Minnesota
Low Carbon Fuels Standard Study

Final Report

Contract No. B24112

University of Minnesota

Prepared by:

Steven J. Taff, Principal Investigator
Department of Applied Economics

Jeffrey Apland, Co-Investigator
Department of Applied Economics

David B. Kittelson, Co-Investigator
Department of Mechanical Engineering

Timothy M. Smith, Co-Investigator
Bioproducts & Biosystems Engineering

*See the following report sections for additional contributors

June 2011

Prepared for:

Minnesota Department of Commerce

This project was made possible by a Minnesota Department of Commerce, Office of Energy Security competitive grant program (Laws of Minn. 2007, Ch 57, article 2, sec 3 subd 6) award; a program funded through the Xcel Energy Renewable Development Fund (Minn. Stat. 116C.779) as directed by those Laws for fiscal year 2008.

Project Overview

Under a Minnesota Department of Commerce, Office of Energy Security contract, the University of Minnesota investigated and developed modeling and analytical frameworks with available data in order to compare the greenhouse gas, economic, and environmental implications of various low carbon fuel standards (LCFS) policies for vehicles operated on Minnesota public roads. The attached reports provide findings of work performed under this contract.

A low carbon fuels standard (LCFS) would require any person producing, refining, blending, or importing transportation fuels in Minnesota to reduce these fuels' average carbon intensity (AFCI), measured across the full fuel cycle: feedstock extraction, production, transport, storage, and use. An LCFS is expected to lower overall emissions from the transportation fleet.

The framework was used in part to analyze a performance-based LCFS that measures progress in reducing greenhouse gas emissions on a lifecycle basis and the economic and environmental impacts on each transportation fuel and production pathway as compared to the state's current policies to replace gasoline consumption with 20 percent ethanol by 2013, and to replace diesel consumption with 20 percent biodiesel by 2015.

The project made special use of a Technical Assumptions Review Committee (TARC) to review and assess the assumptions proposed as inputs for the analyses performed during the project. The members we recommended for approval by the co-chairs of the state's Next Generation Energy Board included engineers, process experts, and economists who were not directly involved in the project. These members were recommended and approved based on their professional experience and responsibilities, educational degrees, peer review publications, industry recognition or other demonstrations of the qualifications and ability of the recommended committee members to provide a balanced assessment of assumptions used in carbon intensity fuels analysis.

Members of Technical Assumptions Review Committee for LCFS project:

Name	**Expertise**
Al Doering	Applied research; bioproducts testing and market evaluation
Elise Doucette	Engineering and environmental impact assessments; water and air quality
J. Drake Hamilton	Scientific analysis; global warming solutions
John Heer	Engineering; natural gas production
Gary Herwick	Engineering; fuel quality, vehicle performance and emissions, and alternative fuels
Jay Reinhardt	Engineering; petroleum fuels production
Lanny Schmidt	Chemical Engineering and Material Science; thermochemical biofuel production
John Sheehan	Chemical and Biochemical Engineering; biofuels and sustainability

Sarah West	Economics; environmental, transportation fuels and policy
Scott Johnson	Engineering; petroleum fuels production
William Lee	Engineering; ethanol production and biomass gasification heating fuel
Timothy Maneely	Engineering; biodiesel production and vegetable oil production

The University research team is grateful for the diligence, patience, and expertise these TARC members provided the project.

The primary objectives of the project were to:

- Specify and calibrate a "well-to-wheels" Life Cycle Assessment (LCA) procedure for use by interested parties for measuring carbon intensity; and

- Estimate the economy-wide impacts of an LCFS;

- Analyze the interaction of a LCFS with existing energy-related state policies;

- Develop a quantitative approach to evaluate the non-carbon environmental impacts (air, water, habitat, etc.) of a range of potential transportation fuel policies and how they interact with potential LCFS policies.

The fuels, feedstocks, vehicles, and conversion technologies considered in this study are listed below:

Production Pathways	
Fuels	**Technologies**
Gasoline	Gasoline and Diesel refining
Diesel	Ethanol and Biodiesel production:
Electric	Natural gas fired
Ethanol (Corn Grain)	Biomass fired
Ethanol (Cellulosic)	Electricity for transport:
Biodiesel	MN electric grid
Compressed Natural Gas (CNG)	Hydrogen grid
Coal-to-Liquid (CTL)	
Feedstocks	
Conventional North American Petroleum	
Conventional Foreign Petroleum	**Vehicles**
Canadian Tar Sands Petroleum	Passenger cars and light duty trucks
Enhanced Oil Recovery Petroleum	gasoline
Corn Grain	diesel
Soybean	gasoline hybrids
Algae	CNG
Biomass: Grass and Energy Crops	Plug-in hybrids
Biomass: Crop Residue	Heavy duty trucks and buses
Biomass: Wood Residue	
Natural Gas	
Coal	

In the greenhouse gas emissions portion of the study, the University team examined the emissions of fuels produced for supplying the energy needs of the MN transportation fleet. We expand on the Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (Wang 1999a) by incorporating a MN specific database of LCA inputs. We discuss aspects of the MN LCA that make it distinct from other national or international fuel analyses.

In the policy portion of the project, we made use of a "policy linkages" model (now named "Energy Choice Simulator", or ECS), developed in part under this contract. The model allows users to examine multiple alternative policy designs in a consistent and transparent manner and to run multiple analyses with differing combinations of policies and time horizons to demonstrate the impact of and interaction between unique combinations of factors. We used the desktop version of the model both to examine specific issues in LCFS design and to illustrate the range of issues that could potentially be addressed by ECS.

In the economic impact portion of the project, we developed a statewide economic sector model, covering basic motor fuels and crop and livestock sectors. The model allow evaluation of the interactions of economic factors such as: the type and distribution of low-carbon fuel facilities; patterns of crop land use; production of feedstocks and other agricultural products;

transportation; and storage under various environmental, technological and market conditions. The model permits examination of the dynamics of fuel production and consumption, and how these might influence economic conditions throughout the state.

In the environmental impacts portion of the study, the University researchers created a framework to allow analysis of selected environmental impacts due to various transportation fuel policies and estimation of changes in air quality (GHG and criteria air pollutants), water quality changes (nutrients and sediment), and ecological and human health. The framework provides a good basis for discussion on current life cycle analysis models and the work that still needs to be done on them. Such work is critical to development of any future "sustainability indexing system" as a means to compare environmental impacts resulting from various policies and technical pathways.

The research team has provided significant detail in the associated sections. Additional specifics about the models and model outputs are available upon request from the principal authors of Policy, Greenhouse Gas, Economic, and Environmental sections.

This report includes descriptions and results obtained through use of the modeling analytical framework, and outlines opportunities and challenges related to those results. The differences in data consistency and the maturity of modeling software available for greenhouse gas, policy, economic, and environmental impacts were found to be a challenge in our attempt to perform comparative modeling across these three disciplines.

Our investigations revealed a wide range in data quality and availability. Certain data elements were found to be so uncertain—whether because there is no existing technology or because the policies are under active research—that not all pathways could be usefully examined across all disciplines in the study.

In addition to these uncertainties, there is also substantial disagreement in the science community about some of these data and modeling techniques. Consequently, we urge readers not to make policy decisions based upon the specific numbers developed for this report. Both data and modeling will be improved over time through the efforts of current and subsequent researchers. Many of the data elements that are presently unknown or known only within extremely wide bounds will eventually be estimated with more certainty, at which time they might be usefully enfolded into modeling of the sort undertaken for this project.

This report enables informed discussion about the status of data and software available for modeling greenhouse gas, economic, and environmental implications of various LCFS policies. Discovery resulting from the project should be used to prioritize remaining research needed to perform comparative modeling across these three disciplines for each transportation fuel and production pathway influenced by LCFS policies.

Minnesota
Low Carbon Fuels Standard Study

A Lifecycle Assessment of Greenhouse Gas Emissions for Minnesota Transportation Fuels

Contract No. B24112

University of Minnesota

Greenhouse Gas Modeling Research Team:

Adam Boies, Department of Engineering, University of Cambridge (formerly Department of Mechanical Engineering, University of Minnesota)

Winthrop Watts, Department of Mechanical Engineering, University of Minnesota

David B. Kittelson, Department of Mechanical Engineering, University of Minnesota (principal contact)

June 2011

Prepared for:

Minnesota Department of Commerce

Table of Contents

List of Figures

List of Tables

Introduction

As the U.S. moves towards decarbonizing emissions from the transportation fleet each state may evaluate the emissions of its current fuel mix to determine options for future low carbon fuels. While much work has been done to develop nationwide lifecycle analyses (LCAs) (Larson, 2006; Wang, 1999a), better methods must be developed to perform LCAs for fuels on a state and individual refinery basis. Localized differences in electrical generation, crude oil sources, biomass production, refinery efficiencies, and other parameters may cause state LCAs for specific fuel pathways to differ from the national average. Development of LCAs using state-specific data will assist legislators in developing policy that can encourage low-carbon-fuel production that will reduce state GHG emissions.

Emissions from the combustion of fuels for transportation account for the largest portion of end use greenhouse gas (GHG) production within Minnesota (MN). In 2000, an estimated 40 million tons of CO_2e were emitted by the MN transportation sector, an increase of 50% over 1980 levels which is, the highest growth rate in GHG emissions of any sector within MN (Ciborowski, 2007). Over 95% of MN fuel used for transportation is derived from petroleum, with most of the remainder derived from natural gas (Ciborowski, 2007). Renewable fuels derived from biomass are steadily gaining market share within the light and heavy duty vehicle sectors. MN state law (2004) requires that all diesel fuel sold must contain 5% biodiesel (B5) and gasoline must contain 10% ethanol (E10), which will increase to 20% ethanol pending US EPA approval.

In the current study, we examine the emissions of fuels produced for supplying the energy needs of the MN transportation fleet. We expand on the Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (Wang, 1999b) by incorporating a MN specific database of LCA inputs. We discuss aspects of the MN LCA that make it distinct from other national or international fuel analyses.

A variety of fuels are being investigated by researchers, many of which are not discussed in this report. This report is not intended to give difinitive values for the present or future carbon intensities of fuel, but aims to depict where fuel production stands and where future advancements may come from. The plethora of future fuel options makes it impossible to predict which fuel will achieve significant carbon reductions while being produced at an economical price and in significant quantities. Rather than predict future outcomes, the purpose of this report is to provide a transparent way in which to model fuels and provide a framework in which future fuel producers can evaluate their specific fuels so that they can figure out the best way in which to achieve carbon reductions.

Fuel Life Cycle Analysis for Minnesota

To model the quantity of emissions that occur as a result of transportation fuel consumption the entire fuel lifecycle must be examined, which includes resource extraction, refining, distribution and storage, and energy consumption as shown in Figure 1. The definition of lifecycle used here is consistent lifecycle as defined in the Energy

Independence and Security Act of 2007 (EISA 2007), Title II, Subtitle A, Sec. 201, but does not include land use emissions which are discussed later. Performing a life cycle analysis (LCA) for each fuel pathway from extraction to combustion (well-to-wheels) allows for comparison of dissimilar fuels on an equivalent basis. LCA analysis includes the tracking of all GHG emissions that occur within each stage of the lifecycle for a specific fuel pathway. Total GHG emissions can vary for the same fuel depending on the pathway of the fuel, which includes initial feedstock, refining type and efficiency of the engine in which the fuel is used. Variations can even occur within the same fuel pathway depending on the assumptions that are input into the LCA model. Therefore, each fuel pathway needs to be examined separately using as detailed inputs as available and explicitly noting what data and assumptions were used to model the pathway emissions. Assumptions and inputs used in an LCA can result in diverse results and unequivocal conclusions are difficult without detailed case-by-case specific information. Care must be taken not to generalize LCA from a specific fuel pathway to other fuels, nor in all cases will the use of industry averages represent specific fuels produced by individual refiners. Therefore, to compare all fuels produced or sold within MN, an LCA would ideally be performed for each fuel sold by each refiner or blender using data specific to that fuel's individual lifecycle.

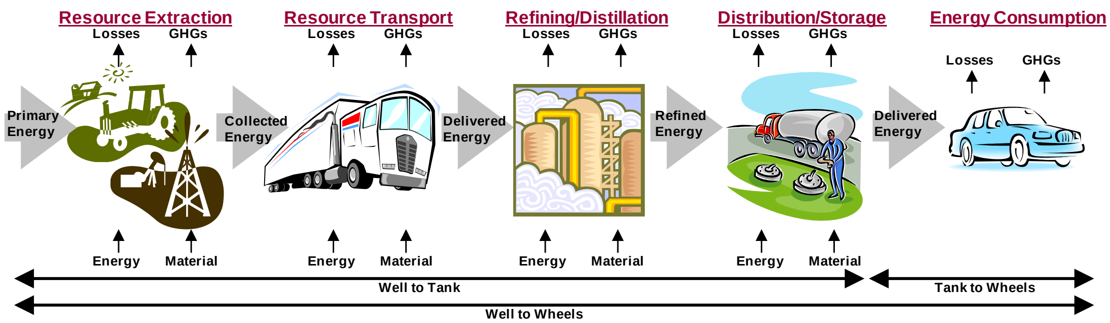


Figure 1: Schematic of transportation fuel life cycle from resource extraction to distribution and storage, well to tank (WTT), and distribution and storage to energy consumption, pump to wheel (PTW).

There are a variety of GHG emissions that occur during the production and consumption of fuels. While, the primary GHG emitted from traditional fossil fuels is CO_2, other fuels result in significant emissions of other GHGs, such as CH_4 and N_2O, which have a much larger deleterious effect on the atmosphere. To facilitate comparison among all GHG emissions they are compared in terms of their equivalence in global warming potential to CO_2. Thus non-CO_2 emissions are converted to equivalent emissions of CO_2, CO_2e, as defined by global warming potentials presented by the International Panel on Climate Change (IPCC, 2007).

In the present study, LCAs were performed using GREET 1.8b software to model lifecycle GHG emissions per unit of energy (gCO_2e/MJ) for MN fuels. The GREET modeling platform was chosen because of its wide use within the U.S., accepted status within academic and government studies as an LCA modeling platform, and ease of use. While other models were considered, such as BESS and LEM, none contained the breadth of fuel pathways required for a state-wide study or the modeling community. For a further review of LCA software that highlights each of the LCA model's fuel strengths and weaknesses see Tessum, Boies et al. (2010). A summary of the Tessum, Boies et al. findings are shown in Table 1. In addition to providing the breadth necessary to allow for the modeling of all the fuels in this study, GREET was also chosen because it is available at no charge from Argonne National Labs and members of the research staff had previous knowledge of the model.

Table 1: Summary of LCA models considered for this study. (Tessum 2010)

GREET The greenhouse gases, regulated emissions, and energy use in transportation (GREET) model was developed by Argonne National Laboratories to calculate the full lifecycle emissions and energy use from the transportation sector. The model is among the most reviewed of the US models and has been used in many peer reviewed studies (Farrell, Plevin et al. 2006; Farrell and Sperling 2007; Wang, Wu et al. 2007; Hill, Polasky et al. 2009). The model is composed of two separate spreadsheet based modules that calculate the emissions associated with the well-to-wheels production of fuels (current model 1.8C) and the vehicle production and disposal cycle (current model 2.7). GREET calculates the energy consumption (with delineated fossil fuel and petroleum consumption) for the entire fuel lifecycle. The current model contains more than 100 distinct fuel lifecycles. The GREET model converts all greenhouse gas emissions to carbon dioxide equivalent, CO_2e, emissions based on the IPCC's global warming potential. The primary advantage of GREET over other models is its breadth of fuel pathways covered, which is greater than any other current model. Additionally, the GREET model is an Excel-based model that allows the user access to all model inputs and calculations. By allowing users access to the model's inner operations, it can be modified to perform state-specific lifecycle studies as is done in this study. For more information refer to http://www.transportation.anl.gov/modeling_simulation/GREET/.
LEM The Lifecycle Emissions Model (LEM) was developed by Mark Delucchi at U.C. Davis. While the LEM has been used for a variety of studies and is the basis for the GHGenius mode the model itself has not been published in any peer reviewed journals, so the validity of the model remains unverified. The LEM model is not publicly available for independent use, but the model results along with critical inputs are available in a series of reports (Delucchi 2003; Delucchi 2004; Delucchi 2005). The model is spreadsheet based and currently calculates emissions for 28 fuel pathways and over 20 different vehicles, including passenger vehicles, buses, scooters, bicycles, heavy-rail, light-rail, diesel trains and cargo ships. The model calculates emissions for 12 pollutants, more than any other LCA model. The LEM contains historical data that allows for results to be calculated for any target year from 1970-2050. The historical data also allows LEM to make predictions about future fuels based on historical data using the model's dynamic capabilities (Delucchi 2003). This model was not chosen for this study because it has not been published in any peer-reviewed journals and was not publically available. For more information refer to http://www.its.ucdavis.edu/publications/2002/UCD-ITS-RR-02-02.pdf.
BESS Biofuel energy system simulator (BESS) is a LCA model developed by University of Nebraska. The BESS model specializes in calculating the well-to-tank emissions of corn ethanol produced in different states and regions within the US. Like other models BESS is spreadsheet based, but incorporates a user friendly interface that allows for easy updating of data inputs. BESS tracks three GHG gases: carbon dioxide, nitrous oxide and methane. Like other LCAs, BESS combines emissions into CO_2-equivalent emissions using the IPCC's 100 year global warming potential. The BESS model calculates emissions and resource use from four separate modules that consist of crop production, ethanol biorefining, cattle feeding and anaerobic digestion (Liska, Klopfenstein et al. 2008). The inclusion of anaerobic digestion is unique to the BESS model and highlights the importance of accounting for coproduct credits within the lifecycle of fuels. Because BESS only examines ethanol pathways it did not contain the breadth of scope necessary in this model. Therefore it was not chosen as the modeling platform for this study. For more information refer to http://www.bess.unl.edu/.

The GREET model's system boundaries are defined to include the primary inputs to each stage of the lifecycle process. Each stage of the lifecycle has material and energy inputs, such as natural gas or coal, that are tracked by GREET and the emissions are calculated. Our GREET models include consumable inputs such as fuel or fertilizer but does not include infrastructure-related activities such as farm machinery or refinery plants. While infrastructure development initially is responsible for large energy use and greenhouse gas emissions, Argonne National Lab has found that over the entire lifecycle items such as farming equipment contribute $<2\%$ of energy use and $<1\%$ of greenhouse gas emissions to the total fuel lifecycle.

MN specific lifecycle input data were collected from a variety of sources and stored as a spreadsheet apart from the GREET software. The spreadsheet of MN data contained macros that uploaded input data to GREET. GREET generated lifecycle emissions for each stage in the fuel pathway including resource extraction, refining, distillation, distribution, storage, and energy consumption. These results were exported from GREET and stored in the spreadsheet. Outputs from GREET represent well-to-wheel emissions per unit of fuel energy including fuel combustion, which does require any assumptions regarding vehicle efficiency. Further well-to-wheel analysis is conducted outside of GREET to model GHG emissions on a per mile basis which does require assumptions regarding vehicle efficiency.

As shown in Table 2, our LCAs included the two primary conventional fossil fuels, gasoline and diesel, produced from sweet and oil sands crude. In addition, future fossil fuels were examined including Fischer-Tropsch diesel derived from coal, compressed natural gas, liquefied natural gas, and liquefied petroleum. Biofuels analyzed included those that are currently used within the state, corn ethanol and soy biodiesel, as well as second generation biofuels including cellulosic ethanol derived from prairie grass, miscanthus, switch grass, forest residue, algae, and crop residue. Not modeled in this study were gasoline and diesel produced from conventional foreign petroleum and enhance oil recovery from petroleum because not enough data existed within MN to accurately model these fuels. These fuels have been modeled and the authors refer readers to these reports (NETL, 2008; Unnasch et al., 2009) for further information on foreign fuels. A comparison of this study's results to similar results from other studies as well as a discussion of uncertainty is included in the summary section

Table 2: Summary of fuels and feedtocks analyzed in this study.

Fuels	Conversion	Feedstocks	Fuels	Conversion	Feedstocks
Gasoline			Ethanol		
	MN Refining	Sweet Crude		MN Refining	MN Corn grain
	US Refining	Sweet Crude	14 Individual MN Refiners	MN Refining	Corn grain
	MN Refining	Canadian Oil Sands		US Refining	US Corn grain
	US Refining	Canadian Oil Sands			Cellulosic
	MN Refining	MN Specific Blend		MN Refining	Grass (Switchgrass)
Diesel				MN Refining	Energy Crop (Miscanthus)
	MN Refining	Sweet Crude		MN Refining	Crop Residue (Stover)
	US Refining	Sweet Crude		MN Gasification	Wood Residue
	MN Refining	Canadian Oil Sands		MN Refining	Prairie Grass
	US Refining	Canadian Oil Sands	Biodiesel		
	MN Refining	MN Specific Blend		MN Refining	MN Soybean
Electricity				US Refining	Algae
	MN Mix of Production	MN electric grid		US Refining	US Soybean
	US Production	US Electricity	Compressed Natural Gas (CNG)		
	US Production	Coal		MN Production	Natural Gas
	US Production	Natural Gas		US Production	US Natural Gas
	US Production	Petroleum	Liquified Natural Gas (LNG)		
	US Production	Biomass		MN Production	Natural Gas
Hydrogen				US Production	US Natural Gas
	US Production	Electricity	Liquified Petroleum Gas (LPG)		
Coal-to-Liquid Fuels (CTL)				MN Production	Petroleum Gas
	US Production	Coal		US Production	US Natural Gas
	MN Production	Coal			

Electricity: An Input for Fuel Production

All fuels used within the state require electricity for production at some point along their lifecycle. The quantity and mix of electricity generation can significantly impact the total GHG emissions of the fuels. In this study, we used the Midwest regional electricity generation data in GREET to better reflect the Midwest regional electricity generation mix. The electricity profile is most appropriately examined at the regional level since there is little transfer of electricity among regions, but significant transfer within a region. The Midwest Independent Transmissions System Operator (MISO) manages the grid by bringing on or shutting down additional electricity generation to meet demand within an entire region (Plevin, 2009). Therefore, a change in electricity demand in MN causes changes in the entire MISO and is therefore the appropriate level of analysis. For this reason, we modified GREET's stationary electricity mix to match that of the 2007 MISO (Rose et al., 2007). According to IFC International the MISO electricity generation mix in 2007 was heavily dominated by coal which accounted for 79% of total electricity production. Nuclear also contributed 14% of total electricity production with natural gas and other sources producing 3% and 4%, respectively.

Gasoline and Diesel Fuel Production

Life cycle data were imported into GREET that were representative of MN specific fuel pathways. In the case of petroleum based gasoline and diesel default GREET values were used because pathway specific information was not available for each of the two refineries within the state. We assume that the GREET defaults are reasonable because MN refineries are similar to refineries of the same type located within other parts of the nation, i.e. the energy efficiency of oil sands refining in Minnesota is similar to other states. Nevertheless, individual fuels within MN may vary dramatically from national average production. Deviations from each default GREET input for each fuel pathway are discussed below.

Petroleum based fuels (gasoline and diesel) account for the majority of transportation fuel used within MN (Boies et al., 2009). These fuels are imported into the state as either fully refined end use products or as a crude oil, which is refined within the state. Currently, MN refines slightly less fuel than is consumed within the state (Ciborowski, 2007), and some refined fuel is exported to nearby markets. Therefore transportation fuels consumed in MN are a mixture of fuels produced within the state and imported from others. One difference between fossil fuels consumed in MN versus nationally is that 83% of the total percentage of crude oil consumed within MN (Energy, 2008) is refined from Canadian oil sands, a mixture of clay and bitumen which requires more energy to extract and refine than sweet crude oil.

To model the total GHG emissions of fossil fuels produced for MN, LCAs were conducted for four fuel pathways, sweet crude to gasoline, sweet crude to diesel, oil sands to gasoline, and oil sands to diesel. GREET 1.8b default values were used for sweet crude oil production of which 58% were assumed to come from abroad with the rest coming from US land and off-shore reserves. All oil sands were assumed to come from Canada via pipeline directly into the US. Each fuel pathway was examined using the default GREET average national electricity generation profiles as well as an electricity generation profile specific to Midwest Independent Transmission System Operator (MISO) region which includes MN (see discussion in the following section for justification of MISO).

Figure 2 shows that for petroleum-based fuels the largest contributor to GHG emissions is the release of carbon from tank-to-wheels, *i.e.* the combustion of the fuel. As the amount of carbon per megajoule is fixed, there is little that can be done to reduce the portion of GHG emitted per megajoule, since all of the carbon contained within the fuel would have otherwise remained sequestered if not for anthropogenic uses. The lifecycle stage that contributes most to the deviation in carbon intensities among the fuels is the feedstock extraction. Because oil sands crude require more energy to extract than sweet crude, the emissions associated with the feedstock extraction are higher, thus increasing the carbon intensity of fuels by 15% relative to fuels derived from sweet crude gasoline. The effect of producing fuels with MN electricity has little effect on the overall emissions, causing an increase of 1% in fuel carbon intensity for MN produced hydrocarbon fuels. MN gasoline and diesel do have higher carbon intensities, 102.8 and 103.3 gCO2e/MJ, respectively, than US sweet crude gasoline and diesel because of the high content of oil sands crude.

