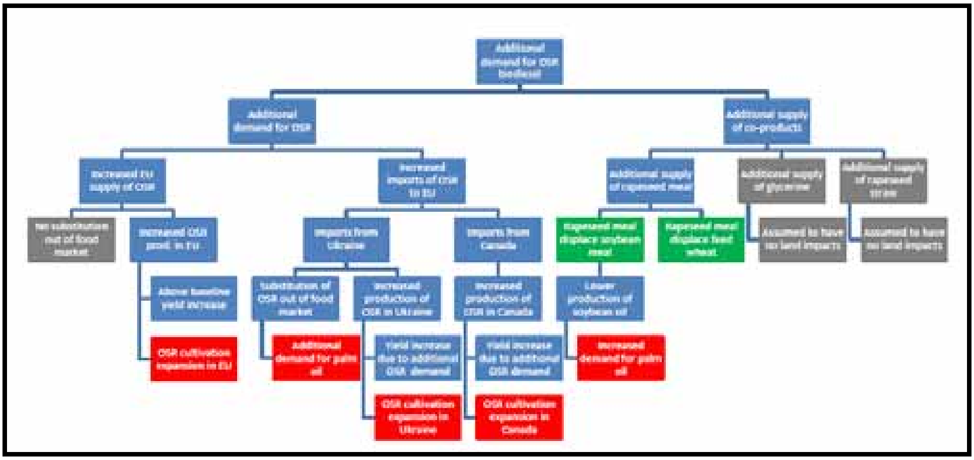
Land use change thus results in large emissions (or in some instances uptake) of GHGs. While the change in land use happens over a short time frame, the changes in the carbon stocks and associated emissions or uptake can take up to several years, while agricultural products are grown on the land. All emissions or uptake over 30 years were added up to calculate the emission factors due to land use. These emissions factors were then annualized over 30 years again to calculate the final ILUC impact of biofuels in terms of GHG emissions per MJ of biofuel per year.

Finally, for each of the feedstock chains studied, a number of scenarios were developed with different assumptions. E4tech developed a baseline for the year 2020 and then applied the biofuel shock on top of that baseline.

14.4.1.1 E4Tech Results

The rapeseed chain studied by E4tech produced the following market response to an increase in biofuel demand. The green boxes (rapeseed meal displacing wheat and imported soybean meal) provide land use credits and the red boxes create land use debits. Note that Canada and the Ukraine are expected to be the suppliers of rapeseed outside of the EU but that some increase in palm oil use is projected to replace the soy oil that is not produced due to lower demand for soybean meal.

Figure 14-8 Market Response to Increased Rapeseed Biodiesel



The increased land use in Canada is expected to come from cereals and to reduce the rate of abandonment of cropland in Canada. Canadian cropland has been very constant for many years and any reduction in cropland has been the result of urbanization, this assumption may therefore not be valid.

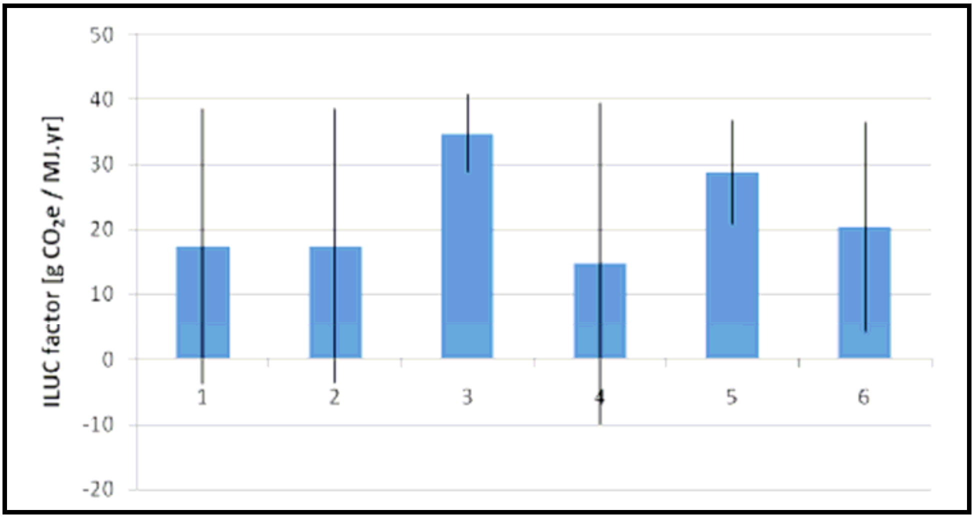
The scenarios modelled are summarized in the following table.