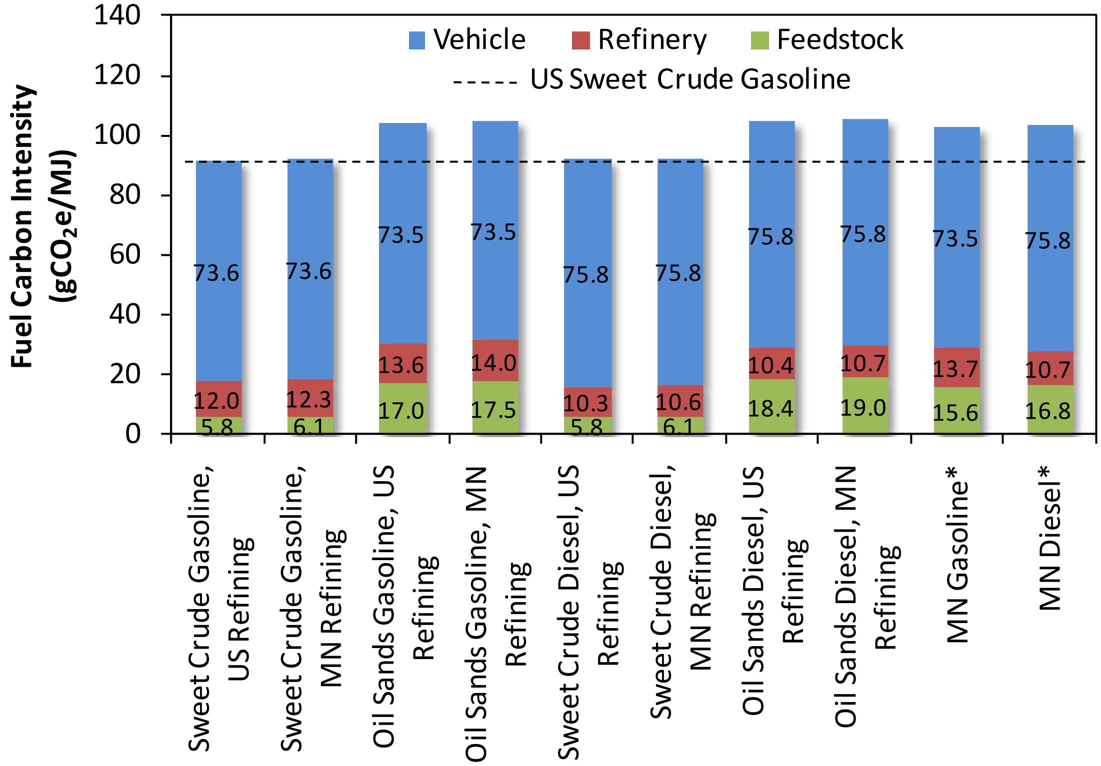


Figure 2: Fuel carbon intensity for gasoline and diesel fuel refined from sweet crude and oil sands gasoline produced nationally and within Minnesota (MN). Note: MN gasoline and diesel consist of 83% MN oil sands gasoline and diesel, respectively.

The future fuel carbon intensity of gasoline and diesel fuel refined from sweet crude is not expected to change significantly. As shown in Figure 2, the contribution from feedstock extraction and refining is minimal compared to the combustion of the fuel, which is fixed. The future of gasoline and diesel refined from oil sands does have potential for improvement if carbon capture and storage is employed during feedstock extraction. However, such efforts are costly, have yet to be achieved and will at best result in a fuel with a carbon intensity similar to sweet crude gasoline and diesel.

LNG, CNG, LPG and Coal-to-Liquids

Non-traditional fossil fuels may lower overall emissions, decrease the dependence on foreign oil, and hedge against fluctuations in crude oil prices. Due to their low emissions, natural gas, compressed natural gas (CNG) and liquefied natural gas (LNG) are possible alternatives to traditional transportation fuels derived from petroleum (Azar et al., 2003). Another alternative fossil fuel is liquefied petroleum gas (LPG), which recent studies have found to reduce primary emissions, such as particulate matter and NO_x, when used as a transportation fuel (Qi et al., 2007; Yang et al., 2007). Also due to the abundance and low cost of coal in the US many are proposing diesel fuel derived from coal using a Fischer Tropsch (FT) refining process, i.e. coal-to-liquids (CTL).

None of these fuels are produced in large quantities for the MN market, and MN has no significant reserves of natural gas or coal. Therefore for this analysis it is assumed that these fuels would be produced elsewhere and delivered to MN or the crude feedstocks would be delivered to MN and refined within the state. The only difference between being produced in MN and being shipped to the state is the electricity used to produce the fuels. It is assumed that MN refineries would be similar to the rest of the nation. Using the electricity assumptions discussed previously LCAs were calculated for LNG, CNG, LPG and FT Diesel, and the results are shown in Figure 3. With the exception of fuel produced from coal, the fuels have lower GHG emissions compared to gasoline because of lower GHG emissions produced during combustion. LNG, CNG, and LPG have lower carbon content per megajoule of energy than gasoline because they are shorter hydrocarbon chains with less energy in C-C bonds then longer chained hydrocarbons found in petroleum based fuels. Alternatively, FT diesel from coal has nearly the same emissions during combustion as diesel but has significantly more carbon emissions released during the refining stage than traditional petroleum based fuels. As a result the overall fuel carbon intensity is 140% greater than traditional sweet crude diesel. Without greater control of GHG emissions during the FT processing of coal, even a small portion of FT diesel within the MN fuel mix would increase the overall fuel intensity of MN fuels.

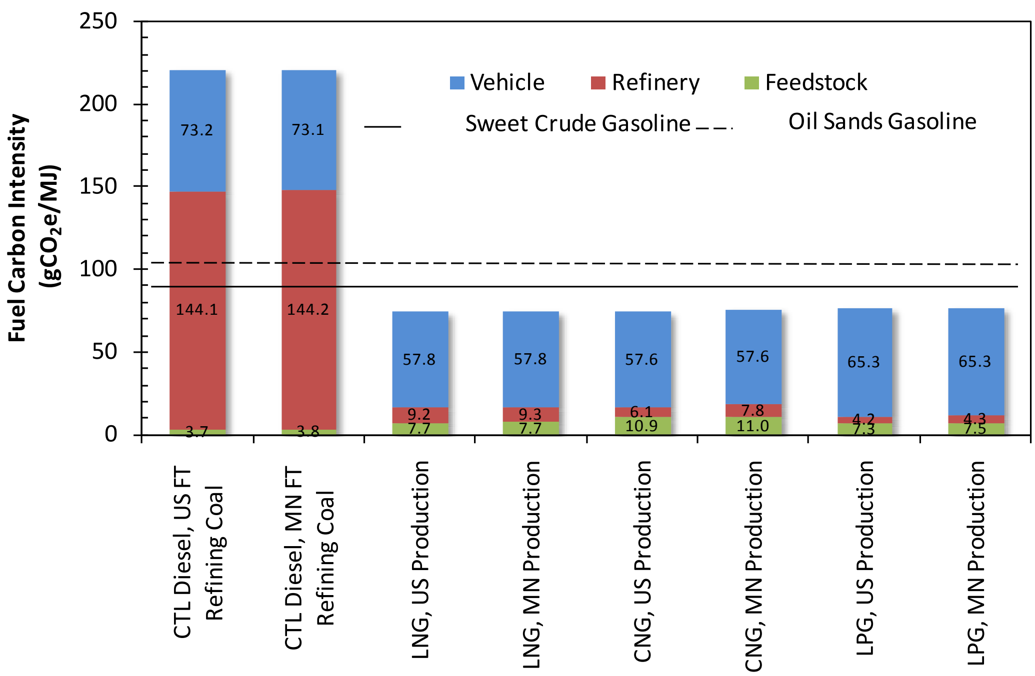


Figure 3: Lifecycle fuel carbon intensity of Fischer Tropsch (FT) diesel derived from coal (coal-to-liquid, CTL), liquefied natural gas (LNG), compressed natural gas (CNG) and liquefied petroleum gas (LPG) for national and MN production.

Corn and Soybean Production

MN is a leader nationally in corn and corn ethanol production, ranking 4th and 5th respectively among US states (RFA, 2009 and USDA, 2008). Additionally, MN is a large producer of biodiesel with a production capacity of 58 million gallons per year. Because MN is a net exporter of biofuels, exporting roughly two thirds of the ethanol it produces, we assumed that ethanol and biodiesel consumed within the state are largely produced by MN refineries. Therefore, to understand the potential for biofuels to reduce GHG emissions as a part of a low carbon fuel standard we analyzed the well-to-wheels GHG emissions of biofuels that are grown, refined, and consumed within the state and compared the results to national averages.

Corn farming within MN is more efficient than average national corn as shown in Table 3 where the energy required to produce a bushel of corn or soybeans within the state of MN is 14% and 26% less, respectively, than the national average (Liska et al., 2009; Wang, 1999b). Because fertilizer and energy use are typically a function of acres farmed, not bushels produced, some of the reduction in the energy required to produce a bushel of corn is a result of the higher than national average yields for corn, 160 bushel/acre in MN versus 152 bushel/acre nationally (5-year average) (USDA, 2008). For soybeans, yields are not greater than the national average, 40 bushel/acre in MN versus 42 bushels/acre nationally, which indicates that farming practices also play an important role in reducing the energy required to produce a bushel of soybeans. Nitrogen fertilizers are also used less per bushel in MN than the national average for both corn and soybeans, 8% and 58% lower, respectively. As a result of the lower fertilizer and energy use required for MN corn farming, the associated GHG emissions calculated by GREET of corn production in MN are 10% lower per bushel than US average corn (national corn 1,166 gCO_2e/bushel and MN corn 1,046 gCO_2e/bushel). Likewise the GHG emissions associated with MN soybean production are less than nationally produced soybean emissions (4,403 gCO_2e/bushel for MN versus 5,857 gCO_2e/bushel for US).

Table 3: National and Minnesota agricultural data used in GREET for corn and soy production.

	Corn			Soy		
	National[1]	Minnesota[2]	% Difference	National[1]	Minnesota[3]	% Difference
Nitrogen (g/bushel)	420.0	385.6	-8%	61.2	25.5	-58%
Phosphorus (g/bushel)	149.0	149.9	1%	186.1	87.4	-53%
Potassium (g/bushel)	174.0	156.2	-10%	325.5	87.6	-73%
Herbacide (g/bushel)	8.1	7.8	-3%	43.0	26.8	-38%
Insecticide (g/bushel)	0.7	0.2	-70%	0.4	1.4	230%
Total BTUs (BTUs/bushel)	12635.0	10910.2	-14%	22087.0	16251.7	-26%
Share Gasoline	18.2%	11.3%	-38%	17.8%	19.3%	8%
Share Diesel	45.2%	39.9%	-12%	64.4%	77.7%	21%
Share LPG	16.8%	40.9%	143%	7.6%	0.0%	-100%
Share Nat. Gas	14.5%	2.7%	-81%	7.3%	0.0%	-100%
Share Electricity	5.3%	5.3%	-1%	2.9%	3.0%	3%

[1]Default GREET1.8b input data
[2](Liska et al., 2009)
[3](Economic Research Service, 2006)

Corn Ethanol Production

Individual Ethanol Plant LCA

To examine refinery specific ethanol production within MN, 2007 data derived from the Air Emission Inventory gathered by the Minnesota Pollution Control Agency (MPCA) were used in GREET. Emission inventory data are collected to track regulated emissions from ethanol refineries, and by examining the individual MPCA reports it was possible to calculate the total energy usage, GHG emissions, ethanol and byproduct production, and corn consumption for 14 of the 18 ethanol refineries. As a whole, the MN ethanol refineries are predominantly dry mill, natural gas fired facilities that dry distillers' grains for export.

Figure 4 shows that the total carbon intensity of corn ethanol produced within MN varied from 50 gCO_2e/MJ to 88 gCO_2e/MJ with a production weighted average carbon intensity of 63 gCO_2e/MJ. Since it was assumed that all refineries used corn and electricity with the same average profile, specific to MN, all differences in the fuel carbon content are due to the refining process. Therefore the variation in the vehicle carbon captured by feedstock, which represents the uptake of carbon from the atmosphere during plant growth, less any CO_2e emitted to cultivate the feedstock, is due to variations in the efficiency of the refinery, as estimated by gallons of ethanol per bushel of corn. The change in the emissions associated with feedstock farming are a direct result of the refineries' efficiency of producing ethanol from corn, *i.e.* refineries with higher production efficiencies use less corn, and thus farming emissions are lower per megajoule of fuel produced. The results indicate that the majority of refineries produced ethanol with a carbon intensity that is within 10% of the production weighted average and is below the national average. Because MN refineries are largely natural gas-fired facilities there is a tight distribution of emissions characteristics and lower than national ethanol carbon intensity.

Those refiners that produce ethanol substantially outside the +/-10% band around the mean, namely Refineries F and J, have fundamental differences in operation compared to the other refineries. Refinery J's emissions are substantially higher than both the MN and GREET averages because it is the sole MN refinery that uses coal to produce the process heat needed for refining corn into ethanol. Refinery F produces ethanol with substantially lower carbon intensity than the MN average due to lower natural gas energy use than any other MN refinery. To achieve reduced natural gas usage, Refinery F uses biomass as an energy source, which it combusts to produce process heat. In our analysis it is assumed that the biomass used for heat would otherwise be left to decompose naturally (such as corn stalks in a field) and is therefore a carbon free source of energy.

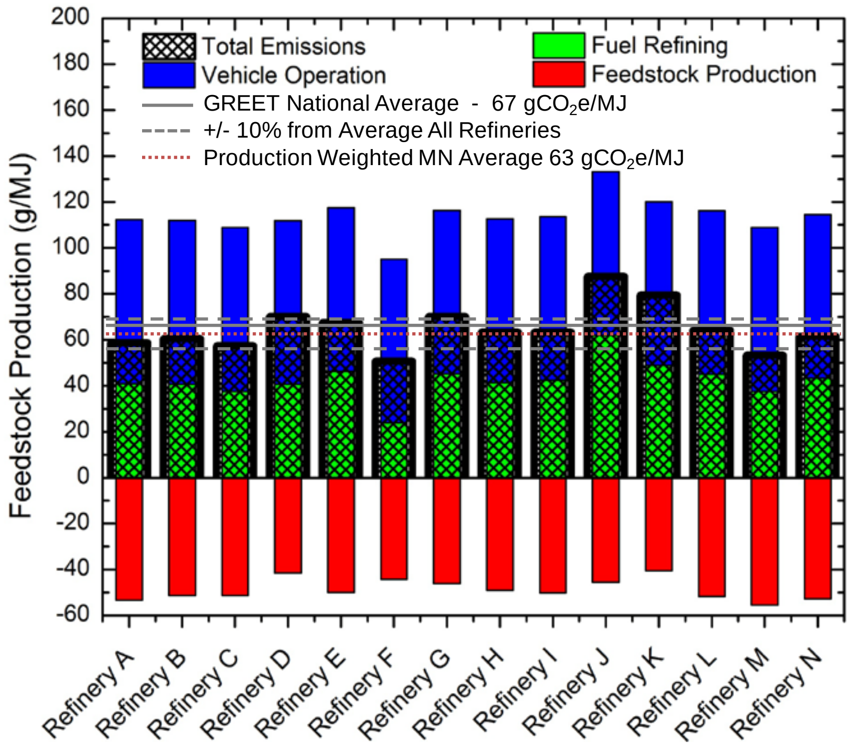


Figure 4: Fuel carbon intensity of corn ethanol produced from 14 Minnesota refiners.

Sensitivity of Corn Ethanol Refinery LCA to Uncertain Inputs

One source of uncertainty within the lifecycle analyses of MN ethanol refineries is their electricity usage rates. Because electricity usage from the ethanol refineries is not public data, the amount of electricity usage for each facility is not known. Questionnaires were distributed along with preliminary LCA results to each of the ethanol facilities asking for voluntary reporting of electricity usage data. Of the 14 facilities contacted only refineries B and D reported their electricity usage, which were 0.81 kWh/gallon and 1.09 kWh/gallon in 2007, respectively. The GREET default value of 0.90 kWh/gallon was used for refineries that did not provide information on their electricity usage to calculate the LCA values shown in Figure 4.

Due to the high percentage of electricity produced from coal in MN, the electricity used to produce ethanol has higher associated GHG emissions than the national average. While modifying the electricity mix within GREET better represents the electricity that is consumed in MN, those changes also affect other upstream processes such as fertilizer and pesticide production that may use electricity with emissions profiles that are different from MISO electricity. This “bleed-through” effect is inherent within GREET and is difficult to correct. To determine the magnitude of the bleed-through effect an LCA was conducted for a fuel pathway that produces ethanol from MN corn and a typical MN refinery, but uses separate electricity mixes for electricity consumed by MN farmers and refiners and the electricity consumed by upstream process which produce fertilizers and insecticides (agricultural products use national mix and MN farmers and refiners use MISO mix). The result of the analysis indicates that this bleed-through effect results in a change of emissions of less than 1%. Therefore, due to the relatively small change in overall emissions, because of the bleed-through effect, all MN pathways use the MISO mix for all electricity usage unless otherwise noted.

To examine the sensitivity of GREET results to individual input parameters, such as electricity usage, separate LCAs were conducted varying one parameter while all others were held constant. Using the high and low electricity usage rates (1.2 kWh/gal and 0.6 kWh/gal) from a recent Minnesota technical assistance program (MnTAP) refinery efficiency study by Kelly *et al.* (2007), we examined how the carbon intensity of ethanol from a typical dry mill refinery varies (Kelly, 2007). Refinery B, which produces ethanol with a carbon intensity near the production-weighted average for all refineries was used in the analysis. The high and low rates of electricity usage were used in GREET to calculate the ethanol carbon intensities. As shown in Figure 5 the resulting carbon intensity for the high and low electricity usage were 65 gCO_2e/MJ and 58 gCO_2e/MJ, respectively. The uncertainty due to electricity usage rates can cause as much as a 10% difference in calculated fuel carbon intensity. While we are uncertain as to each plants specific electricity usage, we believe that the 0.9 kWh/gal electricity usage rate to be a conservative average for MN refiners as the MnTAP study reports 0.8 kWh/gal as a benchmark with several refiners achieving 0.6 kW/gal.

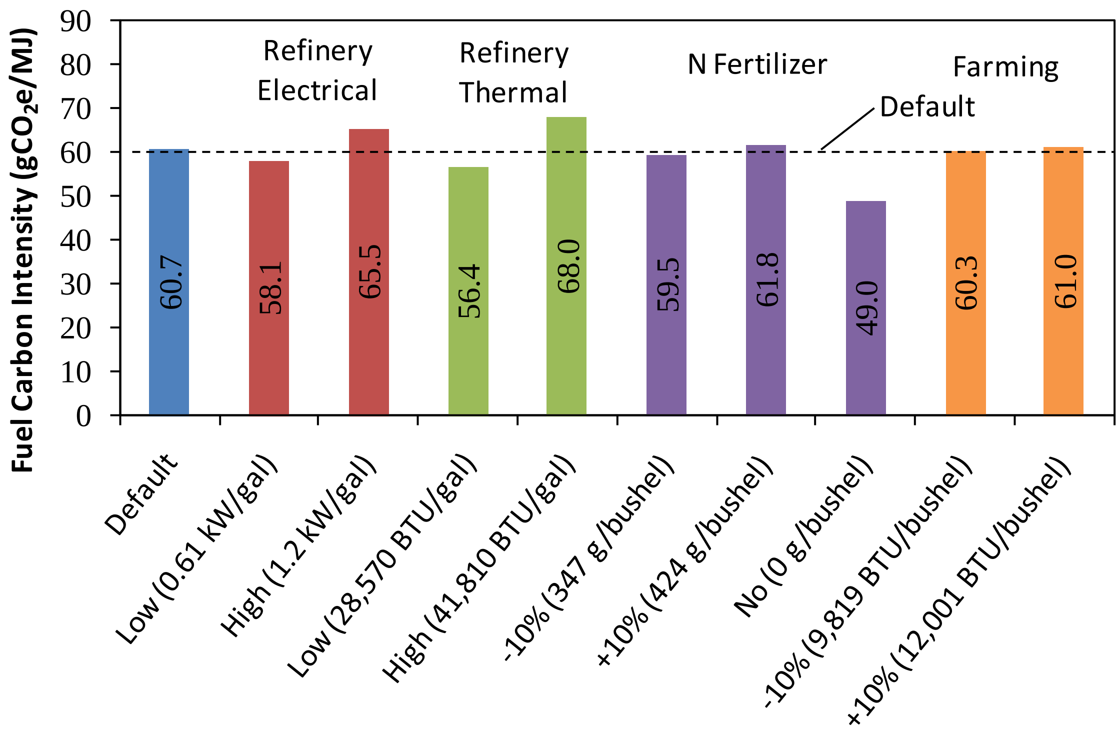


Figure 5: Sensitivity of ethanol carbon intensity produced using MN corn in Refinery B with variations in electricity, thermal, nitrogen and farming energy usage.

The sensitivity to GREET projections caused by energy use for thermal processing within the refinery was also estimated. Refinery B was modeled using the high and low energy use reported by MnTAP (Kelly, 2007), 41,810 BTU/gal and 28,570 BTU/gal, respectively. While some plants used trace amounts of diesel fuel and propane, the vast majority of energy for all MN ethanol plants is supplied by natural gas, with the exception of Refineries F and J as discussed previously. As shown in Figure 5, using inputs specific to Refinery B supplemented with the high and low energy consumption, the carbon intensity of the resulting fuels were calculated to be 56 CO_2e/MJ and 68 gCO_2e/MJ. This 20% spread in carbon intensities is indicative of the spread of the fuels seen in Figure 4 with a few exceptions. While thermal energy usage data are well known for all refineries in this study, it is nonetheless useful to see how an individual plant is affected by changes in thermal energy usage.

In addition to looking at variations in ethanol carbon intensity resulting from changes in refinery practices, we also modeled how changes in corn farming can influence the total emissions from ethanol. To examine the effect of farming energy use, the carbon intensity of ethanol was calculated for a fuel pathway that included Refinery B using corn that took ±10% of the energy average MN farming energy use shown in Table 3. As shown in Figure 5 the resulting fuel carbon intensities of the higher and lower energy usage resulted in a net change of nearly 0.5% in the overall carbon intensity.

To examine the effect that variations in fertilizer use causes in carbon intensity, the rate of nitrogen fertilizer was also varied to ±10% of the average MN value of 385 g/bushel. As shown in Figure 5, the high and low nitrogen fertilizer application rates results in fuel carbon intensity of 61.8 gCO_2e/MJ and 59.5 gCO_2e/MJ, respectively. When the 10% change in application rates was compared to the pathway that includes an average fertilizer rate the change in emissions was nearly 2%, a relatively large effect for a small change in one input parameter. Because such small changes in nitrogen fertilizer usage have such large overall effects, further research into both the variation in fertilizer usage and ways to reduce it may lead to significant reductions in overall fuel carbon intensity. If methods are developed to eliminate the need for nitrogen based fertilizers, the modeled resulting carbon intensity of fuels produced using non-nitrogen fertilized corn (holding all other farming inputs constant) would be 49.0 gCO_2e/MJ, or nearly a 20% overall reduction from similarly produced ethanol.

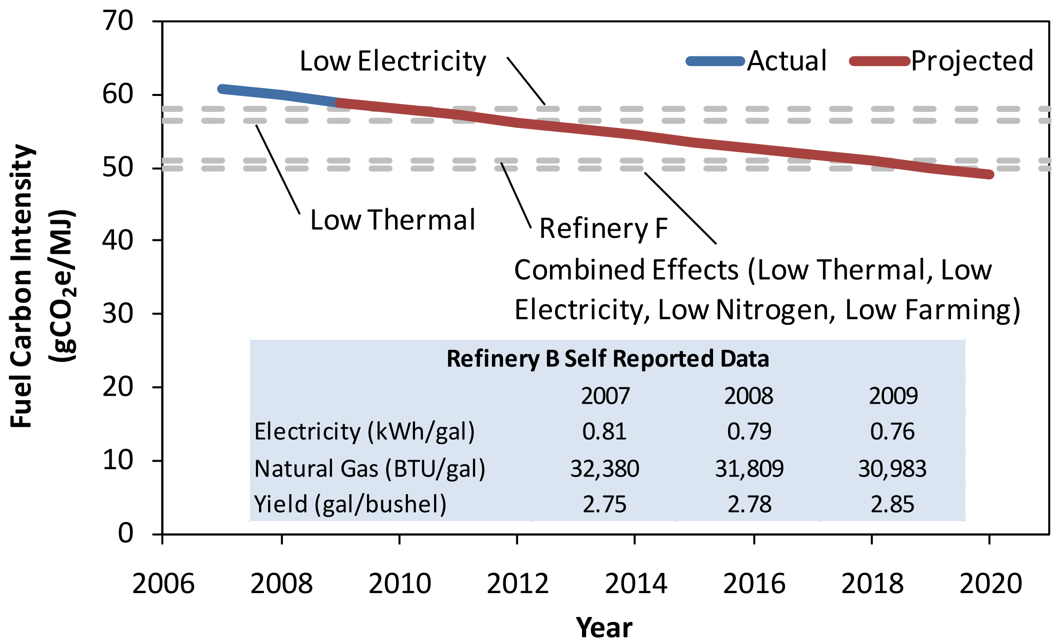
Incremental Improvements of Corn Ethanol Production

Advanced biofuels may achieve significant reductions in fuel carbon intensity if improvements to existing methods of ethanol production are made or if different feedstocks and new fuel production pathways are introduced. Although many proposed technologies have yet to achieve commercial scale, this study examines the potential of future fuels to reduce carbon emissions.

One method of improving the fuel carbon intensity of corn ethanol is by making incremental improvements in the production process. We examine future fuel production by extrapolating the improvements that have been made over recent years by MN refiners into the future.

In addition to supplying electrical usage data for 2007, Refinery B (see Figure 4) also supplied electrical and thermal energy usage along with yield data for 2007, 2008 and

2009. Using the self-reported data with corrections to normalize it to fit more comprehensive data gathered by the MNPCA, ethanol carbon intensities were calculated based on past and current performance of the refinery. As shown in Figure 6, the carbon intensity of ethanol was reduced by nearly 3% from 2007 to 2009. If Refinery B was able to continue the rate of improvements over the next several years it could reduce the carbon intensity of ethanol by 20% relative to 2006 by 2020. Several points from the variability analysis indicate how low electricity usage (0.61 kWh/gal vs. 0.81 kWh/gal), low thermal energy usage (a 10% reduction), and a switch to using biomass like Refinery F (see Figure 4) could each individually reduce emissions to make future reductions. Additionally if reductions were combined to meet the current best practices as outlined in the MnTAP report, such as the low thermal energy use, low electricity use, low nitrogen use and low farming energy use as shown in Figure 4, the resulting emissions would be 50 gCO_2e/MJ. While these approaches have been achieved on an individual basis, none of these approaches have been verified to be possible for every refiner or farmer within the state. Instead this analysis is used to illustrate that improvements in GHG emissions from corn ethanol may be achievable. By combining these effects using today's technology a reduction of 20% compared to average MN ethanol (50 gCO_2e/MJ compared to 63 gCO_2e/MJ) can occur if ethanol producers have an incentive to do so. Currently ethanol producers have no direct incentive to reduce carbon emissions, but potential for fuel carbon intensity reduction does exist.



Refinery B Self Reported Data	2007	2008	2009
Electricity (kWh/gal)	0.81	0.79	0.76
Natural Gas (BTU/gal)	32,380	31,809	30,983
Yield (gal/bushel)	2.75	2.78	2.85

Figure 6: Current and projected fuel carbon intensity of ethanol produced from Refinery B using self-reported inputs with lines indicating how future reductions may be achieved by incorporating refining current best practices.

Biodiesel from Soy and Algae

In addition to calculating LCA emissions for ethanol, biodiesel emissions were modeled for production of biodiesel in MN and nationally. Inputs for soybean production were modeled based on inputs from Table 3. Additionally, MN electricity was assumed for the MN produced fuels as discussed previously. For MN production information, the MPCA Air Emission Inventory was insufficient in providing the level of detail necessary to model the production operations of the three biodiesel plants operating within the state. Therefore, data for biodiesel production was obtained from recently released reports from the National Oilseed Processors Associations (NOPA) and National Biodiesel Board (NBB) (National Biodiesel Board, 2009; NOPA, 2009). These reports indicate that the energy required to extract a pound of soyoil is 2,705 BTU/lb, rather than the GREET default of 5,867 BTU/lb. Additionally, the energy required for soyoil transesterification is reduced from the GREET default of 2,116 BTU/lb of biodiesel to 1,294 BTU/lb.

The allocation of GHG emissions to co-products produced with biodiesel were included in the overall calculation of lifecycle GHG emissions from biodiesel. Using the default settings within GREET, the soy oil was assigned 34% of the lifecycle emissions from soy-oil extraction with the remaining 66% going to meal. For fuel production 90% of the emissions were assigned to the fuel while 10% were credited to glycerin production. The assignment of some of the emissions to coproducts results in a lower lifecycle emission profile of the final fuel than if all emissions were assigned to the fuel.

As shown in Table 4, the resulting emissions for biodiesel produced using MN agricultural practices, electricity and updated refining numbers were less than the default GREET biodiesel national average. As shown, the majority of the changes in emissions were due to the difference in fuel refining. Whether biodiesel production in MN is best represented new NOPA and NBB data is unclear. Further reporting is necessary to better model the emissions specific to individual biodiesel production facilities within the state.

Table 4: Biodiesel fuel carbon intensity for MN and US produced fuel.

	Fuel Carbon Intensity (gCO_2e/MJ)			
	Feedstock	Refinery	Vehicle	Total
US Biodiesel	-65	12	77	24
MN Biodiesel	-68	8	77	17

Microalgae is also a biomass feedstock that is of interest to produce biofuels because of the higher solar efficiencies of microalgae (10-20%) when compared to other biomass crops such as switchgrass (0.5%) (Yanqun et al., 2008). While the solar efficiency is encouraging, it is unlikely that microalgae production facilities will be located in MN due to the states low annual solar yield (NREL, 2009), but algae-based-diesel fuel might be imported from other states. Several key barriers remain to be overcome before algae biodiesel can become a successful commercial venture. A major obstacle is the high amount of energy required to produce fuel. A recent study of the lifecycle energy and environmental impacts of algae biodiesel found that of four pathways investigated three took significantly more energy to produced algae biodiesel than the final product contains (Lardon et al., 2009). The remaining fuel pathway achieved lower energy usage by producing biomass from a strain of algae that had low nitrogen requirements and was processed without drying of the algae, a pathway that has yet to be realized. If such a pathway was to be achieved, Lardon *et al.* calculate that the resulting lifecycle GHG emissions would be approximately 30% less than standard diesel fuel. Despite a relatively small improvement in GHG emissions, algae biodiesel is attractive because of the large yields and small land requirements necessary for production. Therefore while the ultimate success of algae biodiesel remains uncertain, it is a potential feedstock for future biomass-based fuel.

Ethanol Production from Biomass: Corn Stover, Forest Biomass, Switchgrass, Prairie Grass and Miscanthus

While current MN biofuel production is dominated by corn based ethanol, researchers within the state and nationally are developing fuels in processes that have lower GHG emissions and use feedstocks other than corn. One way to lower the overall associated emissions with corn ethanol is to use renewable fuels to produce process heat for the ethanol refineries. Corn stover is often discussed as a biomass resource option for refiners because of its proximity to refining facilities and it is currently tilled under or left to decay naturally in most fields. While there is ongoing debate as to how much stover can be removed from fields, several studies have indicated that 30-40% of stover can be removed with current harvesting technologies and without significant degradation of land from reduced carbon, soil nutrients or soil moisture (Graham et al., 2007; Hoskinson et al., 2007; Sokhansanj et al., 2002). If farmers switch to no till practices up to 100% of stover can be removed without affecting soil conditions (Graham et al., 2007; Sheehan et al., 2003). If stover removal is conducted so that additional nutrients need not be added to the soil, the only emissions that results from stover use are those associated with the energy used to harvest and transport the biomass to the refinery.

LCAs were conducted to model the total GHG emissions of ethanol produced using corn stover combustion for process heat. The MN specific pathway assumed current MN farming practices and the current electricity generation mix with Refinery B's processes using all process heat derived from corn stover. Two different assumptions were used for the production of corn stover. The first assumed that no additional fertilizer was required for stover removal and the second assumed additional fertilizer use to replace nutrients from stover removal with rates of nitrogen at 4.5 kg/ton of stover, P_2O_5 at 1.6 kg/ton of stover and K_2O at 8.3 kg/ton of stover. In both cases it was assumed that the energy required to gather corn stover is 235,244 BTU/dry ton. The resulting fuel carbon intensities of corn ethanol produced with stover heat are 35 gCO_2e/MJ and 32 gCO_2e/MJ with and without additional fertilizer, respectively. Regardless of whether additional fertilizer is required, the resulting fuel carbon intensity of corn ethanol produced with process heat derived from stover are over 40% less than average MN corn ethanol and over a 60% reduction from fossil fuels.

In addition to using corn stover to provide process heat for ethanol refineries, other forms of biomass sources such as forestry products, prairie grasses, and municipal waste can also be used to produce ethanol. While this study did not explicitly calculate the lifecycle emissions from pathways involving these alternate forms of biomass fired ethanol refineries, it is reasonable to assume that the cumulative emissions from such processes would be comparable to stover fired refineries and low compared to fuels derived from fossil fuels, so long as it does not require significantly more energy to produce, collect and transport the biomass.

Several methods are proposed for the production of transportation fuels from biomass, including thermal gasification and fermentation. Woody biomass, or lignocellulosic material, is frequently mentioned as a potential feedstock for biofuel production because of its widespread availability and favorable GHG balance. Gasification of woody biomass is an option that is attractive to MN, because of its active logging industry. To perform an LCA on fuels derived from forestry products data on forest biomass production were obtained from a recent report assessing the carbon flows for the Laskin Lake Biomass Facility (Domke et al., 2008). From data within the report we calculated the average number of miles required to deliver biomass to the plant was 84 miles and the average amount of energy required to extract forest residue was 528,805 Btu/ton. These values were used as inputs to GREET. The default GREET gasification yield of 90.4 gal/ton of biomass was used and no net electricity generation was assumed to occur from the gasification process. All biomass was assumed to come from trimmings and other material that would otherwise be left on the forest floor to decay naturally. Natural biomass decay emits carbon into the atmosphere at a slower rate than removing and combusting it directly, roughly a 15% difference when examined on a 100-year time horizon. Domke *et al.* took into account the decay rate of biomass on the forest floor and used a 100-year time horizon to calculate the emissions of leaving the biomass to decay naturally on the forest floor versus removing it and combusting it. The resulting net emissions were 275,795 gCO_2e/ton of removed forest biomass. The lifecycle fuel carbon intensities of ethanol from gassified forest biomass were calculated to be 58 gCO_2e/MJ and 20 gCO_2e/MJ including and excluding the difference in release rates. However, as Domke *et al.* state, if the removal of biomass was assumed to occur over 100 years, but the analysis calculated emissions net emissions over 120 years, "90-95% decomposition would be achieved" thus leaving only emissions from biomass removal and shipping (Domke et al., 2008). Therefore the fuel carbon intensity of 20 gCO_2e/MJ more accurately depicts the true carbon value of the fuel given a proper timespan for analysis.

Switchgrass, praire grass and miscanthus were also evaluated as potential feedstocks to produce cellulosic ethanol via fermentation. Because these grasses are not currently grown in large quantities for biofuel production within MN national numbers were used to estimate the energy and fertilizer requirements as well as expected yields. Combining fertilizer rates and yield data from Hill *et al.*, we calculated nitrogen fertilizer input rates for GREET to be 9.4 kg/ton, 3.1 kg/ton, 0.0 kg/ton for switchgrass, miscanthus and prairie grass respectively (Hill et al., 2009). For all grass production farming energy use per acre was held constant at 1.3 MBTU/acre. The ethanol yield per ton of biomass was assumed to be 81 gal/ton and the extra electricity generated by the combustion of cellulose was assumed to be 0.572 kWh/gal, both in accordance with Hill et al. (2009). We also examine the fuels produced from corn stover cellulose (stover as feedstock for fuel rather than biomass source for combustion as discussed above). Agricultural data were used for stover production as discussed above and assumes additional fertilizer needed to replenish soils as a result of stover removal.

The resulting lifecycle fuel carbon intensities of the ethanol achieved by fermentation of grasses and corn stover are shown in Figure 7. Also shown in Figure 7 are the fuel carbon intensities of ethanol from forest biomass gasification and corn ethanol with stover heat, which have slightly larger fuel carbon intensities. The production of ethanol via gasification has somewhat higher emissions during the refinery portion of the lifecycle because of the default GREET assumptions regarding the net consumption or production electricity. In all fermentation processes it is assumed that refineries are net generators of electricity thus displacing electricity produced by others. Because the electricity generation mix in MN is dominated by coal, the credits received by displacing electricity generation in MN are greater than if the electricity mix was less coal intensive. In all cases the fuel carbon intensities are substantially lower than corn ethanol as it is produced today, 47-89% below the MN production weighted average. While the fuel pathways show in Figure 7 do not represent all possible fuel pathways, or even the best fuel pathways, they do indicate that fuel pathways such as these can achieve lower fuel carbon intensities, which is necessary for the successful implementation of any low carbon fuel standard.

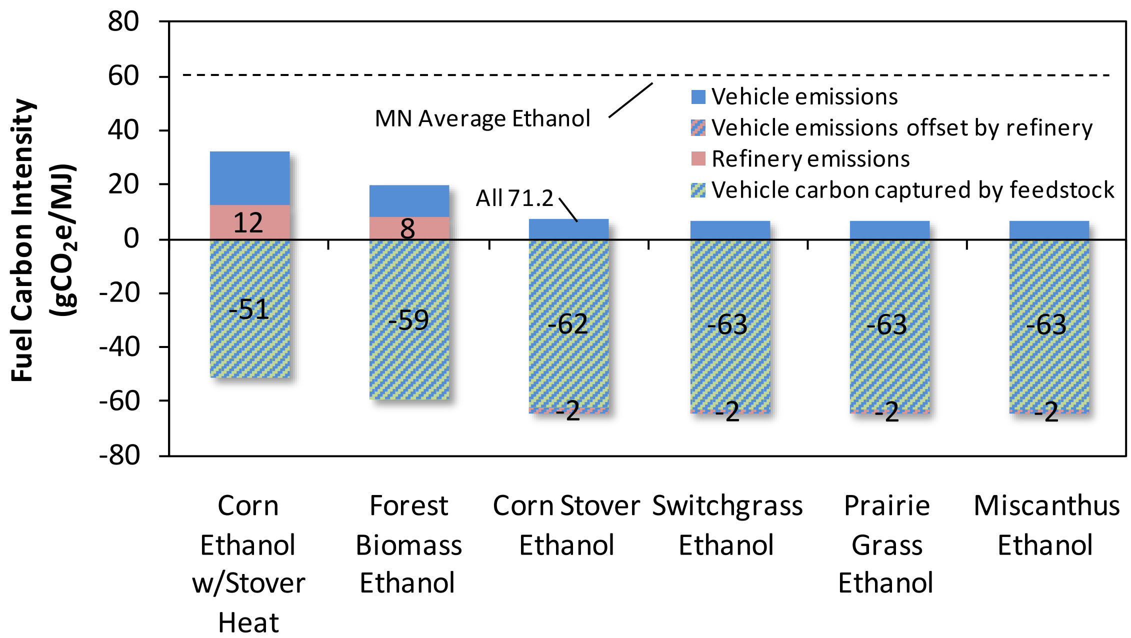


Figure 7: Lifecycle fuel carbon intensity of MN corn ethanol produced with corn stover heat via fermentation, ethanol from forest biomass via gasification, ethanol from corn stover via fermentation, ethanol from switchgrass via fermentation, ethanol from prairie grass via fermentation and ethanol from miscanthus via fermentation.

Liquid Hydrogen

Using hydrogen as a transportation fuel has received attention because it is one of the few fuels that have zero tailpipe emissions when used to power hydrogen fuel cell vehicles, where the only byproduct from hydrogen use is water. While the tailpipe emissions are essentially zero from hydrogen vehicles, the upstream emissions from hydrogen production can be significant. As shown in Table 5, the modeled upstream feedstock emissions from hydrogen are significant when electricity is used to produce hydrogen via electrolysis at decentralized fuel facilities. For MN hydrogen production via electrolysis all other GREET inputs remained the same while the ratio of electricity production facilities was modified to match the MISO values as discussed previously. In MN the use of electricity to produce hydrogen results in significantly higher modeled emissions because the electricity in MN is roughly 25% more CO_2 intensive than the national average due to the high use of coal for generation. While the modeled GHG emissions from electrolysis using grid electricity is extremely high, the production of hydrogen from localized nuclear power plants using high temperature gas reactors (HTGR) has low modeled emissions because of the low GHG emissions from nuclear energy. The emissions reported in this table on a per MJ basis should not be compared directly to the emissions of other liquid fuels due to the inherent difference in drivetrain efficiency between internal combustion engines and fuel cell vehicles. Therefore, an adjusted total is given in Table 5 which takes into account the inherent efficiency of fuel cell vehicles which are approximately twice as efficient when compared to internal combustion vehicles (Farrell, 2007). After adjustment the hydrogen produced via electrolysis remains one of the most GHG intensive fuels studied in this report, while hydrogen produced via nuclear HTGR is one of the lowest GHG emission fuels. These results highlight the importance of analyzing fuels based on the entire lifecycle which can result in significantly different emissions for the same fuel.

Table 5: Lifecycle greenhouse gas emissions from hydrogen production by electrolysis and nuclear high temperature gas reactor (HTGR).

	Fuel Carbon Intensity (gCO_2e/MJ)				
	Feedstock	Refinery	Vehicle	Total	Adjusted Total*
US Liquid H_2 Decentralized Electrolysis	405	0	0	405	195
MN Liquid H_2 Decentralized Electrolysis	520	0	0	520	249
Liquid H_2 Central Nuclear (HTGR)	5	2	0	8	4

* The adjusted total reflects the inherent difference in drivetrain efficiency between hydrogen vehicles and typical Otto-cycle engines with an efficiency factor of 0.48.

Electricity as a Transportation Fuel

In addition to liquid fuels, many within the auto industry are looking towards electricity as a way to power vehicles (Kromer and Heywood, 2007). To compare electricity to liquid fuels it is necessary that the full lifecycle emissions from the production of electricity be calculated in the same manner as for liquid fuels. As discussed previously, the mix of power plants that supplies energy to the electrical grid largely determines the overall GHG emissions associated with the electricity that would ultimately be consumed by vehicles. In addition to the overall mix of power plants, the time of day also impacts what electricity sources are being used to produce the actual electricity that is being used to charge vehicles (Simpson, 2006; Stephan and Sullivan, 2008). These studies have shown that depending on the time of day in which vehicles are charged there can be different emissions associated the electricity, *e.g.* vehicles charged at night when there is little energy use receive electricity supplied by the base load suppliers, which are often nuclear and coal. As shown in Figure 8, the GHG emissions associated with electricity vary depending on what power plant is supplying the power. As shown, the mix of electricity for MN is significantly higher than the US, due in large part to its heavy reliance on coal. Therefore, in order to reduce GHG emissions in the transportation sector, reductions in the carbon content of electricity may be important if electricity is used to power vehicles in the future.

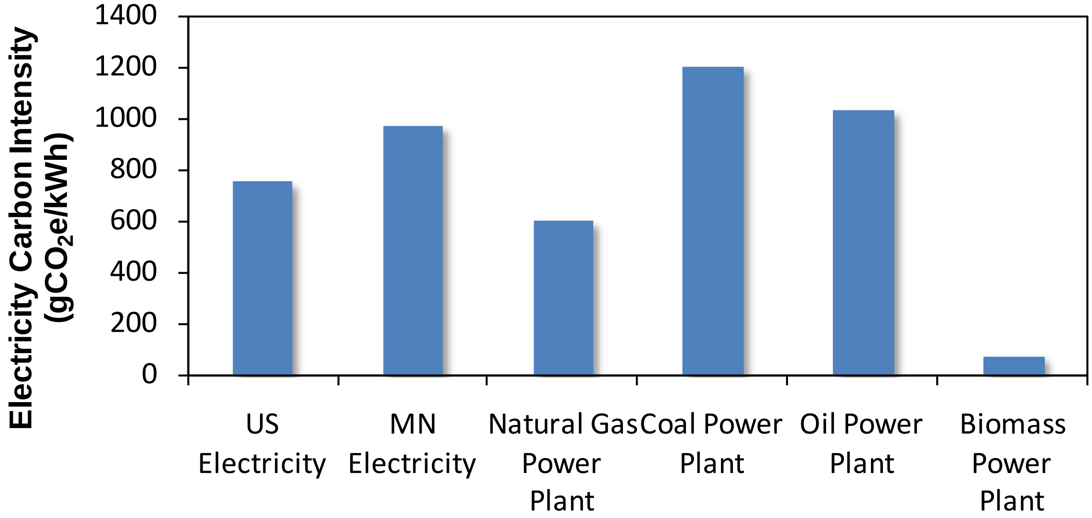
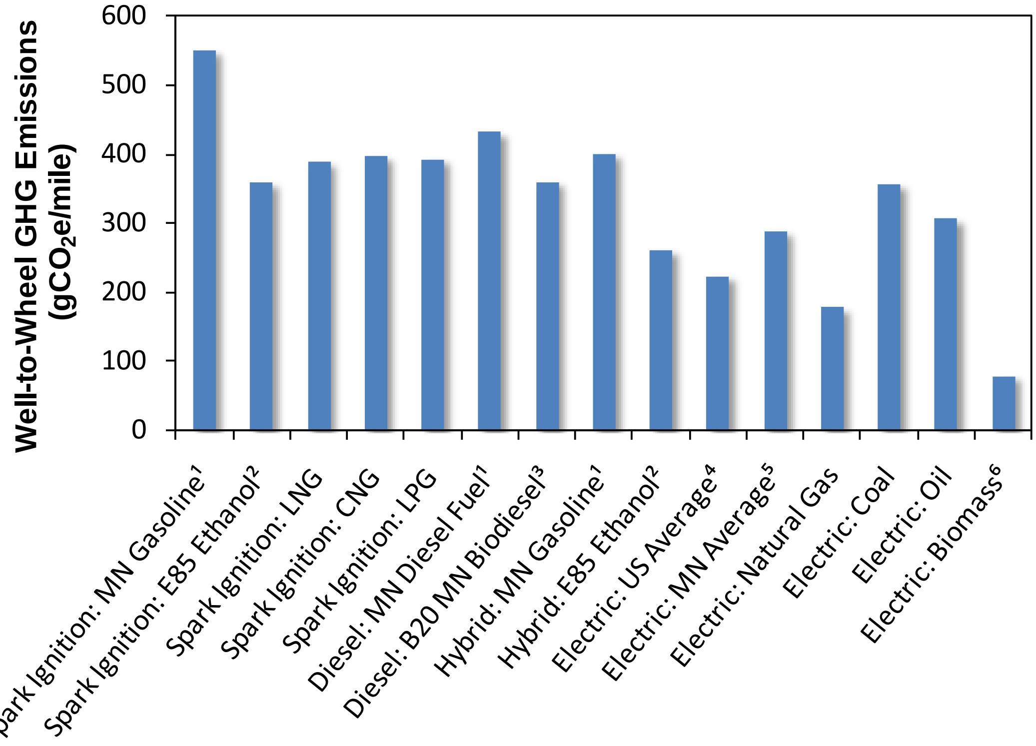


Figure 8: Lifecycle carbon intensity of electricity for both the US and MN mix as well as natural gas, coal and oil power plant.

While Figure 8 summarizes average GHG emissions associated with electricity per unit of energy (kWh), direct comparisons of electricity to liquid fuels on this basis are incorrect due to inherent differences in the fuels. Electricity has already been converted to work in the power plant where losses in energy were incurred to turn the feedstock (coal, natural gas, etc.) into power. However for liquid fuels the conversion of heat to work takes place inside the vehicle engine, leaving a direct comparison of electricity and liquid fuels invalid on a per energy unit basis. Therefore, electricity should be compared with other fuels on a well-to-wheels basis, which takes into account the inherent efficiencies of the different drivetrains. Drivetrain efficiency is not only important for electricity, it should be used to reflect inherent differences when specific fuels are used in engines that have distinctly different efficiencies when compared to a typical spark ignition (SI) engine that runs on gasoline. Drive train efficiency factors, which give the increased efficiency of other engines as compared to a gasoline engine are given by Farrell et al. (2007) for electricity and diesel engines are 5.0 and 1.3 respectively. Therefore, differences in vehicle mileage can approximated for the same vehicle with different drivetrains, *e.g.* a 30 mile per gallon vehicle with an Otto cycle engine running on gasoline would roughly be a 39 mile per gallon vehicle with a diesel engine. Additionally, a vehicle with a gas-electric hybrid engine can be compared to traditionally gasoline engines by using the efficiency factor of 1.4 as reported by Simpson (2006).

Using the efficiency factors discussed above, well-to-wheels vehicle emissions were calculated for several fuel-vehicle combinations based on a vehicle that achieves a mileage efficiency of 22.8 miles per gallon with an Otto cycle engine (Simpson, 2006). As shown in Figure 9, the full lifecycle emissions from electric vehicles are lower than typical gasoline or diesel engines running on fuels derived from fossil resources. Likewise electric vehicles have lower emissions than typical Otto or diesel engines running on E85 or B20, however hybrid electric vehicles running on E85 do have lower emissions than electric vehicles. The lowest emissions per mile possible for all vehicle-fuel combinations are an electric vehicle running on electricity produced from biomass. As reported by Campbell et al. (2009) the best use of biomass for reducing CO_2 emissions in the atmosphere is not the production of liquid fuels but displacing coal electricity generation by biomass to produce electricity.



[1]MN fossil fuels are assumed to be composed of 83% oil sands and 17% sweet crude derived fuel (Energy, 2008).
[2]The E85 ethanol was assumed to be composed of 85% ethanol and 15% of MN gasoline.
[3]The B20 biodiesel was assumed to be composed of 20% biodiesel and 80% of MN diesel.
[4]The US electricity mix is assumed to be 3% oil, 19% natural gas, 51% coal, 19% nuclear, 1% biomass and 7% other.
[5]The MN electricity mix is assumed to 79% coal, 3% natural gas, 14% nuclear and 4% other (Rose et al., 2007).
[6]The lifecycle emissions from electricity produced from biomass come from Domke *et al.*(2008).

Figure 9: Well-to-wheel emissions of fuels used in a vehicle with a mileage efficiency of 30 miles per gallon. Note: For vehicles consuming CNG, LNG, LPG, diesel and electricity as well as for hybrid electric vehicles efficiency factors of 1.03, 1.03, 1.05, 1.3, 5.0 and 1.4 respectively were used to represent the increased mileage efficiency of the different drivetrains relative to spark ignition gasoline vehicles.

Land Use Emissions

None of the fuel carbon intensities discussed above include emissions resulting from direct or indirect land use change. Direct land use emissions result from the conversion of land for the purpose of biofuel production. Indirect land use emissions arise because of land changes that occur due to the use of an existing agricultural commodity for fuel, which raises the overall price of the commodity, thereby encouraging marginal producers to cultivate previously dormant land. If land use effects are included the carbon intensities from biomass derived fuels will increase and in some cases may be greater than fuels derived from petroleum-based fuels.

GHG emissions from land use change contribute to global climate change by affecting the ability of the soil to store or release carbon as well as the ability of the surface of the land to reflect sunlight (albedo) (IPCC, 2007). While changes in surface can affect sunlight reflection, and thus climate, the release of carbon in the soil and in above ground biomass as a result of farming practices has been an area of considerable interest for both academics and policy makers over the last several years.

Studies indicate that emissions from land use changes contribute to the overall GHG emissions associated with biofuels by increasing the net amount of carbon released into the atmosphere as a result of cultivating land for biofuels. Likewise land use changes can affect the overall carbon intensities of fossil fuels if significant land conversion occurs as a result of resource extraction. Land use emissions that result from the direct conversion of land for biofuel production have received attention in the last 5 years and are more readily quantified when compared to indirect effects (de Gorter and Just, 2009; Westhoff et al., 2008). Recently, the effect of indirect land changes has also been investigated and has been shown by initial studies to be a significant contributor to the overall life cycle of ethanol (Fargione et al., 2008; Searchinger et al., 2008). Indirect land use emissions arise because of land changes that occur due to the use of an existing agricultural commodity for fuel, which raises the overall price of the commodity, thereby encouraging marginal producers to cultivate previously dormant land. Because such effects are a result of changes in the worldwide economy, global economic and agricultural models are required to calculate such impacts. While developing a global economic model is beyond the scope of this project models developed by others can be used to compare what the possible emissions associated with indirect land use are. As shown in Table 6, emissions values were gathered to compared the land use emissions from of several recent studies examining worldwide corn ethanol production. As indicated the first study published by Seachinger et al. (2008) calculated that emissions were 104 gCO_2e/MJ, which is more than all other emissions of the corn ethanol lifecycle combined. More recent studies have lowered the estimated emissions to 20-30 gCO_2e/MJ, and highlight the importance of factors such as assumed corn yield rates on newly converted lands, fertilization rates, future yield growth, and coproduct credits for DGS, among others. The authors of all of these analyses emphasize the uncertain nature of land use emissions and that disagreements exist to whether land use changes are quantifiable. Most researchers agree that while land use change emissions are highly uncertain, there omission in a lifecycle analysis of fuels can lead to results that do not accurately depict the true nature of greenhouse gas emissions from transportation fuels.