Table 14-13 Rapeseed Scenarios

Scenario Parameter	1	2	3	4	5	6
Amount of oilseed rape produced in Europe	High	High	High	High	High	Low
OSR displaced out of Ukrainian food market	No	Yes (50%)	No	No	No	No
Deforestation rates in Indonesia and Malaysia	Historical	Historical	Historical	10%	Historical	Historical
Share of rapeseed meal used as animal fodder	100%	100%	50%	100%	100%	100%
Sources of co-product substitution ratios	Lywood et al. (2009)	Lywood et al. (2009)	Lywood et al. (2009)	Lywood et al. (2009)	JEC (2008)	Lywood et al. (2009)

The results for the various scenarios are shown in the following figure. They range from 15 to 35 g CO_2eq/MJ of biodiesel. The uncertainty bars are also shown but they only reflect the uncertainty with respect to the carbon stocks.

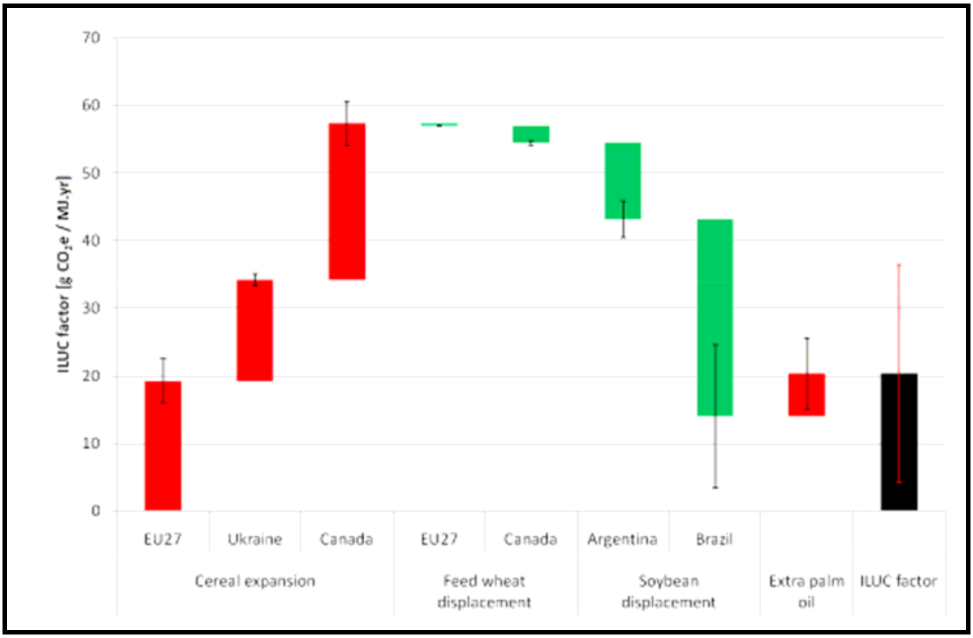
Figure 14-9 Rapeseed Biodiesel Results



It is apparent that some assumptions can drive significant differences. The difference between scenarios 1 and 5, and between 1 and 3 are the assumptions about co-product displacement. The difference between 1 and 4 is the deforestation rate in the Far East. The difference between 1 and 6 deals with the quantity of rapeseed produced in Europe.

E4tech disaggregate the impact of the various factors that lead to the final result. This is shown in the following figure for one of the rapeseed scenarios. The red bars indicate land use emissions and the green bars are emission savings. Land expansion creates almost 60 g CO_2eq/MJ but 75% of that is offset with the co-products.

Figure 14-10 Rapeseed Waterfall Diagram



A similar analysis was undertaken for each of the fuel chains studied. The range of results is shown in the following table. Some of the fuel chains have a very wide range and the wheat ethanol showed negative results. The DDG in the wheat cases displaced soybean meal and that results in avoided deforestation in Brazil and Argentina.

Table 14-14 E4tech Results

Fuel Chain	Number of Scenarios	Low Value	High Value
		g CO_2eq/MJ	
Wheat Ethanol	8	-55	-5
Sugar Cane Ethanol	14	8	27
Rapeseed Biodiesel	6	15	35
Soybean Biodiesel	3	9	66
Palm Oil Biodiesel	10	12	81

14.4.1.2 Analysis of E4Tech Results

The descriptive-causal models have some advantages over the economic models but also suffer from some of the same shortcomings. One of the primary advantages is that the co-product substitution can be done based on physical properties and displacements and not just on economic value. This allows the livestock sector to be properly balanced for nutritional needs and not just a low cost ration that may not meet the nutritional requirements of the animals.

Another advantage is that this approach makes it easier to include other physical limitations such as the performance properties of the biofuels, local laws governing land use change, etc.

The disadvantage of this approach is that it requires expert knowledge of agriculture in many countries around the world and this knowledge is difficult to assemble. In the final report, there is one mention of idle land and no mentions of fallow land, and in many countries it is assumed that cropland is decreasing. In Canada they have assumed that the total harvested area of cropland is the sum of wheat, barley, canola, corn, soybean, and sugar beet. All other crops don't exist as far as the model is concerned. These six crops accounted for about 55% of the total Canadian cropland in 2010. As the production of specialty crops increase, the commodity crop production does decrease, but the total area of cropland does not change.

The land base for crop production in the E4tech model is not an improvement over the land bases in the economic models. Other than for wheat ethanol, the results are in the range of emissions found by the econometric models.