Table 6: Land use emissions for corn ethanol from different studies.

	Ethanol (gCO_2e/MJ)	Notes
Searchinger et al. 2008[1]	104	Emissions based on an increase of 14.8 billion gallons ethanol and 26.7 million acres of land use
California (CARB) 2009[2]	30	Emissions based on an increase of 1.174 billion gallons ethanol and 1.92 million acres of land use
Tyner et al. 2010[3]	14-21	Emissions based on an increase of 0-15 billion gallons ethanol and 1.09-3.81 million acres of land use
EPA Modeling for EISA[4]	22-49	Emissions based on an increase of ethanol production to meet EISA 2022 standards with a 30 year time horizon

[1]Searchinger et al. reported their results in terms of a 55.92 billion liter increase in ethanol production which resulted in a 10.8 million hectare change in global land use (Searchinger et al., 2008).
[2]The emissions based on analysis to meet the California low carbon fuel standard (CARB, 2010).
[3]Simulated global land use changes due to the US ethanol production: with yield and population growth after 2006 (Tyner et al., 2010).
[4](EPA, 2010)

In the present study we did not have sufficient data to identify the contributions of individual fuels to model worldwide direct and indirect land use emissions. Rather, we sought to model what land use emissions would occur within MN as a result of a policy change. As discussed in the synthesis report, the policy model was used to calculate the quantity and mix of transportation fuel that resulted from a specific policy. These fuel demands were then input into the agricultural and economic model to examine the amount of land required in MN to supply the biomass needed for biofuel production as a result of a specific policy. Land use changes from the economic model were then used to model the quantity of emissions that resulted from shifting land use from dormant to crop production as a result of different policies.

For our analysis we examined two scenarios, a reference scenario in which there is no legislation regulating the carbon content of fuels and one in which a low carbon fuel standard is enacted. The resulting change in fuel demand for each policy scenario was calculated using the policy linkages model as shown in Figure 14 (to be verified in the other reports once they are finalized) of the policy modeling report associated with this study. The fuel demands were input into the agricultural and economic model, which calculated the land required to produce biomass for each scenario’s fuel mix (see synthesis report and other appendices for further detail). In order to model the change in land use required to supply all of MN’s fuels, we used results from the agricultural and economic model shown in Table B of the agriculture economic model from this study which sought to keep grain exports constant, so that MN would not produce more biofuels by shifting grain production to other states. With these constraints the economic model would not produce results that met the biodiesel production while maintaining grain exports, and therefore grain exports were held constant while biodiesel fuel was allowed to be imported from other states to meet the demand. To calculate the land required to produce biodiesel to import into the MN market, the same soybean and biodiesel yield rates were assumed for non-MN biodiesel production as in MN. The resulting change in crop production from 2010 to 2030 is shown in Table 7. The change in crop production is greater for the LCFS case than the reference scenario for MN corn and non-MN soybeans while the MN wheat and MN soybeans are the same. The change in land use is greatest for soybean production outside of MN due to unmet demand for biodiesel within the state.

To calculate the emissions that result from the land use change as a direct result of MN fuel policy, a total carbon release of 49 $MgCO_2e$/acre was calculated based on work by Hill et al. (2009), which assumes a total sequestration of 2.0 and 11.4 Mg/acre for root and soil sequestration respectively over a 50 yr span of prairie growth. As indicated in Table 7, the resulting emissions from land use are greater for the LCFS when compared to the reference due a larger number of acres in crop production. The emissions are compensated for by the lower cumulative emissions by the combustion of transportation fuels, which is lower for the LCFS than the reference scenario. The resulting total emission remain lower for LCFS policy scenario when compared to the reference scenario indicating that if land use change emissions are included within such a regulatory framework total transportation emissions can still be lowered.

Table 7: Land use change emissions for the reference and low carbon fuel policy.

	Change in Crop Production from 2010 to 2030 (1000 Acres)			
	MN Corn[1]	MN Soybeans[1]	MN Wheat[1]	US Soybeans[2]
Reference	404	162	-5	3,053
LCFS	952	162	-5	3,398
	Cummulative 2030 Emissions (MMTons CO2e)			
	MN Fuel[3]	MN Land	US Land	Total
Reference	920	28	151	1,098
LCFS	862	55	168	1,085

[1] Data from Table B of agriculture study associated with this report.
[2] Values calculated based on the agricultural model results shown in Table B which indicated that the 2030 MN imports of biodiesel will be 715 and 799 million liters for the reference and LCFS policy, respectively.
[3] Data from Figure 18 of the policy report associated with this study.

Fuel Shuffle

In addition to impacting fuels within MN, a low carbon fuel standard may also affect the fuels that are consumed in other states, particularly if those states do not enact similar low carbon fuel policies. One possible outcome of such a scenario is that fuels with low carbon intensities are brought from other states to supply MN and higher carbon fuels are then consumed by other states, thus shifting the fuels from one state to another via leakage. This fuel shifting has the possibility of increasing the carbon content of fuels if fuels are transported further as a result of such a policy. The result of a 100% leakage is that the overall carbon intensity of all fuels consumed over multiple states remains the same with an increase in energy use and emissions due to additional transportation. To model the emissions that may result from fuel shifting, we investigated an extreme scenario where both crude oil and gasoline from the Gulf of Mexico are piped up to MN to replace Canadian oil sands crude that are in turned piped down to Louisiana (LA) for consumption. The total transportation distance is estimated to be 1400 miles from MN to LA for each mode of transportation.

As shown in Table 8, the energy use and emissions for fuel shifting varies by transportation mode. Also, there is little difference with regards to energy use and emissions whether the crude oil itself is transported and then refined or the refined fuel, such as gasoline, is transported, assuming the same mode of transportation. The trucking of fuel is by far the most energy intensive, requiring nearly 5% of the total energy delivered to transport the product. However, pipelines are the way most crude oil is transported into and out of MN and require less than 1% of delivered energy to transport the fuel. The total GHG emissions associated with each of the modes vary from 0.9 to 3.6 gCO_2e/MJ of fuel delivered. When compared to the carbon intensities of the fuels that are likely to be impacted, sweet crude gasoline and oil sands gasoline, the emissions from shifting via pipeline transportation represents less than a 1% change in the overall carbon intensity of the fuels. This 1% increase in emissions must then be compared with the overall reduction in emissions achieved by a LCFP within MN. While not quantified within this study, a 100% leakage is not probable if a LCFP is enacted in coordination with other states. Currently, 11 states in the northeast have signed documents stating their intent to enact a low carbon fuel policy (Memorandum of Understanding, 2008). Governors of the Midwestern governors association have also expressed their interest in enacting similar legislation (Low Carbon Fuel Policy Advisory Group Recommendations, 2010). Combined with California these states would represent 45% of the fuel consumption within the US (US DOT, 2010). Regulations passed in these states would affect the marginal source of fuel, which in many cases is Canadian oil sands crude due to its higher cost for extraction and refinement. Additionally, ethanol producers are more affected by regulations in local markets as ethanol is typically shipped by truck rather than via pipelines because it is miscible with water. Shipping by truck makes the transportation of ethanol more energy intensive and expensive to transport.An LCFP may encourage increased production of low carbon fuels produced within MN, which may ultimately decrease the emissions associated with fuels that are currently exported, *e.g.* ethanol.

Ultimately, an international economic model is necessary to predict the total change in emissions as a result of fuel shifting. However by examining an extreme scenario as shown in Table 8, we have placed an upper bound to emissions that result from fuel shifting. The upper bound to these emissions would be a roughly 1% rise in overall fuel carbon intensities, but this scenario is unlikely if a LCFP is coordinated with other states.

Table 8: Calculated energy use and emissions from transportation that results from fuel shifting.

Feedstock/Fuel	Crude Oil for Use in U.S. Refineries				Federal Conventional Gasoline			
Transportation Mode	**Barge**	**Pipeline**	**Rail**	**Truck**	**Barge**	**Pipeline**	**Rail**	**Truck**
Distance (Miles, one-way)	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400
Energy Intensity (MJ/ton-mile)								
Origin to Destination	0.425	0.267	0.390	1.084	0.425	0.267	0.390	1.084
Energy Consumption (J/MJ of fuel transported)								
Total energy	17,406	11,739	16,716	46,425	17,101	11,533	16,422	45,610
Fossil energy	17,367	11,527	16,670	46,296	17,062	11,324	16,377	45,484
Coal	319	1,106	426	1,184	313	1,086	419	1,163
Natural gas	862	3,194	1,032	2,865	847	3,138	1,014	2,815
Petroleum	16,186	7,227	15,212	42,247	15,902	7,100	14,945	41,506
Total Emissions: g/MJ fuel transported								
CH4	0.001	0.002	0.001	0.004	0.001	0.002	0.001	0.004
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO2	1.395	0.866	1.236	3.441	1.371	0.851	1.215	3.380
GHG	**1.442**	**0.912**	**1.281**	**3.564**	**1.417**	**0.896**	**1.259**	**3.501**

Summary of Findings and Comparison to Other Studies and Uncertainties

A summary of the modeling results of the well-to-wheel emissions per unit of energy for MN fuels is shown in Table 9. These results highlight the great difference in emission characteristics amongst different fuels. While direct comparison of fuels that are used in different engines is not valid, it is apparent that many different lifecycle emissions are possible from MN fuels within the transportation sector. Even for the same fuel pathway significant differences in emissions can occur for different modeled parameters, as highlighted by the analysis of different MN ethanol refineries. Although the results presented within this report are the best estimates of MN fuels, there is a high degree of uncertainty for many of the inputs required for modeling the fuel lifecycle. Many of the critical inputs should be modeled as ranges rather than individual values, but often data do not exist to produce valid ranges for the model inputs. Therefore, to highlight the range of uncertainty associated with the different modeled emissions, Table 9 compares the results of this study to results of similar fuel pathways modeled by others. In some cases there is little deviation among different studies, such as conventional gasoline and diesel. The deviation in reported values is less than 10% for conventional gasoline and diesel because much is known about the process and the processes have evolved over time to a mature state. High uncertainty exists for fuels whose processes are still evolving and ones who have not yet been produced in any significant quantity. As seen, the production of hydrogen from different methods can result in a difference in GHG emissions of nearly 3 orders of magnitude and as a result the GHG emissions of hydrogen production remains highly uncertain. Ultimately, the most accurate way to measure a fuel's lifecycle GHG intensity is to model it at as local a level as possible as was done for the MN ethanol refineries.

Table 9: Summary of modeled lifecycle GHG emissions for fuels pathways modeled in this study compared to similar fuel pathways from other studies.

Production Pathways for LCA GREET Modeling of Transportation Fuels used in Vehicles Operated on Minnesota				Comparison to Other Studies (gCO_2e/MJ)					
Fuels	**Conversion**	**Feedstocks**	**Modeled Average (gCO2e/MJ)**	**Farrell, 2007 GREET**	**Farrell, 2007 LEM**	**Edwards, 2006**	**NETL, 2010**	**EPA, 2010**	**Unnasch, 2009**
Gasoline									
	MN Refining	Sweet Crude	92	92	95	86	Avg. Conv.	Avg. Conv.	Avg. Conv.
	US Refining	Sweet Crude	90				97	93	95
	MN Refining	Canadian Oil Sands	105						Can. Oil Sands
	US Refining	Canadian Oil Sands	104						110
	MN Refining	MN Specific Blend	103						
Diesel									
	MN Refining	Sweet Crude	92	91	89	86	Range	Avg. Conv.	
	US Refining	Sweet Crude	92				103 to 88	92	
	MN Refining	Canadian Oil Sands	105						
	US Refining	Canadian Oil Sands	105						
	MN Refining	MN Specific Blend	103						
Electricity									
	MN Mix of Production	MN electric grid	269						
	US Production	US Electricity	208						
	US Production	Coal	333			267			
	US Production	Natural Gas	166			126			
	US Production	Petroleum	286						
	US Production	Biomass	20	15		19			
Ethanol		*Corn*						Typical Corn	
	US Refining	US Corn grain	67	76				87 to 63	
	MN Refining Natural Gas	MN Corn grain	61					Biomass	
	14 Indiv MN Refiners	MN Corn grain	63					69 to 46	
	~With best practice	MN Corn grain	50						
		Cellulosic						Cellulosic	
	MN Refining	Switchgrass	7	15				-2 to -16	
	MN Refining	Miscanthus	7						
	MN Refining	Corn Stover	7						
	MN Gasification	Wood Residue	20	-10		22			
	MN Refining	Prairie Grass	7	7					
Biodiesel								Typical Soy	
	MN Refining	MN Soybean	17	38	60			72 to 14	
	US Refining	US Soybean	23					Algae	
	US Refining	Algae	64					65 to 25	
Compressed Natural Gas (CNG)	MN Production	Natural Gas	76	68		66			
	US Production	US Natural Gas	75						
Liquefied Natural Gas (LNG)	MN Production	Natural Gas	75			78			
	US Production	US Natural Gas	75						
Liquefied Petroleum Gas (LPG)	MN Production	Petroleum Gas	77	78	75	73			
	US Production	US Natural Gas	77						
Hydrogen				Biomass		NG Electrolysis			
	MN Electrolysis	Electricity	520	47		204			
	US Electrolysis	Electricity	405	Nat. Gas	Nat. Gas	Electrolysis			
	Nuclear HTGR	Fission	8	102	62	430			
Coal-to-Liquid Diesel (CTL)	US Production	Coal	221	214		202			
	MN Production	Coal	221						

Comparison Sources: (Edwards and Larive, 2006; EPA, 2010; Farrell and Sperling, 2007; NETL, 2008; Unnasch et al., 2009)
Note: Hydrogen from biomass and natural gas is by gasification/reforming.

Conclusions

The present study focused on calculating lifecycle GHG emissions for fuels produced and consumed in MN. Results from this study indicate that MN fuels are largely similar to fuels produced nationally with a couple of key distinctions. Traditional hydrocarbons figure prominently in the overall fuel mix, accounting for over 95% of transportation fuels, but unlike in other parts of the country 83% of fuels are derived from Canadian oil sands. Therefore the cumulative emissions from the petroleum fuel mix are higher than the national average. Biofuels are also distinct within MN, as the state has a large production capacity for both biodiesel, 65 million gallons, and ethanol, 1,117 million gallons. Results from the MN LCA of biofuels indicates that the GHG emissions from ethanol are lower than the national average of ethanol production as a result of higher than average crop yields, lower fertilization rates and dominance of natural gas fired ethanol refineries. Likewise GHG emissions from MN biodiesel production are slightly lower than the national average and represent the lowest emissions of any fuel currently produced in MN.

Analysis of cumulative GHG emissions of possible future fuels that may be produced within MN indicate that substantially lower carbon fuels are technologically feasible and will likely be produced if a structure is established that incentivizes low carbon fuels and/or penalizes high carbon fuels. Corn ethanol production is likely to continue to reduce GHG lifecycle emissions through improvements in refinery and farming practices. In particular the displacement of fossil fuels with biomass to provide process heat for the ethanol refiners as well as cultivating corn with less nitrogen fertilizer can substantially reduce the overall emissions of corn ethanol. Fuels produced from biomass such as grasses and forestry products have low associated GHG emissions and are excellent alternatives for a state with many biomass resources such as MN. The future use of electricity to power vehicles will be a viable option for reducing GHG emissions from the transportation sector once electric vehicles are available. The use of biomass to produce electricity and then power vehicles represents a low cost way of turning biomass to power for vehicles and can be implemented within existing power plants.

The GHG emissions associated with land use changes remain an important area of ongoing research. Recent studies have shown that emissions are less than initially calculated, but remain a significant portion of the lifecycle. Emissions as a result of fuel shifting among states appear to be minimal with the overall decrease in emissions as a result of a LCFP likely outweighing any increase as a result of fuel shifting.

References

Azar, C., Lindgren, K., Andersson, B.A., 2003. Global energy scenarios meeting stringent CO2 constraints--cost-effective fuel choices in the transportation sector. Energy Policy 31, 961-976.

Boies, A., Hankey, S., Kittelson, D., Marshall, J.D., Nussbaum, P., Watts, W., Wilson, E.J., 2009. Reducing Motor Vehicle Greenhouse Gas Emissions in a Non-California State: A Case Study of Minnesota. Environmental Science & Technology 43, 8721-8729.

Campbell, J.E., Lobell, D.B., Field, C.B., 2009. Greater Transportation Energy and GHG Offsets from Bioelectricity Than Ethanol. Science 324, 1055-1057.

CARB, 2010. LCFS Lookup Tables. California Air Resource Board Low Carbon Fuel Standard, http://www.arb.ca.gov/fuels/lcfs/121409lcfs_lutables.pdf, Sacramento, CA.

Ciborowski, P., 2007. Minnesota GHG Emissions and Other Transportation Indicators 1970-2004, MS Excel spreadsheet. Minnesota Pollution Control Agency, St. Paul, MN.

de Gorter, H., Just, D.R., 2009. The Welfare Economics of a Biofuel Tax Credit and the Interaction Effects with Price Contingent Farm Subsidies. American Journal of Agricultural Economics 91, 477-488.

Domke, G.M., Ek, A.R., Becker, D.R., Espeleta, J.F., D'Amato, A.W., Reich, P.B., Suh, S., Kilgore, M.A., Current, D.A., Hoganson, H.M., Burk, T.E., Blinn, C.R., 2008. Assessment of Carbon Flows Associated with Forest Management and Biomass Procurement for the Laskin Biomass Facility, Staff Paper Series No. 198. Department of Forestry Resources, College of Food, Agricultural and Natural Resource Sciences, University of Minnesota, St. Paul, Minnesota.

Economic Research Service, 2006. Soybean Nutrient Use and Farm Management Data. USDA, Washington, DC.

Edwards, R., Larive, J.-F., 2006. Well-to-wheels Analysis of Future Automotoive Fuels and Powertrains in the European Context: Well-to-Wheels Report. EUCAR, CONCAWE and JRC/IES.

Energy, U.S.D.o., 2008. DOE Runs of CAD Crude, in: Administration, E.I. (Ed.), Washington, D.C.

EPA, 2010. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis, in: EPA-420-R-10-006 (Ed.), Washington D.C.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land Clearing and the Biofuel Carbon Debt. Science 319, 1235-1238.

Farrell, A., Sperling, D., 2007. A Low-Carbon Fuel Standard for California Part 1: Technical Analysis. University of California, Berkeley California.

Graham, R.L., Nelson, R., Sheehan, J., Perlack, R.D., Wright, L.L., 2007. Current and Potential U.S. Corn Stover Supplies. Agronomy Journal 99, 1-11.

Hill, J., Polasky, S., Nelson, E., Tilman, D., Huo, H., Ludwig, L., Neumann, J., Zheng, H., Bonta, D., 2009. Climate change and health costs of air emissions from biofuels and gasoline. Proceedings of the National Academy of Sciences 106, 2077-2082.

Hoskinson, R.L., Karlen, D.L., Birrell, S.J., Radtke, C.W., Wilhelm, W.W., 2007. Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biomass and Bioenergy 31, 126-136.

IPCC, 2007. 4th Assessment Report, Working Group I. IPCC.

Kelly, N., 2007. Ethanol Benchmarking and Best Practices: The Production Process and Potential for Improvement, in: MnTAP (Ed.). http://www.mntap.umn.edu/MnTAP%20Ethanol%20Report.pdf, Minneapolis, MN.

Kromer, M.A., Heywood, J.B., 2007. Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet. Masechusetts Institute of Technology, Laboratory for energy and the environmet publication No. LFEE 2007-03 RP.

Lardon, L., Helias, A., Sialve, B., Steyer, J.-P., Bernard, O., 2009. Life-Cycle Assessment of Biodiesel Production from Microalgae. Environmental Science & Technology.

Larson, E.D., 2006. A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. Energy for Sustainable Development, 109-126.

Liska, A.J., Yang, H.S., Bremer, V.R., Klopfenstein, T.J., Walters, D.T., Erickson, G.E., Cassman, K.G., 2009. Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn-Ethanol. Journal of Industrial Ecology 13, 58-74.

Low Carbon Fuel Policy Advisory Group Recommendations, 2010. Energy Security and Climate Stewardship Platform for the Midwest, http://www.midwesterngovernors.org/Publications/LCFPagDoc.pdf.

Memorandum of Understanding, 2008. Northeast and Mid-Atlantic Low Carbon Fuel Standard, http://www.nescaum.org/documents/lcfs-mou-govs-final.pdf/

Minnesota Session Laws Chapter 52 S.F.4., 2004. An act relating to agriculture; increasing minimum ethanol content required for gasoline sold in the state; establishing a petroleum replacement goal, section 239.791, subdivision 1, available at https://www.revisor.leg.state.mn.us/laws/?id)52&doctype)Chapter&year)2005&type)0.

National Biodiesel Board, 2009. Comprehensive Survey on Energy Use for Biodiesl Production. http://www.biodiesel.org/pdf_files/fuelfactsheets/Energy_Use_Survey.pdf, Jefferson City, MO.

NETL, 2008. Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels. DOE/NETL-2009/1346, National Energy Technology Laboratory

NOPA, 2009. TESH Committeee Recommendations to USB on National Renewable Energy Laboratory Database. http://www.nopa.org/content/stats/stats.html, Washington, DC.

NREL, 2009. US Average Annual Solar Yield.

Plevin, R.J., 2009. Modeling Corn Ethanol and Climate. Journal of Industrial Ecology.

Qi, D.H., Bian, Y.Z., Ma, Z.Y., Zhang, C.H., Liu, S.Q., 2007. Combustion and exhaust emission characteristics of a compression ignition engine using liquefied petroleum gas-Diesel blended fuel. Energy Conversion and Management 48, 500-509.

Rose, J., McCarthy, C., Collison, K., Parmar, H., 2007. Independent Assessment of Midwest ISO Operational Benefits, in: ICF International (Ed.). www.icfi.com/Markets/Energy/doc_files/midwest-iso-report.pdf, Fairfax, VA.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, M., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H., 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Changes. Sciencexpress 10.1126/science.1151861.

Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J., Walsh, M., Nelson, R., 2003. Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol. Journal of Industrial Ecology 7, 117-146.

Simpson, A., 2006. Cost-Benefit Analysis of Plug-In Hybrid Electric Vehicle Technology, in: Laboratory, N.R.E. (Ed.). U.S. Department of Energy, Golden Collorado.

Sokhansanj, S., Turhollow, A., Cushman, J., Cundiff, J., 2002. Engineering aspects of collecting corn stover for bioenergy. Biomass and Bioenergy 23, 347-355.

Stephan, C.H., Sullivan, J., 2008. Environmental and Energy Implications of Plug-In Hybrid-Electric Vehicles. Environmental Science & Technology 42, 1185-1190.

Tessum, C., Boies, A., Hill, J., Marshall, J.D., 2010. Expanding Biofuel Production: Sustainability and the Transition to Advanced Biofuels: Summary of a Workshop. Appendix E: Assessing the Sustainability of Biofuels: Metrics, Models, and Tools for Evaluating the Impact of Biofuels.

Tyner, W.E., Taheripour, F., Zhuang, Q., Birur, D., Baldos, U., 2010. Land Use Changes and Consequent CO_2 Emissions Due to US Corn Ethanol Production: A Comprehensive Analysis. Department of Agricultural Economics Purdue University.

Unnasch, S., Wiesenberg, R., Sanchez, S.T., Brandt, A., Mueller, S., Plevin, R., 2009. Assessment of Life Cycle GHG Emissions Associated with Petroleum Fuels, Life Cycle Associates Report LCA-6004-3P, Prepared for New Fuels Alliance.

US DOT, 2010. Our Nation's Highways: 2010, Federal Highway Administration, http://www.fhwa.dot.gov/policyinformation/pubs/pl10023/fig5_2.cfm.

USDA, 2008. Agricultural Statistics, in: National Agricultural Statistics Service (Ed.), Washington DC.

Wang, M., 1999a. GREET 1.5 - Transportation Fuel-Cycle Model, Volume 1: Methodology, Development, Use, and Results. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory.

Wang, M., 1999b. GREET 1.5 - Transportation Fuel Cycle Model, Volume 2: Appendices of Data and Results. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory.

Westhoff, P., Thompson, W., Meyer, S., 2008. Biofuels: Impact of Selected Farm Bill Provisions and other Biofuel Policy Options, in: Series, F.-M.R. (Ed.).

Yang, H.-H., Chien, S.-M., Cheng, M.-T., Peng, C.-Y., 2007. Comparative Study of Regulated and Unregulated Air Pollutant Emissions before and after Conversion of Automobiles from Gasoline Power to Liquefied Petroleum Gas/Gasoline Dual-Fuel Retrofits. Environ. Sci. Technol.

Yanqun, L., Mark, H., Nan, W., Christopher, Q.L., Nathalie, D.-C., 2008. Biofuels from Microalgae. Biotechnology Progress 24, 815-820.

Minnesota
Low Carbon Fuels Standard Study

Policy Interactions Modeling

Contract No. B24112

University of Minnesota

Policy Interactions Modeling Research Team:

Ethan Warner, National Renewable Energy Laboratory, Golden, CO (formerly University of Minnesota graduate research assistant)

Dane McFarlane, Great Plains Institute, Minneapolis, MN (formerly University of Minnesota graduate research assistant)

Steven J. Taff, Department of Applied Economics, University of Minnesota (principal contact)

June 2011

Prepared for:

Minnesota Department of Commerce

Table of Contents

List of Figures

List of Tables

Overview

A low carbon fuels standard (LCFS) would require any person producing, refining, blending, or importing transportation fuels in Minnesota to reduce these fuels' average carbon intensity (AFCI), measured across the full fuel cycle: feedstock extraction, production, transport, storage, and use. An LCFS is expected to lower overall emissions from the transportation fleet.

Under a Department of Commerce contract, the University of Minnesota investigated and developed modeling and analytical frameworks with available data in order to compare the greenhouse gas, economic and environmental implications of various low carbon fuel standards (LCFS) policies for vehicles operated on Minnesota public roads. The present report provides findings of work performed for the policy modeling portion of the project.

Funding from the Commerce Department contract enabled the University to develop the transportation fuels components of the ECS model: vehicle demand growth, fuel economy standards, costs and prices, fuel production infrastructure, transportation life cycle emissions include drive train efficiency factors, federal RFS and national fuel prices. The policy model used best available data for assessing effects of a low carbon fuel standard on the fuel production pathways shown in Table 1. The table also shows how the pathways are aggregated in some of the results discussed in this report.

The project made use of a "policy linkages" model (now named "Energy Choice Simulator", or ECS), which was developed in part under this contract. We use the desktop version of the model both to examine specific issues in LCFS design and to illustrate the range of issues that could potentially be addressed by ECS. (The desktop version of the model accompanies submission of this report and is available to the public from Department of Applied Economics, University of Minnesota upon request.) The LCFS modeled in this project applies to all transportation fuels currently used in Minnesota, including electricity and natural gas.

Data and exogenous policy assumptions, developed through a thorough review of the literature, consultations with state and federal agency personnel, and continued interaction with the Technical Assumptions Review Committee (TARC) associated with this project, are detailed in the References section and in Appendix B. A previous advisory committee, assembled by the University as part of pre-contract research on an LCFS, met once in 2008, but has not been convened subsequently.

Investigation revealed a wide range in data quality and availability. For example, Ethanol's production costs and GHG emissions have been studied and published far more than have those of petroleum fuels, especially oil sands. Certain data elements were found to be so uncertain—whether because there is no existing technology or because the policies are under active research—that they were not usefully examined in this section of the study. Many of the data elements that are presently unknown or known only within extremely wide bounds will eventually be estimated with more certainty, at which time they might be usefully enfolded into the ECS model. We do not include an indirect land use change element in our greenhouse gas accounting scheme. Also, data for production of "green diesel" from gasification of biomass and the so-called "hydrogen grid" was found to be so uncertain that they could not be usefully included in the policy model at this time. The fuel pathways included in analysis are provided in Table 1.

The policy model used here is newly developed. Like all new models, it will be improved over time through the efforts of current and subsequent researchers. As such, it should be thought of as a tool for “policy exploration” and not for “policy guidance.” We urge readers not to make policy decisions based upon the specific numbers developed by the model for this report.

In general, we find that an LCFS, as modeled here, reduces overall greenhouse gas emissions relative to a no-LCFS baseline, especially after 2020. This finding holds whether or not the LCFS also governs electric vehicles on a drive-train-efficiency adjusted basis. A major reason for the post-2020 increase in emissions reduction is the modeled increase in LCFS stringency after that date. Of course, had we modeled a less-stringent standard, its effects would have been less. A greenhouse gas emissions tax could result in similar emissions reductions, although it would have different distributional consequences.

We estimate the effects of a Minnesota LCFS policy on Minnesota only. Whether or not such a state-level policy would be technically achievable at the modeled levels, or whether or not it would have net positive or negative effects on the nation as a whole are research topics beyond the scope of the present contract. Hence, although the modeling framework developed provides the means to compare implications of a wide range of LCFS options implemented in Minnesota, it is not possible for it to estimate the impact a MN LCFS would have on regional, national or global GHG emissions.

The model associated with this technical report in part relies upon LCFS emission estimates from the Greenhouse Gas Model section of this project. As noted there, a Minnesota low carbon fuel policy would work best if enacted with other states as a part of a broader coalition. Enactment of a Minnesota-only LCFS will provide an incentive for MN fuel producers to decrease emissions of their own fuels and will provide a disincentive for the use of fuels with increased carbon intensity such as fuels derived from oil sands. Leakage of higher carbon fuels into neighboring states is expected to occur when a policy is enacted unilaterally, although the GHG emission effects of increased transportation of fuels are minimal as calculated in the GHG Modeling Report. The data input assumptions used are detailed in Appendix A. It is important to note, however, that ECS allows a user to change input assumptions if they choose. In the online version of the model, this is accomplished on the Assumptions Tab (see Appendix B). In the desktop version of the model, these assumptions are directly modifiable.

The Expenditures section aggregates transportation fuels as they are actually sold in Minnesota (for the most part): as blends of gasoline/ethanol and diesel/biodiesel plus natural gas and electricity. Each year’s expenditures are calculated separately in the model; each year’s prices are based on the cost of feedstocks, conversion, distribution, and taxes in place for that year.

Table 1: Assignment of fuel pathways to reporting categories.

	Reported in Production and Emissions sections	**Reported in Expenditures section**
"Fuel Pathway"	**"Transportation Technologies"**	**"Transportation Fuels"**
Tar Sands Refinery	Oil Sands	Gasoline/Diesel
North American Refinery	Refinery	Gasoline/Diesel
Foreign Refinery	Refinery	Gasoline/Diesel
EOR Refinery	Refinery	Gasoline/Diesel
Coal CTL	Coal to Liquids	Gasoline/Diesel
Corn Ethanol	Corn Grain Ethanol	Ethanol
Grass Ethanol	Cellulosic Ethanol	Ethanol
Crop Residue Ethanol	Cellulosic Ethanol	Ethanol
Wood Ethanol	Cellulosic Ethanol	Ethanol
Soybean Biodiesel	Biodiesel	Biodiesel
Algae Biodiesel	Biodiesel	Biodiesel
Natural Gas	Natural Gas	Natural Gas
Feedstock Adv Biodiesel	Advanced Biodiesel	Biodiesel
SNG	electricity	electricity
IGCC and CCS	electricity	electricity
Existing Pulverized Coal	electricity	electricity
New Pulverized Coal	electricity	electricity
Gas Electric	electricity	electricity
Biomass	electricity	electricity
Photovoltaic	electricity	electricity
Wind Turbines	electricity	electricity
Old Nuclear	electricity	electricity
New Nuclear	electricity	electricity
Hydroelectric	electricity	electricity

Current Federal and State Policy Context

There are several current state and federal policies that could interact with a low carbon fuel policy (LCFS). These policies can be divided into biofuel mandates, taxes and subsidies for fuels, and vehicle economy standards. Several different state and federal taxes and subsidies are currently in effect. First are state and federal fuel excise taxes. The federal excise tax on gasoline blends is 18.4 cents per gallon, on diesel blends is 24.4 cents per gallon, and state excise tax is 25.6 cents per gallon of fuel (Energy API, 2009). In 2004, President Bush signed into law H.R. 4520, the American Jobs Creation Act of 2004 (JOBS Bill), which created the Volumetric Ethanol Excise Tax Credit (VEETC) (Renewable Fuels Association, 2009). In late 2010, these biofuels subsidies allow for a tax refund of 45 cents per gallon on each gallon of ethanol blended with gasoline and 1 dollar per gallon on each gallon of biodiesel.

On top of the ethanol subsidy there is an additional 50 cent per gallon subsidy for cellulosic ethanol from the Energy Independence and Security Act of 2007 (Renewable Fuels Association, 2009). While several of these policies were not created to address greenhouse gases (GHG) or energy use in the transportation sector, they do have impacts on biofuel use and production. There is both a state and federal biofuel mandate in effect.

The state of Minnesota mandates that all gasoline fuel sold or offered for sale in Minnesota must blend at least 10% ethanol currently and 20% by 2013. For biodiesel, the requirement is that the blend increase from 2% currently to 20% in 2015. In this report, we contrast an LCFS policy regime with the alternative scenario that these 20% targets are met, assuming any necessary federal approvals will be obtained.

The federal version of the RFS requires that a certain volume of various classifications of biofuels be blended each year. There are five semi-overlapping biofuel classifications. Renewable biofuels are considered to include all fuels that would achieve a 20% emission reduction compared to the baseline GHG emissions (i.e. gasoline) on a life cycle basis. Advanced biofuels would include all fuels not derived from corn starch that can achieve a 50% reduction from baseline GHG emissions. Within this grouping there are additional specific requirements for cellulosic biofuels which must achieve a 60% reduction in GHG emissions from the baseline and biomass-based diesel fuel.

These classifications are based in part on feedstock sources for the biofuels, but also lifecycle emission scores for those fuels. The EPA uses projections of demand to produce a percentage-based blending rate to act as the standard for a given year. The end goal is 15 billion gallons of renewable biofuels and 21 billion gallons of advanced biofuels by 2022 which includes cellulosic biofuels, biomass based diesel, and some level of undifferentiated advanced biofuels (Environmental Protection Agency, 2009). These biofuel mandates directly encourage the use of particular biofuels in fuel blends which are generally considered to reduce the emission intensity (this may depend on the method of measurement) of a gallon of fuel.

The CAFE standards are intended to improve the fuel efficiency of vehicles in the fleet by mandating that the average fuel efficiency of new vehicles that weigh 8,500 pounds or less and that are sold in the US be higher than the standard. Previous CAFE standard required that the average fleet of new passenger vehicles have a fuel efficiency of 27.5 miles per gallon (MPG) and combined light trucks have a fuel efficiency of 22.2 MPG. These standards are higher than the average fuel efficiency of a vehicle in the current fleet. However, these standards (which are now more correctly referred to as the Federal Clean Car Standard) will increase to a combined 35.5 MPG by 2016 for passenger vehicles and light trucks. This is equivalent to about 39.5 MPG for passenger vehicles and 29.8 MPGs for combined light trucks. Therefore improvements in the average fuel efficiency of a vehicle in the fleet will continue to occur for the next decade, leading to reductions in consumer fuel use.

Policy Linkages Model

Our examination of the literature showed that there existed no suitable modeling framework that could be used to assess the implications of various policies on energy production, GHG emissions, and consumer expenditures in an internally consistent manner. Fortunately, a concurrent effort was underway at the Great Plains Institute to develop a "policy linkages model," now named Energy Choice Simulator, in association with the Midwestern Governors Association with financial support from the Energy Foundation and Joyce Foundation. The University policy team chose to leverage that effort by combining model-building forces. Project-funded University activities focused on the transportation fuels portion of the ECS model using Minnesota-specific data where available.

The policy model compares changes in GHG emissions and costs to consumers due to different LCFS policies compared to the state's current biofuel mandates.

Key Energy Choice Simulator assumptions and policy design variables are listed in the appendix of this document. They are also available on the Help Wiki that is part of the online version of Energy Choice Simulator.

Here is a brief description of the ECS model, drawn from the GPI explanatory materials. The Energy Choice Simulator (energychoicesimulator.com) was co-developed by the Great Plains Institute, the University of Minnesota, and Forio Business Simulations, with additional input from the World Resources Institute. The Energy Choice Simulator utilizes system dynamics programming through Ventana Systems' Vensim software to model the interaction of a wide range of federal and state energy policies. These policies, along with a multi-sector energy consumption baseline, provide a context for the simulation of supply- and demand-side economic decisions between now and the year 2050. An on-line version of the model, in which the baseline assumptions and policy combinations can be customized, is available for any user to create an extensive series of alternative scenarios (http://energychoicesimulator.com). A desktop version of the model, which requires use of the Vensim modeling software (available from Ventana Systems (www.vensim.com), is available upon request.

The Energy Choice Simulator has been used for a number of analyses in both state and regional policies. These include: a Minnesota Department of Commerce funded study at the University of Minnesota to research the impacts of a low carbon fuel policy in Minnesota; broad level policy scenario guidance for the MGA Energy Security and Climate Stewardship Roadmap; quantitative policy analysis for the MGA Bioeconomy and Transportation Advisory Group; and ongoing analysis and support for the MGA Low Carbon Fuel Standard Advisory Group.

The Energy Choice Simulator is a flexible tool that can be configured for a wide variety of energy policy analyses. As both an in-depth analysis program and a public graphical interface, the model can also be used in group settings to reach consensus on the structure and effect of theoretical energy policies.

ECS produces a projection of demand growth and capacity expansion from a baseline compiled of federal data sources and academic or industry research publications. The data sources, modeling assumptions and policy implementation programming have been reviewed by a number of MGA advisory groups as well as the Technical Assumptions Review Committee for the present project. By modeling the economic decision-making process of new plant construction, ECS demonstrates the effect that energy and climate policies have on the electric generation portfolio, liquid transportation fuel production and blending rates, consumer vehicle purchasing and driving decisions, and much more.

Using financial data on the economics of fuel plant construction and blender operation collected from a variety of industry sources, the Energy Choice Simulator projected a series of economic and GHG impacts until the year 2035. Factors such as the development of next generation fuel production capacity, annual blending rates of fuel at the consumer level, growth and transformation of the state's vehicle fleet, and the utilization of various feedstocks were tracked under a set of policy scenarios. Each scenario was developed to contain a unique combination of state and federal policies, which present likely political landscapes in which an LCFS would operate. The economic and environmental outcomes of each policy scenario modeled by Energy Choice were used as data inputs for the other project teams involved in this study.

Modeling Approach

Four LCFS policy scenarios were created and compared to a reference policy scenario. Each contains a combination of state and federal policies that present likely political landscapes in which an LCFS would operate. The scenarios are summarized in Table 2.

First, a reference policy scenario was created to reflect current and expected federal and state policies that would interact with and affect the outcomes of an LCFS. While there are additional federal and state policies that might interact with an LCFS, this study focuses on those that are the most principal policy drivers. This is a "business-as-usual" scenario that provides a baseline projection of what CO2e emissions would be with no further state policy actions.

Against this reference scenario, two variations of an LCFS were analyzed to observe the impacts of specific LCFS components. Then, to compare an LCFS to other state policy options for reducing greenhouse gases, the effects of a GHG tax (defined below) was analyzed.

The policy mixture for each scenario used in this paper was designed to explore the combined impacts of policies seeking to reduce GHGs from the transportation sector in Minnesota. To fully assess the potential synergies, conflicts, and overlap of policies with a LCFS it was necessary to create scenarios first using individual policies and then combing them. By doing this, the individual impacts of scenarios could be identified and then compared to the cumulative effect of the implementation of several policies. This allows for precise accounting of the relative contributions of each policy to environmental and economic impacts in order to properly assess how the LCFS could interact with potential policies, existing policies, and policies that will eventually be enacted.

The reference scenario serves as starting point against which the outcomes of all design scenarios are compared. It assumes continuation of federal policies currently in use and all currently proposed state and federal policies (i.e. new federal clean car standards). Two subsequent scenarios build on each of these baselines by adding one of two policies that have either been proposed in the past: a low carbon fuel standard and a GHG tax. Finally, the baseline scenarios were combined with both of these potential state policies to look at the cumulative effects of these policies.

Three specific exogenous conditions are held consistent through all scenarios. The first is the initial annual exogenous economic growth rates for vehicle miles traveled (VMT) and for vehicles purchased. For modeling purposes, we needed to make these exogenous in order for the user to be able to adjust them, rather than to adjust VMT and vehicle volume directly. However, feedback effects on demand related to fuel prices and vehicle prices are endogenous. These changes in demand are either added or subtracted from the initial demand assumption. The second is the rate of technology innovation. For example, commercial use of cellulosic ethanol plants becomes available at the same point in time in each scenario and does not change even if the user adds additional research dollars to cellulosic ethanol to speed up deployment. The last major exogenous factor is the assumed level feedstock, capital, and operation and maintenance costs. While these do vary over time, these variations are not modeled as dependent upon fuel decisions within Minnesota.

Current and Expected Federal Policies

Excise tax: The federal excise tax on gasoline blends is 18.4 cents per gallon on gasoline blends, and 24.4 cents per gallon on diesel blends. The excise tax would have minimal interaction with an LCFS except through the combined impacts of fuel price changes on consumer fuel demand.

Biofuel subsidies: Federal biofuel subsidies include a tax credit of 45 cents per gallon on each gallon of ethanol blended with gasoline, $1 per gallon on each gallon of biodiesel. An additional 50-cent-per-gallon subsidy for cellulosic ethanol will be paid if any plants come into operation.

Renewable fuels standards: The federal renewable fuel standards, including the 2009 revisions, set a goal of 15 billion gallons of renewable biofuels and 21 billion gallons of advanced biofuels by 2022; the EPA determines yearly biofuel blending rates to reach the yearly goal. This policy has the most overlap with the LCFS as biofuel blending is one option for reducing the emissions intensity of a gallon of fuel.

CAFE standards: The Federal Combined Average Fuel Economy (CAFE) standards establish an average fuel efficiency level for new vehicles produced by a single company and sold in the United States. Currently, passenger vehicles fleets must have a combined fuel efficiency of at least 27.5 miles per gallon, and light truck fleets a combined fuel efficiency of 22.2 miles per gallon. The CAFE standards will increase to a combined 35 miles per gallon by 2020 for passenger vehicles and light trucks. This policy would complement an LCFS, with the effects of lowered fuel consumption augmenting those of lowered fuel emissions intensity from an LCFS.

Clean car standards: This policy requires that the average greenhouse gas emissions of new motor vehicles each year meet a standard, currently set for 225 gCO2e/mile for passenger vehicles and 280 g/mile for light trucks by 2016. There are several ways to meet the standard including improvement in the fuel efficiency of vehicles and offering alternative vehicles such as flex-fuel vehicles.

Current and Expected State Policies

Excise tax: The current state excise tax is 25.6 cents per gallon of fuel.

Biofuel subsidies: Minnesota pays 20 cents per gallon, up to $3 million annually for ethanol produced in a facility each year.

Renewable Fuel Standards (RFS): Minnesota has established standards for renewable fuels. All diesel fuel sold or offered for sale in Minnesota must blend at least 2% biodiesel by 2005, 5% for six summer months and 2% for six winter months by 2009, 10% by 2012, and 20% by 2015; dependent upon resolution of cold weather properties of these higher blends (2009 Minnesota Statutes, Chapter 239.77); and all gasoline fuel sold or offered for sale in Minnesota must blend at least 10% ethanol by 2000 and 20% by 2013; dependent upon EPA approving a 21(f)(4) waiver certifying use of higher than 10% blends for use in all vehicle years (2009 Minnesota Statues, Chapter 239.761). . In the policy model results reported here, we compare the adoption of an LCFS with the imposition of these 20% blending requirements which assumes necessary approvals are attained.

Low Carbon Fuel Standard Design

An LCFS would reduce the average GHG emissions intensity for certain fuels from an initial level, applied at some point in the fuel lifecycle, to a lower level of emissions intensity over a specific period of time. The six main design factors are listed below.

Average GHG emissions intensity score: In the study LCFS design, the average GHG emissions intensity score for each regulated fuel based on the three main greenhouse gases (carbon dioxide, methane, and nitrous oxide) are tracked over the fuel lifecycle and aggregated into a single CO2e (Carbon Dioxide Equivalent) score, using the same procedures detailed in the GHG section of the project.

Fuels to be regulated: The LCFS in this study regulates liquid transportation fuels for all on-road cars and light trucks, including gasoline, diesel, ethanol, and biodiesel, as well as natural gas and electricity.

Initial emissions intensity level: The study LCFS design uses the 2005 level of average fuel GHG emissions intensity for Minnesota, developed by the GHG portion of the UM study, as the initial level. The initial emissions intensity level is based on a rough split of 80% oil sands and 20% sweet crude gasoline and diesel.

Point of regulation: The study LCFS design places the point of regulation at the blender, refiner, and/or importer of fuels. LCFS compliance is calculated annually by regulated firms based on emissions and fuels produced for that year.

Policy timing: The study LCFS starts with a 10% reduction by 2020, increasing linearly to a 30% reduction by 2030. All other policies are as shown in Table 2.

Inclusion of Offset and Credit Systems: The policy model does not model a larger credit market or the availability of offsets. The model estimates aggregate emission reduction, not that by individual firms.

Table 2: Scenarios examined in this report.

Scenario name	Description
Reference[1]	All current and expected Federal and State policies: Federal and State excise taxes Federal and State biofuel subsidies Federal RFS including 2009 revisions State ethanol and biodiesel RFS increasing to 20% in 2013 and 2015, respectively Federal CAFE standards (until 2011) Federal clean car standard (after 2011)
LCFS Basic[2]	Reference scenario policies, without the State 20% RFS With LCFS
LCFS with Electricity[3]	Reference scenario policies, without the State 20% RFS With LCFS Basic policies With electric utilities implicitly regulated under LCFS
GHG Tax[4]	Reference scenario policies, without the State 20% RFS With GHG tax Without LCFS

[1]Reference

The reference scenario assumes the continuation of all existing and currently in-effect state and federal policies. This includes the CAFE standards, biofuel subsidies, and state RFS mandates as outlined in Table 2

This scenario includes the current federal and state ethanol RFS of 10%, the enacted state biodiesel RFS of 20% by 2015, federal biofuel subsidies, and existing CAFE standards increasing in stringency until 2020. It also includes the more stringent state RFS for ethanol of 20% by 2013, the updated version of the federal RFS requiring various classifications of biofuels to be produced in large volumes with lifecycle emission intensity requirements, and the new clean car standard which continues the previous clean car standard goal to 2016. In the Reference case, there is no liquid fuel blend wall, in which the amount of biofuels blended into conventional fuels is limited by federal policy. Additionally, the production tax credit for wind electricity generation is not renewed after 2010.

[2]LCFS Basic

This scenario includes all policies used in the Reference scenario (above), but also includes a low carbon fuels standard. The added State 20% RFS for ethanol and biodiesel is removed. In short, the LCFS requires a 10% reduction below a 2000 average fuel GHG intensity by 2020 and a 25% reduction by 2030. The LCFS covers liquid fuels and is placed on the blender, refiner, and/or importer of fuels. Finally, LCFS compliance is calculated annually by regulated firms based on emissions and fuels produced for that year.

[3]LCFS with Electricity
This scenario includes all polices used in the LCFS Basic scenario, but also includes a GHG tax on emissions from the production of electricity used for transportation fuel. This tax is intended to mimic a policy that would bring electric vehicles into the scope of the LCFS. It increases linearly to 50 dollars per metric ton of CO2e over a ten year period starting in 2010. The emissions score for electric vehicles is adjusted for the superior efficiency of electric vehicles at converting “fuel” into vehicle miles traveled. The effect is to reduce the cost of electric vehicle operation by reducing the emissions tax paid on electricity production, compared to a policy that doesn’t make such an adjustment. This policy has two major impacts. It increases the price of electricity used for fuel and therefore has an impact on driving behavior, and it has an impact on the long term costs of electric vehicles through operation and maintenance costs.

[4]GHG Tax
A greenhouse gas tax is a tax on CO2e emissions collected from the producers of fuels (as opposed to a tax collected from consumers of fuel at the fuel pump), set at $0 in 2010 and increasing linearly to $75 per metric ton of CO2e in 2020, equivalent to an annual accumulating $3.75 per ton CO2e emissions This level was chosen in order to produce similar lifecycle emission reductions compared to an LCFS. The GHG Tax is imposed in place of the LCFS.

Overall Results

The desktop version of the Energy Choice Simulator model was used to project a series of economic and GHG impacts until the year 2035 under the four policy scenarios. The reference scenario provided a "baseline" based on annual energy and emissions data from federal agencies and a variety of other sources, as detailed in the policy interaction model summary found in the appendix.

Against this reference case, two LCFS policy variations were analyzed to observe the impact of specific LCFS components. Additionally, to compare an LCFS to other transportation policies, the effects of a GHG tax were analyzed. These analyses demonstrate how the policy model, which is available online, could be used by interested parties to examine the implications of LCFS designs not analyzed here. In all cases, the effects of the LCFS policy are contingent upon the existence of all the other federal and state policies that we assume continue as stated in this report. Users of the ECS model can explore the differential effects of each of these policies by selectively adjusting or even suppressing them.

Under each of the policy scenarios examined here, overall transportation fuel production declines for a number of years due to reduced vehicle miles because of higher fuel prices, as well as to efficiency improvements made as the vehicle fleet adopts updated federal fuel efficiency/clean car standards, which are operative in all scenarios. After 2030, however, growing demand surpasses the efficiency improvements, resulting in a steady overall fuel use increase through 2035, with most scenarios returning to a total consumption level somewhat above current levels.

As noted earlier, all assumptions and their sources are shown in Appendix B and on the online ECS documentation.

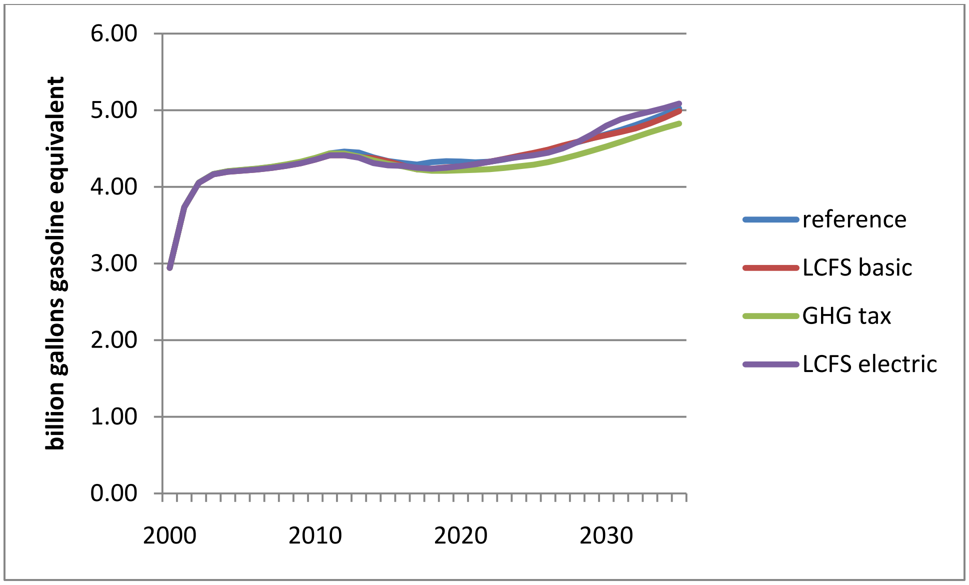


Figure 1: Total transportation fuels produced in Minnesota, by policy.

All three non-reference scenarios result in emissions roughly the same as current levels (Figure 2). These emissions are from transportation fuels consumed by Minnesota residents: we do not track here the emissions from fuels produced in the state but exported from the state.

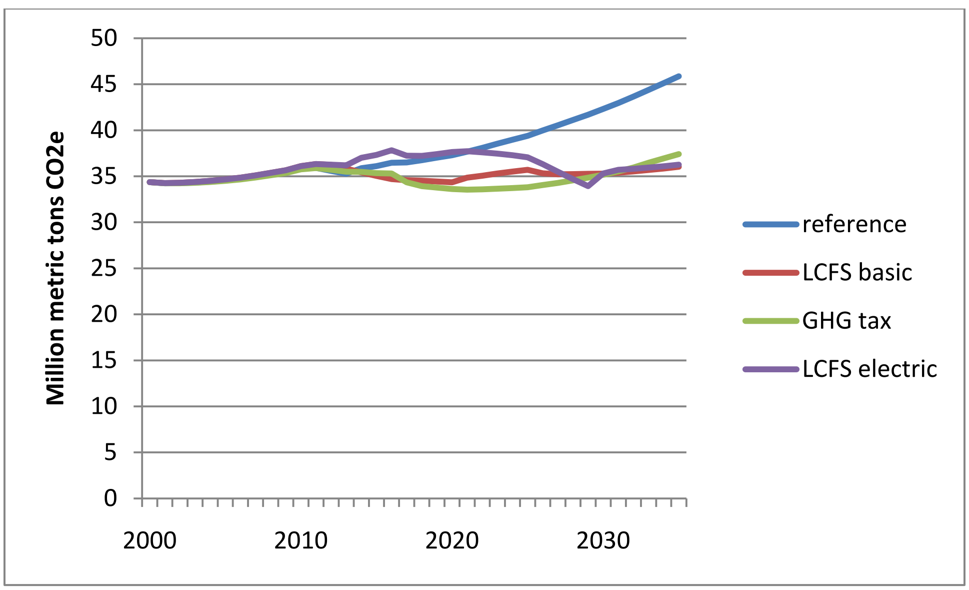


Figure 2: Total annual CO2e emissions from transportation fuels consumed in Minnesota, by policy.

Figure 3 tracks expenditures on transportation fuels by Minnesota residents. None of the carbon-reduction strategies has a large effect on expenditures, but all three result in higher expenditures than the reference scenario.

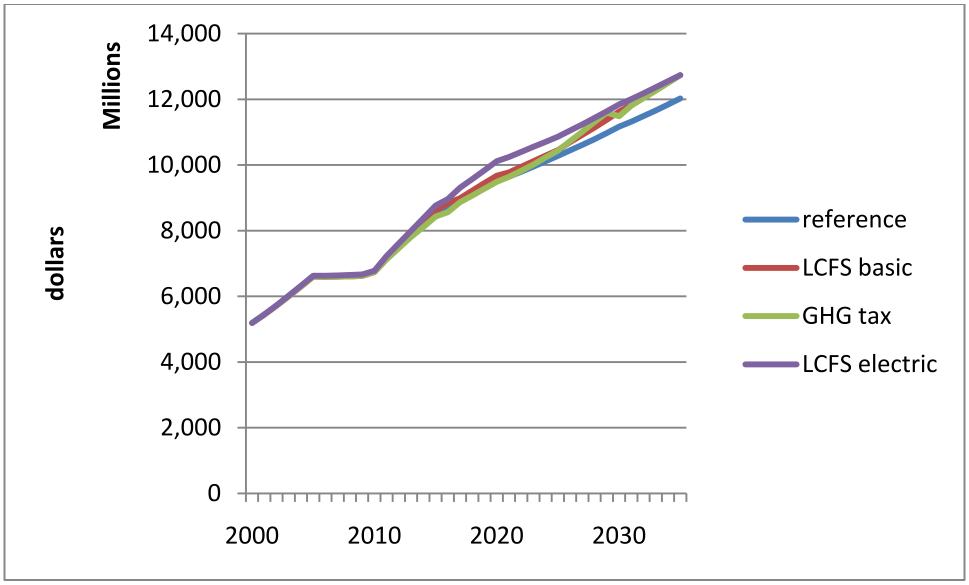


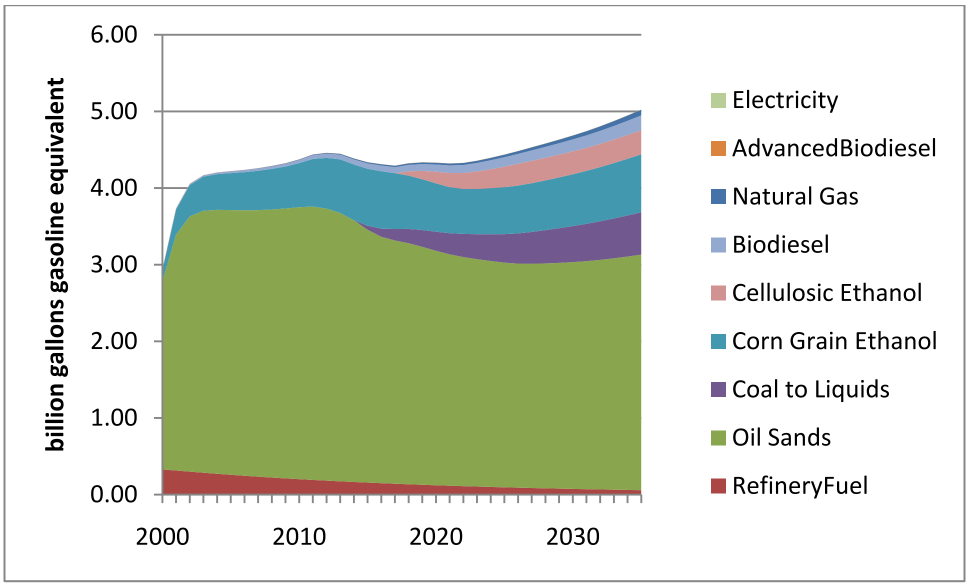
Figure 3: Total annual consumer expenditures on transportation fuels consumed in Minnesota, by policy.

Results: Transportation Fuels Processed in Minnesota, by Policy

The numbers reported in this section are transportation fuels processed by Minnesota firms to meet both in-state demand and exports. Some portion of some fuels, especially gasoline and ethanol refined in the state, are also exported. For natural gas and electricity, we report only that portion actually used for transportation purposes. All the fossil fuels shown here are imported as "feedstocks" and refined ("produced") into transportation fuels.

Reference Scenario

Figure 4 shows fuel production through the year 2035 under the Reference scenario, representing "business as usual" with no LCFS. As fuel demand increases after 2020, new production needs are met by cellulosic ethanol, coal to liquid (CTL) synthetic oil, and increased biodiesel production. Corn grain ethanol maintains a substantial level of production, while oil sands use is reduced



Charts presented in same order as legend entries.

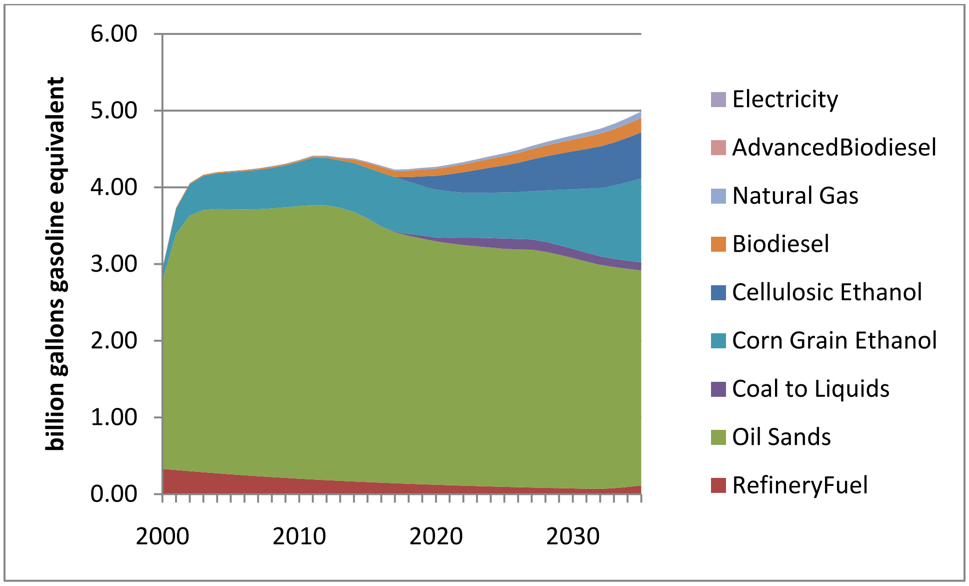
Figure 4: Transportation fuels processed in Minnesota, reference scenario.

LCFS Basic Scenario

Under this scenario, total fuel production follows much the same path as the reference scenario; however, the composition of fuel production is different. Increasing demand after 2015 is met primarily by cellulosic ethanol and biodiesel, and coal to liquid use is minor, because its emissions intensity "score" is high enough to discourage its use by blenders. Oil sands use declines through 2030. As under the reference policy scenario, corn grain ethanol use stays level throughout.

In this scenario, the RFS requires blenders to meet the basic LCFS until approximately 2020. The LCFS does not substantially affect production--compared to the RFS alone--until about 2020. After this date, the LCFS becomes more stringent than the RFS, and the production of cellulosic ethanol is increased significantly**.** Additionally, CTL production is reduced or prevented because its fuel intensity would make it difficult for a blender to meet the average fuel carbon intensity required by the LCFS.

The LCFS described above (a 10% reduction by 2020, increasing linearly to a 30% reduction by 2030) is used as the basis for the charts on the following pages. The model has the capacity for users to alter this policy design. For example, a user could examine the implications of a different set of LCFS onset dates, such as a single linear increase to a 25% level by 2025.

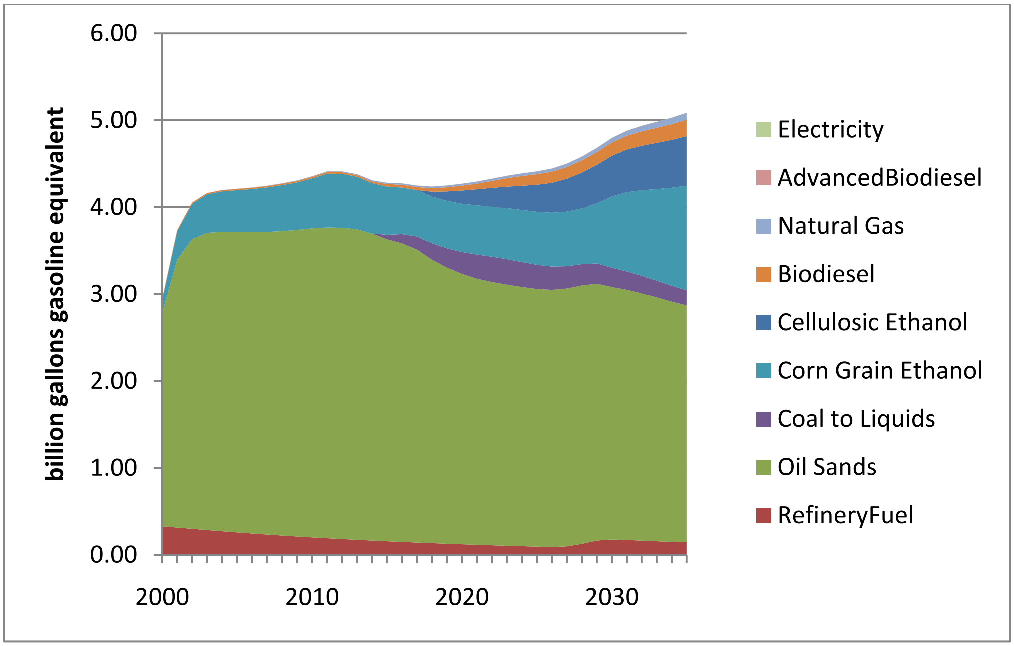


Charts presented in same order as legend entries.

Figure 5: Transportation fuels processed in Minnesota, LCFS basic scenario.

LCFS with Electricity Scenario

This is an alternative formulation of the LCFS where electricity and utilities are regulated under the LCFS, *with* an adjusted fuel emission intensity score to account for the drive train efficiency of end use vehicles. However, despite a lower score for electricity, this drive train adjustment factor does not result in much more electricity production.



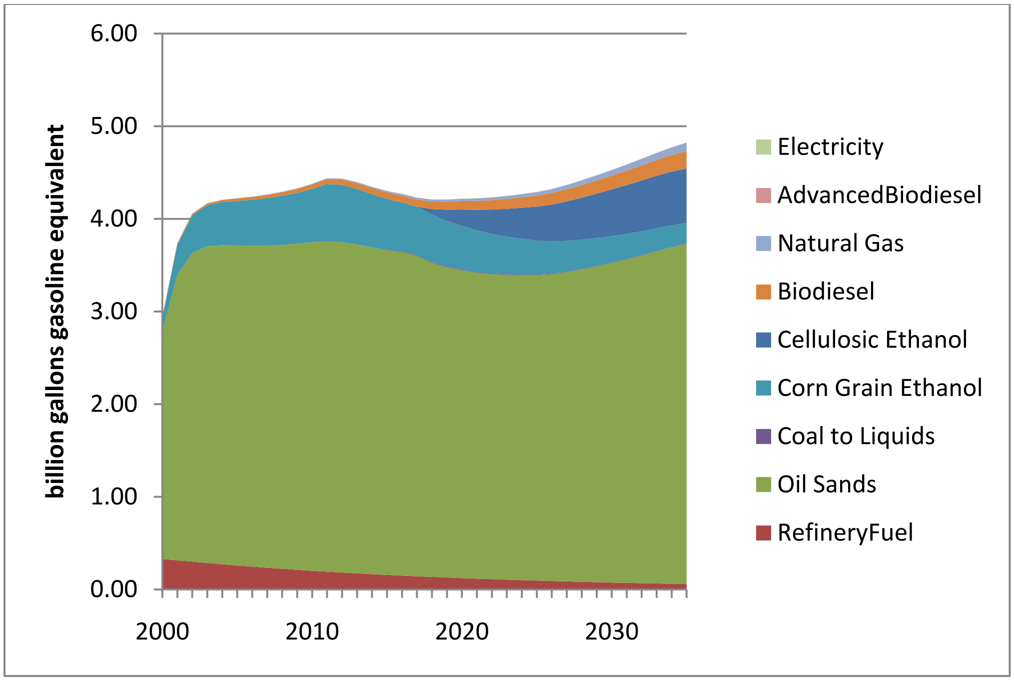
Charts presented in same order as legend entries.

Figure 6: Transportation fuels processed in Minnesota, LCFS plus electricity used in fleet scenario.

GHG Tax Scenario

This scenario combines the policies outlined in the reference case with a CO2e tax on emissions from the producers of fuels (as opposed to consumers of fuel at the fuel pump). The CO2e tax was set to a level that would produce similar life cycle emission reductions compared to the LCFS basic scenario. This required a $75 per metric ton of CO2e emission tax, starting from $0/tCO2e in 2010 and increasing linearly towards the full $75 by 2020.

Under the GHG tax, as with an LCFS, CTL is less appealing as a fuel source relative to oil sands, and corn grain ethanol is less economically efficient relative to cellulosic. As a result, the conventional biofuel classification of the federal RFS is met by primarily cellulosic ethanol.



Charts presented in same order as legend entries.

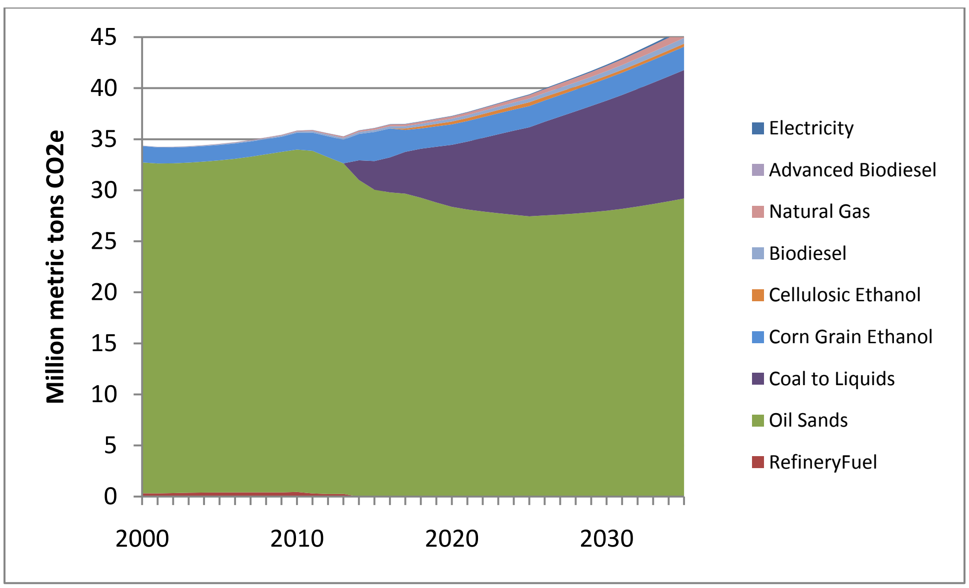
Figure 7: Transportation fuels processed in Minnesota, GHG tax scenario.

Results: Greenhouse Gas Emissions from Processing and Use of Transportation Fuels

The results of all scenarios for each type of transportation fuel (gasoline, diesel, electric and natural gas) are displayed below. For each fuel, the GHG emissions (CO2e) under each scenario are shown. These emissions totals are for those transportation fuels actually consumed in Minnesota. We do not report emissions from exports that are consumed (combusted) in other states.

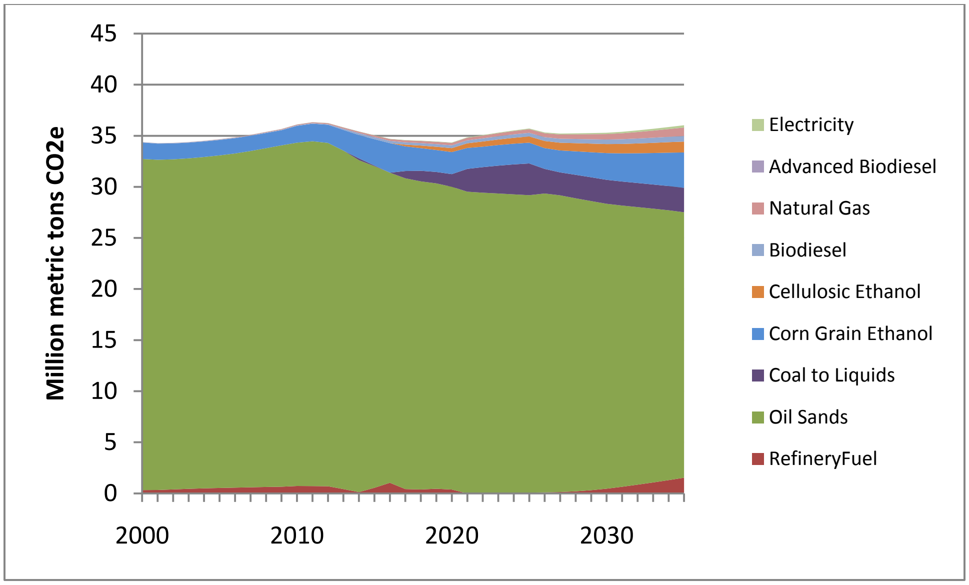
A "cleaner" fuel is not necessarily the lowest cost way for producers to comply. It could be cheaper to buy a larger quantity of a lower-priced but higher-scoring fuel. For example, if a fuel like ethanol has a considerably lower carbon intensity score than gasoline, then the blender does not need as much ethanol to combine with fossil gasoline and still meet the LCFS blended average intensity target as would be the case if the ethanol were scored higher (but still lower than gasoline). In the second situation, the ethanol producer would sell more ethanol. Faced with a choice, the blender would choose between different "types" of ethanol and choose that which best balanced price and quantity.

The charts show that all three low-carbon policies reduce total emissions, as shown above. However, the source of the emissions changes with the production mix induced by the different policies.



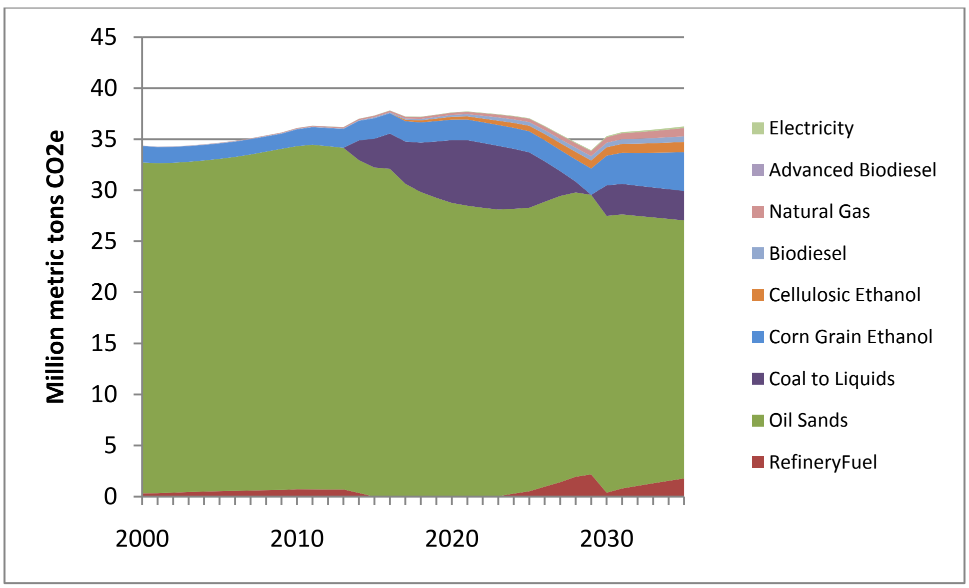
Charts presented in same order as legend entries.

Figure 8: Total emissions from fuels used in transportation, reference scenario.



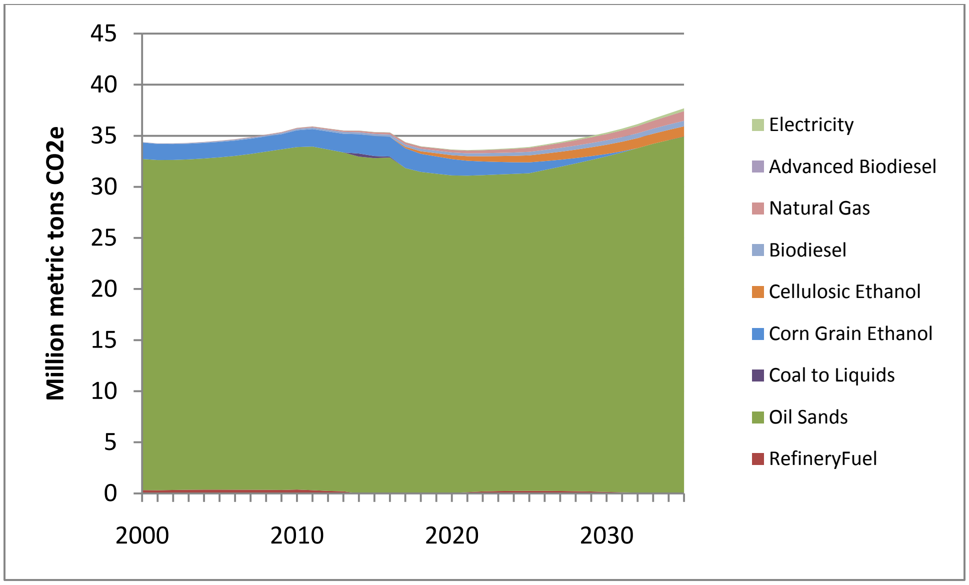
Charts presented in same order as legend entries.

Figure 9: Total emissions from fuels used in transportation, LCFS basic scenario.



Charts presented in same order as legend entries.

Figure 10: Total emissions from fuels used in transportation, LCFS plus electricity used in fleet scenario.



Charts presented in same order as legend entries.

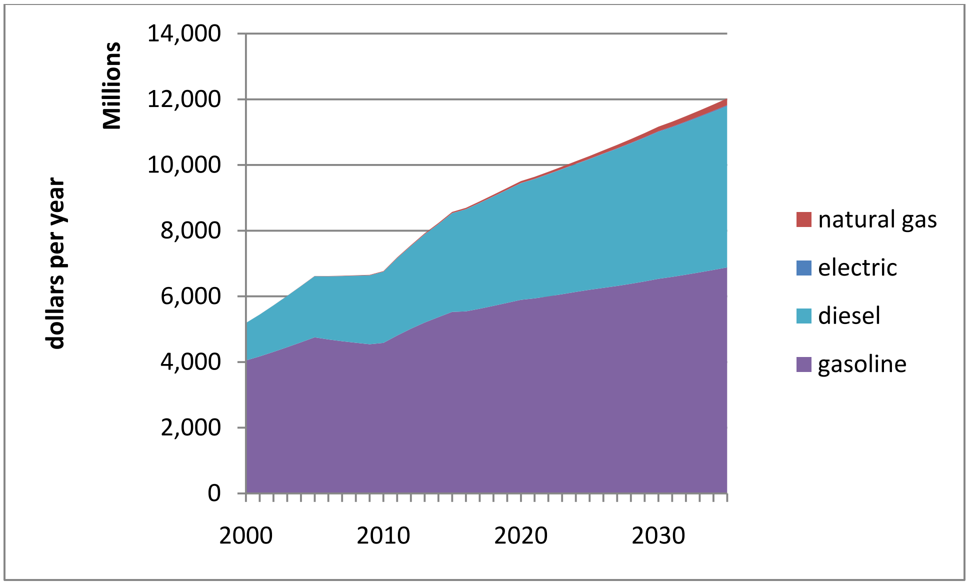
Figure 11: Total emissions from fuels used in transportation, GHG tax scenario.

Results: Consumer Expenditures on Transportation Fuels

Expenditures for each broad type of transportation fuel (gasoline, diesel, electricity, and natural gas) are displayed below. (The aggregations used for this report are listed in Table 1.)

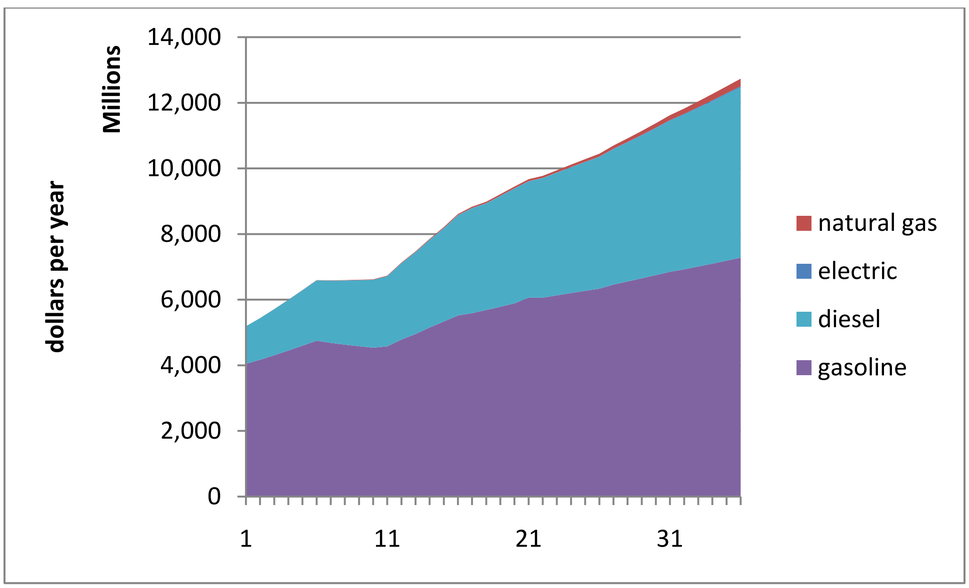
These expenditure totals are for transportation fuels actually consumed in Minnesota, paid for by Minnesota residents. We do not report here any spending on state-produced fuels that are consumed in other states, nor on expenditures by tourists from outside the state. These totals include sales and other fuel-specific taxes, plus any scenario-specific taxes and credits. Gasoline and diesel blends are adjusted to any required state renewable fuel standard in place at each year in the reference scenario. In the other scenarios, blends are 10% and 2%, respectively.

As noted earlier, this section aggregates transportation fuels as they are actually sold in Minnesota (for the most part): as blends of gasoline/ethanol and diesel/biodiesel plus natural gas and electricity. Each year's expenditures is calculated separately in the model; each year's prices are based on the cost of feedstocks, conversion, distribution, and taxes in place for that year.



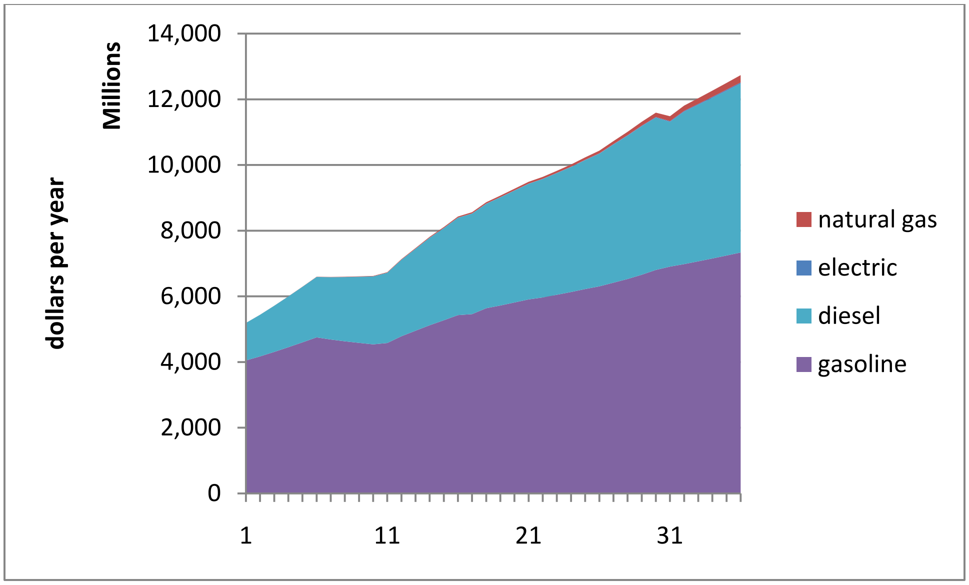
Charts presented in same order as legend entries.

Figure 12: Total consumer expenditure on fuels used in transportation, reference scenario.



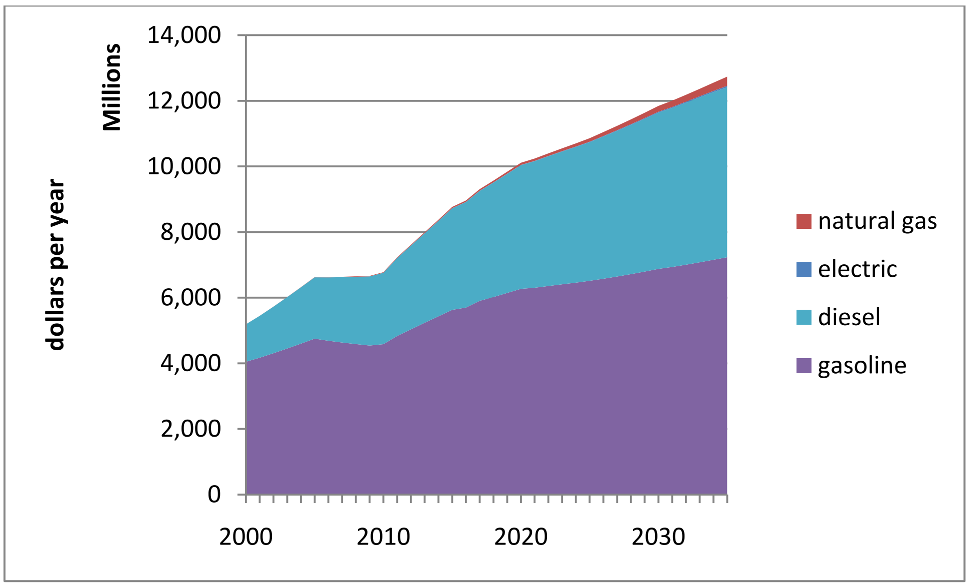
Charts presented in same order as legend entries.

Figure 13: Total consumer expenditure on fuels used in transportation, LCFS basic scenario.



Charts presented in same order as legend entries.

Figure 14: Total consumer expenditure on fuels used in transportation, LCFS plus electricity used in fleet scenario.



Charts presented in same order as legend entries.

Figure 15: Total consumer expenditure on fuels used in transportation, GHG tax scenario.

Selected Sources

Renewable Fuels Association (RFS). 2009. "Volumetric Ethanol Excise Tax Credit." Accessed May 3, 2009. http://www.ethanolrfa.org/resource/veetc/.

Energy API. 2009. "April 2009 Notes to State Motor Fuel Excise Tax Report."

Environmental Protection Agency (EPA). 2009. "Renewable Fuel Standard Program." Accessed May 3, 2009. http://www.epa.gov/OMSWWW/renewablefuels/index.htm.

National Highway Traffic Safety Administration (NHTSA). 2004. "Automotive Fuel Economy Program Annual Update." U.S. Department of Transportation. Accessed May 10, 2009. http://www.nhtsa.dot.gov/cars/rules/cafe/FuelEconUpdates/2004/index.htm.

Senate Bill S.F. No. 674. 2009. *Minnesota Clean Car Act*.

Minnesota Statutes 2004, section 239.791, subdivision 1. *Gasoline minimum ethanol content requirement increase; petroleum replacement goal*. (2005 Amendment)

Minnesota Session Laws 2008, Chapter 297, S.F. No. 3683. *Omnibus agriculture and veterans policy provisions modification*.

Warner, E. (2009). *Evaluating Lifecycle Assessment Models for Use in a Low Carbon Fuel Standard Policy*. MA Thesis, University of Minnesota.

Senate Bill S.F. No. 17. 2009. *Minnesota Clean Car Act*.

Appendix A: Key Parameters/Assumptions Used in Transportation Fuels Section of Energy Choice Simulator

Users of the online version of Energy Choice Simulator (http://energychoicesimulator.com) can find and modify nearly every data assumption used in the model. Below we present the specific assumptions used in the transportation fuels section.

To find a particular value used in the online version, click on the Assumptions tab, then either scroll through all the variables or type in the first several letters of the variable name in the Find box. So, for example, type in "demand growth for vehicles" (just the first several letters are really needed) and look in the resulting filtered list for the specifics on that variable.

Detailed instructions are located on the web site listed above.

Demand Growth	Baseline Reference Values
Demand Growth for Vehicles	0.015 from 2010
Demand Growth for VMT	rising from -.02 to +.01 by 2015
Initial Vehicles by Engine Type in 2000	diesel, high 275.77K diesel, low 643.47K electric, high 3 electric, low 8 gasoline, high 1.16M gasoline, low 2.70M natural gas, high 158 natural gas, low 368
Initial Vehicle Miles Traveled in the Year 2000	11.89K for each fuel type
Electricity - Production	
Life Cycle CO2e Emission Intensity	MT CO2e/GWh biomass electricity 20 existing pulverized 269 gas electric 166 hydroelectric 0 IGCC and CCS 269 New Nuclear 2 New Pulverized coal 269 old nuclear 2 photovoltaic 0 SNG 240 wind 0
Combustion Carbon Intensity Emissions	MT CO2e/GWh biomass 7 existing pulverized 316 gas electric 191 hydroelectric 0 IGCC and CCS 315 New Nuclear 0 New Pulverized coal 316 old nuclear 0 photovoltaic 0 SNG 222 wind 0
Transportation - Vehicles	
Vehicle Availability in 2000	diesel, high 500M diesel, low 500M

	electric, high 250M electric, low 250M gasoline, high 500M gasoline, low 500M natural gas, high 125M natural gas, low 125M
Average Vehicle Life	13 years for all fuels
Ecodriver Improvement Rate	0.1
Federal CAFE Passenger Vehicle Standards	39 mpg by 2020
Federal CAFE Truck Standards	33 mpg by 2020
Federal Clean Car Passenger Vehicle Standards	227 grams per mile by 2015
Federal Clean Car Truck Standards	280 grams per mile by 2015
Initial Vehicle Fuel Economy in 2000	diesel 17.4, electric 99.75, gasoline 20.63,natural gas 27.;08
Initial New Vehicle Fuel Efficiency in 2000	mpg: diesel 21.3, electric, 99.75, gasoline 26.47, natural gas 27.08
Annual Percent Change in Vehicle Fuel Efficiency from Improvements in Technology	0
Transportation - Vehicle Costs and Prices	
Vehicle Investment Discount Rate	0.08
Vehicle NonFuel Operation and Maintenance Costs	7K annually for all fuels
Vehicle Demand Elasticity	-0.3
Vehicle Average Annual Insurance Cost	700/year for all types
Pay as You Drive Insurance Costs	0.5
Vehicle Prices	diesel high 22K, diesel low 22K, electric high 47K, electric low 47K, gasoline high 17K, gasoline low 17K, natural gas high 22K, natural gas low 22K
Fuel Economy Range	0.2
Transportation - Fuel Production Infrastructure	
Average Time to Build Fuel Production Capacity	years: biomass 4 existing pulverized 4 gas electric 1.5 hydroelectric 5 IGCC and CCS 4 New Nuclear 6 New Pulverized coal 4 old nuclear 6 photovoltaic 3 SNG 4 wind 3

Annual Maximum Fuel Market Capture Rate	biomass .03 existing pulverized .05 gas electric .05 hydroelectric .03 IGCC and CCS .05 New Nuclear .03 New Pulverized coal .05 old nuclear .03 photovoltaic .03 SNG .03 wind .03
Excess Imports or Exports as a Fraction of Total Fuel Demand	0
Average Life of Fuel Production Capacity	20 years for all types
Imported Fuel Price Relative to State or Region Prices	.1 for all types
Transportation Technology Availability Start Date	2050 for algae and advanced biodiesel, 2020 for crop residue ethanol and grass ethanol and wood ethanol, 2010 for coal CTL, 2000 for all others
Initial Fuel Production Capacity in 2000	TBTU: advanced biodiesel 0, biodiesel 1.67, cell. Eth 0, CTL 0, corn grain eth 16.72, natural gas 0, oil sands 280, crude oil 37.46 (TBTU)
Excess Imports or Exports as a Fraction of Total Fuel Demand	Ethanol: 200-2010: 1 rising to 2 2015: down to 1 2015-2035: rising to 2 All other fuels: 0
Transportation - Fuel Infrastructure Costs	
Transportation Technology Construction Costs	
Transportation Investment Discount Rate	.08 all types
Transportation Technology Operation and Maintenance Costs	
Federal Fuel Feedstock Taxes or Subsidies	$/TBTU: 0 for CTL and foreign refinery and natural gas and north am refinery and oil sands refinery; -8M for all rest except corn grain eth -4M
Transportation - Lifecycle Emissions	
Coal to Liquids Biomass Percentage	0.1
Coal to Liquids Carbon Capture and Storage	0.3
Emissions from Vehicle Construction	0 for all types (not used)
Indirect Land Use	0 for all types (not used)

Upstream Emissions Gasoline	MT CO2e/TBTU algae biogasoline -44K coal CTL 4K corn ethanol -52K crop residue -66K EOR 4K feedstock adv biogasoline -44K foreign refinery 4K gas NG 7K grass ethanol -50K north american refinery 4K soybean biogasoline -71K oil sands 17K wood ethanol -22K
Upstream Emissions Diesel	MT CO2e/TBTU algae biodiesel -44K coal CTL 4K corn ethanol -52K crop residue -66K EOR 4K feedstock advanced biodiesel -44K foreign refinery 4K gas NG 7K grass ethanol -50K north american refinery 4K soybean biodiesel -71K oil sands 17K wood ethanol -22K
Emissions from Blender or Refiner Gasoline	MT CO2e/TBTU algae biogasoline -31K coal CTL 156K corn ethanol 40K crop residue -2K EOR 13K feedstock advanced biogasoline -31K foreign refinery 13K gas NG 9K grass ethanol -3K north american refinery 13K soybean biogasoline 13K oil sands 13K wood ethanol 8K
Emissions from Blender or Refiner Diesel	MT CO2e/TBTU algae biodiesel -31K coal CTL 156K corn ethanol 40K crop residue -2K EOR 13K feedstock advanced biodiesel -31K foreign refinery 13K gas NG 9K grass ethanol -3K north american refinery 13K soybean biodiesel 13K oil sands 13K wood ethanol 8K
Emissions from Combustion Diesel	MT CO2e/TBTU advanced biodiesel 80K biodiesel 80K cell ethanol 74K CTL 80K corn grain eth 74K natural gas 60K oil sands 80K crude oil 80K
Emissions from Combustion Gasoline	MT CO2e/TBTU advanced biodiesel 80K biodiesel 80K cell ethanol 74K CTL 80K corn grain eth 74K natural gas 60K oil sands 80K crude oil 80K
Drive Train Efficiency Adjustment Factor	diesel .78, electric .20, gasoline 1.0, NG 1.0
Transportation - Federal Renewable Fuel Standard	

Federal Renewable Fuel Standard for Cellulosic Biofuel	.15 by 2025
Federal Renewable Fuel Standard for Advanced Biofuel	.20 by 2025
Federal Renewable Fuel Standard for Conventional Biofuel	.14 by 2015
Federal Renewable Fuel Standard for Biomass Based Diesel	0.2
Portion of the Vehicle Fleet Composed of Flex Fuel Vehicles	rising to .1 by 2030
Transportation - Fuel Prices	
Impact of VMT Reducing Policy	$/mi. Bike lanes .7 highspeed rail .15 intercity rail .15 transit 2.2 vanpools .5
Federal Fuel Energy Based Taxes or Subsidies	$/gge biodiesel .24 diesel .24 ethanol .18 gasoline .18
Fuel Demand Elasticity	-0.3
4. Initial Price of the Fuel Blend in the Year 2000	$/TBTU: diesel 15.93M, electric 28.66M, gasoline 15.96M, natural gas 16M
Feedstock - Availability	
Algae Availability	0 TBTU
Corn Grain Availability	248.58 TBTU
Wind Electric Availability	7.65K TWh
Coal Availability	27.69K TBTU
Soybean Availability	43.95 TBTU
EOR Oil Availability	500 TBTU
Oil Sands Availability	500 TBTU
North American Oil Availability	22.89K TBTU
Foreign Oil Availability	122.12K TBTU
Nuclear Fuel Availability	348.45K TWh
Biogas Availability	.09 TWh
Natural Gas Availability	19.5K TBTU
Biomass Availability	TBTU: grass 35.93, residue 248.58, wood 3.15
Sunlight Availability	1.03 TWH
Hydro Availability	2.26
Advanced Biodiesel Feedstock Availability	0
CO2e Emissions and CO2e Buyout	
CO2 Sequestration per Acre of Corn Converted to Grass	40 MT/ac
Transportation - Fuel Infrastructure Costs	$million/TBTU advanced biodiesel 80M biodiesel 13M cell ethanol 64M CTL 57M corn grain eth 29M natural gas 25M oil sands 80K crude oil 19M

Transportation Technology Operation and Maintenance Costs	$million/TBTU advanced biodiesel 8M biodiesel 1.3M cell ethanol 6.4M CTL 5.7M corn grain eth 2.9M natural gas 2.5M oil sands 8M crude oil 1.9M

Appendix B: Key Variables in Energy Choice Simulator Model

Users of the online version of Energy Choice Simulator (http://energychoicesimulator.com) can find and modify nearly every policy structure assumption used in the model. Click on the Policy tab, then drill down to the policy you'd like to view/modify. Detailed instructions are located on the web site listed above.

(Reproduced from online ECS documentation, 9/30/2010)

This document summarizes definitions and sources for Energy Choice Simulator (ECS) model variables and graphs. This document lists the name, description, model use, units, subscripts, and data source(s) for each variable in the user interface. This information is also located in the ECS Wiki.

Summary Tab

Total Energy
Graph of total annual energy demanded in the transportation, electricity, and nonelectric building heating sector in trillion BTUs.

Total GHG Emissions
Graph of total annual GHG emissions from the transportation, electric, and nonelectric building heating sector in million metric tons CO2e from both combustion and full fuel cycle emissions.
Emissions from Direct Combustion only include CO2 emitted during combustion of the fuel while Full Fuel Cycle includes CO2 emitted over the entire lifecycle process of generating, transporting, and using the fuel.

Total Public Revenue
Graph of annual total public revenue generated by the use of tax and subsidy policies from the transportation, electric, and nonelectric building heating sectors in dollars. Positive values mean taxes dominate and negative values mean subsidies dominate.

Total Private Spending
Graph of total annual private spending in the transportation, electric, non-electric building heating sectors and on energy efficiency projects in dollars. It also includes any spending on importing electricity or fuels.

Policies Tab

EFFICIENCY/TERRESTRIAL SEQUESTRATION- EFFICIENCY MANDATES

Electricity Efficiency Mandate:
UNIT: Fraction
DESCRIPTION: Electricity Efficiency Mandate is a state or regional policy that can be put in place to require that the utility create efficiency improvements in the three primary sectors (residential, industrial, and commercial). Used to reduce demand for electricity from the three main sectors (residential, industrial, and commercial) relative to previous years average demand.
USE: Change the fraction up to 0.05 to mandate energy efficiency up to 5% below the average electricity demand in previous years.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

Nonelectric Building Heating Efficiency Mandate:
UNIT: Fraction

DESCRIPTION: Nonelectric building efficiency mandate requiring an annual reduction in nonelectric building heating use for residential, industrial, and commercial sectors. The mandate is based on a reduction of the average nonelectric building heating used to calculate average demand.
USE: Used to reduce nonelectric building heating demand in all building sectors.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

New Public Building Efficiency Mandate:
UNIT: Fraction
DESCRIPTION: Required percentage increase in efficiency only for new public buildings. Public buildings are considered to only be commercial buildings. Used to reduce electricity and nonelectric building heating use.
USE: Increase the efficiency requirements for new commercial public buildings being constructed by up to 100% to reduce electricity and heating energy use.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Existing Public Building Efficiency Mandate:
UNIT: Fraction
DESCRIPTION: Required percentage increase in efficiency for only existing public buildings. Public buildings are considered to only be commercial buildings. Used to reduce electricity and nonelectric building heating use.
USE: Increase the efficiency requirements for existing commercial public buildings by up to 100% to reduce electricity and heating energy use.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Electricity Building Code Mandate for New Construction:
UNIT: Fraction
DESCRIPTION: Required percentage increase in required building efficiency in new buildings. Used to reduce electricity use in all building sectors; residential, industrial and commercial.
USE: Increase efficiency requirements for new buildings being constructed in all sectors by up to 100% to reduce electricity usage.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

Other Appliance Code Efficiency Mandate:
UNIT: Fraction
DESCRIPTION: Appliance Code Efficiency Mandate is a state or regional policy requiring energy efficiency improvements in appliances installed in newly constructed buildings. Used to reduce electricity and nonelectric building heating demand.
USE: Increase appliance efficiency requirements for new buildings being constructed in all sectors by up to 100% to reduce electricity usage.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

Private Efficiency Improvements Beyond Code:
UNIT: Fraction
DESCRIPTION: Required percentage increase in the efficiency of private residences by residents. Used to increase energy efficiency in residential sector only.
USE: Increase efficiency requirements for buildings in the residential sector by up to 100% to reduce energy usage.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

NonElectric Building Heating Building Code Mandate for New Construction:
UNIT: Fraction
DESCRIPTION: Required percentage increase in required building efficiency in new buildings. Used to reduce nonelectric building heating use in all building sectors; residential, industrial, and commercial.

USE: Use the building code to increase efficiency requirements for nonelectric building heating for new buildings being constructed in all sectors by up to 100% to reduce energy usage. SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

Space Heating Appliance Code Efficiency Mandate:
UNIT: Fraction
DESCRIPTION: Required percentage increase in the efficiency of heating appliance codes in new buildings. Used to increase efficiency in heating for new buildings in all sectors; residential, industrial, and commercial.
USE: Use the appliance code to increase efficiency requirements for space heating for new buildings being constructed in all sectors by a percentage amount to reduce energy usage.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

Appliance Standard Electricity Saving:
UNIT: Fraction
DESCRIPTION: Electricity savings from miscellaneous appliance standards. Used to decrease electricity use in all sectors; residential, industrial and commercial.
USE: Use appliance standards to increase electricity savings up to 5000 GWh for appliances.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

EFFICIENCY/TERRESTRIAL SEQUESTRATION- EFFICIENCY SPENDING

Public Investment in New Private Building Conservation:
UNIT: Dollars
DESCRIPTION: Public investment in improvements in new private building conservation in all building sectors. Used to reduce electricity demand and nonelectric building heating demand.
USE: Increase public investment in conservation improvements for new private buildings being constructed to reduce energy demand.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

Public Investment in Existing Private Building Conservation:
UNITS: Dollars
DESCRIPTION: Public investment in improvements in existing private building conservation in all building sectors.
USE: Reduce electricity demand and nonelectric building heating demand.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

EFFICIENCY/TERRESTRIAL SEQUESTRATION-TERRESTRIAL SEQUESTRATION

Spending on Terrestrial Sequestration:
UNIT: Dollars
DESCRIPTION: Policy on spending to alter land use to lead to carbon sequestration through the use of prairie grass. Used to reduce total emissions from all energy sectors.
USE: Increase public spending on planting of prairie grass to sequester carbon by up to $1 Billion to reduce emission levels.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

ELECTRICITY-SYSTEM WIDE

Electricity Taxes or Subsidies:
UNIT: Dollar/KWh
DESCRIPTION: State, regional or federal taxes or subsidies for electricity provided consumers. Has an indirect impact on electricity demand.

USE: Use to increase or decrease taxes or subsidies on electricity in all sectors. Positive values indicate taxes, negative values indicate subsidies.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input

CO2e Combustion Emissions Tax on Electricity:
UNIT: Dollar/Metric Ton
DESCRIPTION: CO2e Based tax on emissions from the plant producing electricity. Used to affect levelized average cost of various electricity technologies.
USE: Create a tax on CO2 emissions for electricity production.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Electricity CO2e Cap as a Percentage of the 2000 Baseline:
UNIT: Fraction
DESCRIPTION: Policy that imposes a cap and trade system as a percentage reduction above or below a baseline assumption. Implementation of this policy leads to credit purchases, implementation of rehab technologies, or efficiency projects to reduce CO2e emissions.
USE: Input the emissions cap as a fraction of baseline emissions- for instance, a 15% reduction would equate to 85% of baseline emissions, or 0.85. User can draw a line that changes over time to increase or decrease cap.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Use Electricity Performance Standards:
UNIT: N/A
DESCRIPTION: A toggle variable to turn on or off performance standards. Used to impose a moratorium on electricity technologies that exceed the standards.
USE: Turn on performance standards to require electricity performance for a given year by choosing the value of 1 for that year.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Performance Standards Maximum Combustion CO2e Intensity:
UNIT: Metric Tons CO2e/GWh
DESCRIPTION: Maximum limit for the emission intensity of an electricity technology allowed without placing a moratorium
USE: Set a maximum emission intensity as a limit above which a moratorium is placed.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Carbon Capture and Storage Tax Credit:
UNIT: Dollar/Metric Tons CO2e
DESCRIPTION: Tax credit given to IGCC plants for using CO2 capture and storage technology. Impacts the levelized average costs of IGCC plants with CCS.
USE: Create a tax credit for a given electricity technology for capturing and storing CO2 emissions.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: User input

Maximum Limit on per Plant Carbon Capture Counted Toward the Carbon Sequestration Credit:
UNIT: Metric Tons CO2e
DESCRIPTION: Absolute limit on the tax credit one plant will receive. Used as an upper end limitation on the CCS tax credit policy
USE: Set a limit on the Carbon Sequestration Tax Credit for one plant to receive.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

NonFederal Renewable Portfolio Standard:
UNIT: Fraction
DESCRIPTION: NonFederal Renewable Portfolio Standard is a state or regional policy mandated use of a particular electricity technology to produce electricity to a given percentage of total demand. Used to calculate how much of the new mandated electricity technology must be constructed given new construction to meet consumer demand.
USE: Use to mandate the fraction of electricity demand to be from a certain electricity technology up to 50%. For example, a nonfederal renewable portfolio standard requiring 15% of electricity production by biomass technology would be entered in the graph as a line at 0.15 for a given year.
SUBSCRIPT USED: Electricity Technology
DATA SOURCE: User input

Electricity Annual Taxes or Subsidies:
UNIT: Dollar/KWh
DESCRIPTION: Taxes or subsidies paid annually. Used to affect levelized average cost of various electricity technologies.
USE: Create annual taxes or subsidies for a given electricity technology. Positive values indicate taxes charged and negative values indicate subsidies given to the electricity producer for a given technology based on how much electricity is produced each year.
SUBSCRIPT USED: Electricity Technology
DATA SOURCE: User input

Electricity Technology Taxes or Subsidies:
UNIT: Dollars/TWh
DESCRIPTION: Electricity Technology Taxes or Subsidies is a state or regional policy that imposes a tax or subsidy on the technology used to produce electricity.
USE: Used to calculate electricity technology average levelized costs and therefore impacting electricity technology construct decisions. This is a a one time cost.
SUBSCRIPT USED: Electricity Technology
DATA SOURCE: User input

Ban Electricity Technology:
UNIT: N/A
DESCRIPTION: Ban Electricity Technologies is a state, regional, or federal policy banning the use of a particular electricity technology. Immediately stops the use of a particular electricity technology used. This includes production, current construction, and all future construction. USE: Use to stop using an electricity technology in a given year. Enter a line at the top value of 1 to enable the ban.
SUBSCRIPT USED: Electricity Technology
DATA SOURCE: User input

Moratorium on Electricity Technologies:
UNIT: N/A
DESCRIPTION: Moratorium on Electricity Technologies is a state, regional, or federal policy instituting a moratorium on all future use of a particular electricity technology. Stops all future construction of a particular technology. Existing construction and production for a technology in which a moratorium has been imposed will continue until decommissioned.
USE: Use to stop future construction of a particular technology and decommission all existing infrastructure for producing electricity from that technology for a given year. Enter a line at the value of 100 to enable the moratorium.
SUBSCRIPT USED: Electricity Technology
DATA SOURCE: User input

Production Tax Credit:
UNIT: Dollar/KWh

DESCRIPTION: Annualized subsidy that only lasts a certain number of years instead of over the entire lifetime of the electricity technology.
USE: Create a production tax credit to provide a subsidy for a certain number of years for a particular electricity technology.
SUBSCRIPT USED: Electricity Technology
DATA SOURCE: User input; baseline data based on American Wind Energy Association, Federal Wind Production Tax Credit (PTC) policy, http://awea.org/policy/ptc.html.

Length of Time Production Tax Credit is Paid:
UNIT: Years
DESCRIPTION: Amount of time over which that the PTC is paid.
USE: Enter the number of years to pay out the Production Tax Credit.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input for wind Production Tax Credit (PTC) policy

TRANSPORTATION- PRODUCERS- SYSTEM WIDE

CO2e Combustion Emissions Tax on Emissions from Blender/Refiner:
UNIT: Dollar/Metric Ton CO2e
DESCRIPTION: A tax on emissions from the blender/refiner of fuel. Used to increase the levelized average cost of using fuel pathways that create significant emissions at the refiner/blender step such as CTL.
USE: Create a tax on emissions from fuel.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

TRANSPORTATION- PRODUCERS- LOW CARBON FUEL STANDARD POLICIES

NonFederal Low Carbon Fuel Standard Below the 2000 Baseline:
UNIT: Fraction
DESCRIPTION: This policy is considered to apply to blender, refiner, and importers of fuel and the liquid fuels that they produce. Since regulated entities are modeled as one entity, a corresponding credit system is not modeled as a part of the LCFP. This leads to the use of less emission intensive fuels on a life cycle basis through blending of different fuel pathways. Used as a percentage reduction in average fuel blend emission intensity below and established baseline.
USE: Create a low carbon fuel standard to reduce CO2 emissions to levels as percentages below the year 2000 baseline. For example, to mandate fuel combustion emissions to be 15% below the year 2000 levels, create a line at 0.15 for a given year.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

Use Alternative Low Carbon Fuel Standard Baseline:
UNIT: N/A
DESCRIPTION: Use Alternative Low Carbon Fuel Standard Baseline is set of three sub-policy options to be used in tandem with the NonFederal Low Carbon Fuel Standard. Option one (set the level to zero) consists of a regulated entity calculating their carbon intensity based on total firm emissions divided by current year demand. Option two (set the level to one) consists of a regulated entity calculating carbon intensity base on total firm emissions divided by demand in the baseline year 2000. Option three (set the level to two) consists of a regulated entity calculating carbon intensity base on annual emissions divided by a rolling average (Uses the Number of Years in Low Carbon Fuel Standard Rolling Average policy) of previous year's demand. Used to influence how restrictive a low carbon fuel standard is and how much fuel blending must occur to meet the LCFS. That is, by not allowing for the growth in demand, options 2 and 3 are more restrictive with option 2 being the most restrictive.
USE: Change the low carbon fuel standard baseline. The three options use different calculations for carbon intensity : option 1 uses fuel demand for each year, option 2 uses demand in the year 2000, and option 3 uses a rolling average of the demand from the previous year. To change the option, set the level to 0, 1, or 2 for options 1, 2, and 3 respectively.
SUBSCRIPT USED: N/A

DATA SOURCE: User input

Number of Years in Low Carbon Fuel Standard Rolling Average:
UNIT: Year
DESCRIPTION: Number of years used in LCFS sub policy alternative three to control how many years of energy demand are to be averaged for use in calculating the carbon intensity of a regulated entity (see Use Alternative Low Carbon Fuel Standard Baseline). Used to calculate the number of years to include in the rolling average formulation of the LCFS.
USE: Change the number of years in the rolling average used to calculate carbon intensity for the alternative LCFS baseline.
USE: Used to calculate the number of years to include in the rolling average formulation of the LCFS.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

Use Drive Train Efficiency in Low Carbon Fuel Standard:
UNIT: N/A
DESCRIPTION: This toggles the use of drive train efficiency in the low carbon fuel standard in NonFederal Low Carbon Fuel Standard Below the 2000 Baseline. Used to include drive train efficiency in fuel pathway emission intensities as a part of a LCFP. A drive train is used to calibrate the carbon intensity score of alternative fuels under an LCFS to account for unique engine efficiencies present in some alternative vehicles.
USE: Click "use this policy" to include drive train efficiency in the calculations for emission intensity used for the low carbon fuel standard policy. See Transportation- Life Cycle Emissions under the Assumptions tab to edit the Drive Train Efficiency Adjustment Factors.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

Use Electricity in Low Carbon Fuel Policy:
UNIT: N/A
DESCRIPTION: This toggles the use of electricity in the low carbon fuel standard (LCFS, NonFederal Low Carbon Fuel Standard Below the 2000 Baseline). This would make an electricity provider an obligated party under an LCFS/LCFP, which would be subject to an annual intensity standard according to the goals of the program.
USE: Click "use this policy" to include electricity in the calculations for emission intensity in the LCFS/LCFP.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

Include Exports in Low Carbon Fuel Policy:
UNIT: N/A
DESCRIPTION: A toggle variable to use or not include exports in the low carbon fuel standard NonFederal Low Carbon Fuel Standard Below the 2000 Baseline. Used in formulation of the LCFP that counts amount of fuel produced within the state or region in the LCFP.
USE: Click the "use this policy" button to include exports in the calculations for emission intensity used for the low carbon fuel standard policy.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

Baseline Year CO2e Intensity Emission for Use in a Low Carbon Fuel Standard:
UNIT: Metric Tons CO2e/Trillion BTUs
DESCRIPTION: Reference standard used for the functioning of the low carbon fuel standard in NonFederal Low Carbon Fuel Standard Below the 2000 Baseline. Used to change the baseline standard used in the LCFP.
USE: Change the baseline used in the calculation of intensity emissions in the LCFS policy. Enter a value in the input box of Metric Tons CO2e/Trillion BTUs that will become the baseline for each year's calculations.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

TRANSPORTATION- PRODUCERS- BY VEHICLE

NonFederal Clean Car Passenger Vehicle Standards
UNIT: g/mile
DESCRIPTION: This is a standard for passenger vehicles that requires improvements in vehicle fuel economy based on emission from vehicle operation and maintenance. It does not allow for other methods of emission control. It does take into account how current fuel blends impact vehicle emissions. This policy is imposed on the manufacturers of vehicles and designed to increase the fuel economy of new vehicles offered to consumers, but does not address whether consumers will select these vehicles. Used to increase fuel economy of new passenger vehicles offered to consumers.
USE: Increase level of improvements of vehicle fuel economy by decreasing the allowed emission levels in grams of CO2 emitted per mile from new passenger vehicles being produced.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

NonFederal Clean Car Truck Standards
UNIT: g/mile
DESCRIPTION: This is a standard for trucks that requires improvements in vehicle fuel economy based on emission from vehicle operation and maintenance. It does not allow for other methods of emission control. It does take into account how current fuel blends impact vehicle emissions. This policy is imposed on the manufacturers of vehicles and designed to increase the fuel economy of new vehicles offered to consumers, but does not address whether consumers will select these vehicles. Used to increase fuel economy of new trucks offered to consumers.
USE: Increase level of improvements of vehicle fuel economy by decreasing the allowed emission levels in grams of CO2 emitted per mile from new trucks being produced.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

NonFederal CAFE Truck Standards:
UNIT: miles/gallon
DESCRIPTION: This is a vehicle standard for trucks that requires improvements in Corporate Average Fuel Economy (CAFE) vehicle fuel economy. This policy is imposed on the manufacturers of vehicles and designed to increase the fuel economy of new vehicles offered to consumers, but does not address whether consumers will select these vehicles. Used to require improvements in vehicle fuel economy for new vehicles offered to consumers
USE: Create additional vehicle standards to require new vehicles to get a certain number of miles per gallon.
SUBSCRIPT USED: N/A
DATA SOURCE: User input, baseline data from Research and Innovative Technology Administration (RITA) Table 4-23: Average Fuel Efficiency of U.S. Passenger Cars and Light Trucks:
http://www.bts.gov/publications/national_transportation_statistics/html/table_04_23.html

NonFederal CAFE Passenger Vehicle Standards
UNIT: miles/gallon
DESCRIPTION: This is a vehicle standard for passenger vehicles that requires improvements in Corporate Average Fuel Economy (CAFE). This policy is imposed on the manufacturers of vehicles and designed to increase the fuel economy of new vehicles offered to consumers, but does not address whether consumers will select these vehicles. Used to require improvements in vehicle fuel economy for new vehicles offered to consumers
USE: Create additional vehicle standards to require new vehicles to get a certain number of miles per gallon.
SUBSCRIPT USED: N/A
DATA SOURCE: User input, baseline data from Research and Innovative Technology Administration (RITA) Table 4-23: Average Fuel Efficiency of U.S. Passenger Cars and Light Trucks:
http://www.bts.gov/publications/national_transportation_statistics/html/table_04_23.html
TRANSPORTATION- PRODUCERS- BY FUEL

NonFederal Renewable Fuel Standard:
UNIT: Fraction
DESCRIPTION: NonFederal Renewable Fuel Standard is a state or regional policy mandating a certain portion of fuel demand be met by particular fuels. Used to mandate particular types of fuel production.

USE: Create a requirement for a fraction of total fuel demand to be provided by a particular fuel up to 50%. For example, to mandate that 15% of fuel produced to come from soybean biodiesel, change the line to 0.15 for a given year.
SUBSCRIPT USED: Transportation Technology
DATA SOURCE: User Input, Minnesota baseline data from Minnesota Statutes 2008:
http://www.mpmaonline.com/Tool%20Box%20Items/Biodiesel%20Mandate%20239.77.pdf and Minnesota Senate S.F. No. 4, 3rd Engrossment - 84th Legislative Session (2005-2006):
https://www.revisor.leg.state.mn.us/bin/bldbill.php?bill=S0004.3&session=ls84

NonFederal Fuel Feedstock Taxes or Subsidies:
UNIT: Dollar/Trillion BTUs
DESCRIPTION: NonFederal Fuel Feedstock Taxes or Subsidies is a state or regional tax or subsidy on transportation fuel feedstocks used. Used to calculate levelized average cost of transportation fuel technologies to impact blender and producer construction and blending decisions. It is an annual cost.
USE: Create yearly taxes or subsidies on transportation fuel. Positive values indicate a tax, negative numbers indicate a subsidy.
SUBSCRIPT USED: Transportation Technology
DATA SOURCE: User input, baseline data from the US Department of Energy (DOE) Biomass Program Volumetric Ethanol Excise Tax Credit (VEETC), accessed 2008,
http://www1.eere.energy.gov/biomass/federal_biomass.html

Fuel Technology Taxes or Subsidies:
UNIT: Dollar/Trillion BTU
DESCRIPTION: A one-time tax or subsidy on the fuel production technology. Used to produce fuels which impacts levelized average fuel costs.
USE: Create a one time tax or subsidy on transportation fuel. Positive values indicate a tax, negative numbers indicate a subsidy.
SUBSCRIPT USED: Transportation Technology
DATA SOURCE: User input

Ban Transportation Fuel Pathways:
UNIT: N/A
DESCRIPTION: Switch to turn ban on and off. Used to ban all future and all existing fuel production from one particular fuel pathway. Does not have a significant effect on infrastructure development unless all fuel pathways for one fuel production technology are banned.
USE: Turn the switch on by putting the line at the value 1. This will ban the use of the selected fuel pathway technology.
SUBSCRIPT USED: Fuel Pathways
DATA SOURCE: User input

Moratorium on Fuel Pathways:
UNIT: N/A
DESCRIPTION: Similar to the ban on fuel pathways, but instead prevents only future development of the particular pathway. However, this effect is really only realized if all pathways associated with a particular set of technological infrastructure have a moratorium. Used to prevent future development of the particular pathway.
USE: Enact the moratorium by selecting the 1 value on the graph. This will prevent future development of fuel produced from this pathway.
SUBSCRIPT USED: Fuel Pathways
DATA SOURCE: User input

Ethanol Blend Wall:
UNIT: Fraction
DESCRIPTION: Maximum average blend limit for fuel blends used in generic gasoline. Used to set maximum blend limit.
USE: Set the maximum blend limit as a fraction of total fuel composition.
SUBSCRIPT USED: N/A

DATA SOURCE: User input; baseline generated based on the assumption that federal RFS will be met.

TRANSPORTATION- CONSUMERS- BY FUEL

NonFederal Fuel Energy Based Taxes or Subsidies:
UNIT: Dollar/Gallon Gasoline Equivalent
DESCRIPTION: NonFederal Fuel Energy Based Taxes or Subsidies is a state or regional policy to tax or subsidize consumer fuel on an energy basis. Used to increase the price of fuels thus increasing levelized average vehicle costs for some vehicle engine types and it reduces fuel demand through demand elasticity impacts on VMT.
USE: Create a fuel energy tax or subsidy on consumer fuel. Positive values indicate taxes, negative values indicate subsidies.
SUBSCRIPT USED: Liquid Fuels
DATA SOURCE: User input, baseline data from American Petroleum Institute (API), Motor Fuel Notes (2009), http://www.api.org/statistics/fueltaxes/index.cfm

CO2e Combustion Emissions Tax on Consumer Fuels
UNIT: Dollar/Metric Tons CO2e
DESCRIPTION: NonFederal GHG Combustion Emissions Tax on Consumer Fuels is a state or regional policy taxing GHG combustion emissions from consumer fuels purchase at the pump. Used to increase the price of fuels thus increasing operation and maintenance costs for some vehicle engine types and reducing fuel demand through VMT.
USE: Create a tax on CO2 emissions for consumer fuels.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

TRANSPORTATION- CONSUMERS- BY VEHICLE

Vehicle Feebate per MPG:
UNIT: Dollar/MPG
DESCRIPTION: Taxes or subsides on vehicles for being above or below the average fuel economy of new vehicles ($/miles-per-gallon). This is factored into the levelized average costs of vehicles, which affects consumer purchasing decisions. A $100/MPG feebate would give a $100 rebate to a consumer that purchases a car that is 1 mile-per-gallon more efficient than the industry average, and apply a $100 fee to a consumer that purchases a car that is 1 mile-per-gallon less efficient than the industry average.
USE: Create a vehicle feebate by setting the amount of dollars per MPG.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

Ecodriver Compliance Rate:
UNIT: Fraction
DESCRIPTION: This represents programs that encourage changes in driving behavior that leads to improvement is the fleet vehicle fuel economy. Used to improve fleet vehicle fuel economy
USE: Change the fraction of compliance with ecodriver behavior up to 100%. For example, if estimates of public ecodriver activity are 50%, set the level to 0.50.
SUBSCRIPT USED: Liquid Fuels
DATA SOURCE: User input
TRANSPORTATION- CONSUMERS- VMT REDUCTION

VMT Reduction Spending:
UNIT: Dollar
DESCRIPTION: This variable reduces the fixed cost of vehicle insurance while increasing variable fuel consumption costs. This has potential effects on VMT, fuel use, and vehicle selection by consumers. Used to calculate the fraction of people participating in the pay as you drive insurance program.
USE: Change the percentage of people participating in Pay As You Drive insurance.
SUBSCRIPT USED: Liquid Fuels
DATA SOURCE: User input

Fraction Participating in Pay as You Drive Insurance:
UNIT: Fraction
DESCRIPTION: This variable reduces the fixed cost of vehicle insurance while increasing variable fuel consumption costs. This has potential effects on VMT, fuel use, and vehicle selection by consumers.
USE: Used to calculate the fraction of people participating in the pay as you drive insurance program.
SUBSCRIPT USED: N/A
DATA SOURCE: User input

Energy Tab

All wiki entries in this tab have this information:
To copy this data, use the "Copy to Clipboard" button below the table, then paste the data into a spreadsheet or word processor. To download the graph image as a JPEG file, right click the graph and select "Save as Image".
Energy Demand by Sector
Graph of annual energy demand; an aggregation of consumption of electricity and transportation fuels, as well as nonelectric heating and energy use from residential, commercial and industrial buildings (TWh).

Electricity Energy
Graph of electricity energy produced divided out by stacked areas of the technologies used to produce that energy in TWh. Also displayed is a line representing actual electricity energy demand. The difference between the electricity supplied and demanded is what is being imported or exported.

Transportation Fuel Energy
Graph of transportation energy supplied divided out by areas representing fuels in both trillion BTUs and billion gallons of gasoline equivalent. There is also a transportation energy demand line representing actual fuel demand. The difference between the transportation energy demand and supply is what is being imported or exported.

Transportation Fuel Technology Energy
Graph of transportation fuel energy supplied divided out by the technologies used to produce that energy in trillion BTUs.

NonElectric Building Heating Energy
Graph of nonelectric building heating energy supplied divided out by residential, commercial, and industrial portions of the state or region for which that energy is supplied in trillion BTUs.

GHG Emissions Tab

All wiki entries in this tab have this information:
To copy this data, use the "Copy to Clipboard" button below the table, then paste the data into a spreadsheet or word processor. To download the graph image as a JPEG file, right click the graph and select "Save as Image".

Emissions Generated by Sector
Graph of GHG emissions divided out by transport; electricity; and residential, commercial, and industrial nonelectric building heating sectors that produced these emissions within the state or region in million metric tons CO2e from both combustion and life cycle emissions.
Emissions from Direct Combustion only include CO2 emitted during combustion of the fuel while Full Fuel Cycle includes CO2 emitted over the entire lifecycle process of generating, transporting, and using the fuel.

Electricity Emissions
Graph of GHG emissions from the production of electricity energy divided out by the technologies used to produce that energy in million metric tons CO2e from both electricity combustion and life cycle emissions.
Emissions from Direct Combustion only include CO2 emitted during combustion of the fuel while Full Fuel Cycle includes CO2 emitted over the entire lifecycle process of generating, transporting, and using the fuel.

Transportation Fuel Emissions

Graph of GHG emissions from the production of transportation fuel divided out by the fuels created in million metric tons CO2e both from fuel combustion and life cycle emissions.
Emissions from Direct Combustion only include CO2 emitted during combustion of the fuel while Full Fuel Cycle includes CO2 emitted over the entire lifecycle process of generating, transporting, and using the fuel.

Transportation Fuel Technology Emissions
Graph of GHG emissions from transportation fuels divided out by the technologies used to produce those fuels in million metric tons CO2e based on life cycle emissions.

NonElectric Building Heating Emissions
Graph of GHG emissions for nonelectric building heating divided out by residential, commercial, and industrial demand for heating in million metric tons CO2e based on life cycle emissions.
Emissions from Direct Combustion only include CO2 emitted during combustion of the fuel while Full Fuel Cycle includes CO2 emitted over the entire lifecycle process of generating, transporting, and using the fuel.

Fuel Blend GHG Intensity
Graph of the GHG emission intensity of fuel blends consumers purchase in metric tons CO2e per trillion BTUs.

Economics Impact Tab
All wiki entries in this tab have this information:
To copy this data, use the "Copy to Clipboard" button below the table, then paste the data into a spreadsheet or word processor. To download the graph image as a JPEG file, right click the graph and select "Save as Image".

Policy Public Revenue by Policy
Graph of annual public revenue generated divided out by the policies used to generate that revenue in dollars. Positive values mean the policy taxes outweigh the policy subsidies and negative values mean the policy subsidies outweigh the policy taxes.

Policy Public Revenue by Sector
Graph of annual public revenue divided out by the sectors in which that revenue is generated in dollars. Positive values indicate taxes outweigh subsidies in the sector and negative values indicate subsidies outweigh taxes in the sector.

Private Spending by Sector
Graph of annual private spending divided out by the sectors in which that spending occurs in dollars.

Prices Tab
All wiki entries in this tab have this information:
To copy this data, use the "Copy to Clipboard" button below the table, then paste the data into a spreadsheet or word processor. To download the graph image as a JPEG file, right click the graph and select "Save as Image".

Price of Electricity
Graph of the average annual consumer price of electricity based upon electricity taxes, the current portfolio of electricity technologies, and price markup in dollars per KWh.

Prices for Vehicles
Graph of the average annual price of vehicles of various engine types based on vehicle prices and vehicle taxes or subsidies in dollars per vehicle.

Prices for Liquid Fuels
Graph of average annual prices for unblended liquid fuels in dollars per gallon of gasoline equivalent fuel.

Prices for Blended Fuels
Graph of the average annual price of fuels once blended prior to consumer purchase in dollars per gallon of gasoline equivalent.

NonElectric Building Heating Price
Graph of the nonelectric building heating price in dollars per trillion BTU.

Assumptions Tab

DEMAND GROWTH

Demand Growth for Vehicles:
UNIT: Fraction
DESCRIPTION: Expected annual growth in the demand for vehicles and in VMT per vehicle.
USE: Used to increase the total vehicles the system needs to be in the vehicle fleet.
SUBSCRIPTS USED: N/A
DATA SOURCE: Created from data from Fawley, E. (2009, May 7). February: 16th straight month of less driving! *Fresh Energy* historic VMT data from 2000 to 2009 with expected fuel demand growth rate or about 1.4%. 1% of that growth is assumed to be from population growth captured in increased demand for vehicles http://fresh-energy.org/index.php/blog/February-16th-straight-month-of-less-driving-.html

Demand Growth for NonElectric Building Heating:
UNIT: Fraction
DESCRIPTION: Expected annual growth in demand for electricity.
USE: Used to increase the total electricity capacity the system needs to be supplying electricity.
SUBSCRIPTS USED: N/A
DATA SOURCE: Energy Information Administration (EIA) Annual Energy Outlook (AEO) (2009); http://www.eia.doe.gov/oiaf/archive/aeo09/index.html

Exogenous Demand Growth Electricity:
UNIT: Fraction
DESCRIPTION: Expected annual growth in demand for electricity.
USE: Used to increase the total electricity capacity the system needs to be supplying electricity.
SUBSCRIPTS USED: N/A
DATA SOURCE: Energy Information Administration (EIA) Annual Energy Outlook (AEO) (2009); http://www.eia.doe.gov/oiaf/archive/aeo09/index.html

Demand Growth for VMT:
UNIT: Fraction (percentage growth; e.g. 5% would be 0.05)
DESCRIPTION: Initial value for demand growth for vehicle miles traveled (VMT) in the year 2000.
USE: Creates an initial level of growth for determining annual projections of VMT. SUBSCRIPTS USED: N/A
DATA SOURCE: Created from data from Fawley, E. (2009, May 7). February: 16th straight month of less driving! *Fresh Energy* historic VMT data from 2000 to 2009 with expected fuel demand growth rate or about 1.4%. 1% of that growth is assumed to be from population growth captured in increased demand for vehicles http://fresh-energy.org/index.php/blog/February-16th-straight-month-of-less-driving-.html

Initial NonElectric Building Heating Demand in 2000:
UNIT: Trillion BTU
DESCRIPTION: Initial nonelectric building heating demand in the year 2000.
USE: Used to calculate initial nonelectric building heating demand in the year 2000.
SUBSCRIPTS USED: Primary Sector and NonElectric Building Heating Technology
DATA SOURCE: Nonzero baseline data from Energy Information Administration (EIA) State Energy Data System (SEDS) (2000); http://www.eia.doe.gov/emeu/states/_seds.html

Initial Vehicles by Engine Type in 2000:
UNIT: Vehicle
DESCRIPTION: Initial vehicles in the fleet in the year 2000.
USE: Used as a starting point for the vehicle fleet stock which is used to calculate fuel demand.
SUBSCRIPTS USED: Engine Fuel Type and Efficiency

DATA SOURCE: Gasoline and Diesel: Federal Highway Administration (FHWA) State Motor-Vehicle Registrations (2000), http://www.fhwa.dot.gov/ohim/hs00/mv1.htm. Assumed 30/70 split between high and low. Electric and Natural Gas: http://www.eia.doe.gov/cneaf/alternate/page/atftables/afvtransfuel_II.html

Initial Electricity Demand in 2000 by Sector:
UNIT: TWh
DESCRIPTION: Initial electricity demand in the year 2000.
USE: Used to calculate initial electricity demand in the year 2000.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: Energy Information Administration State Energy Data System (EIA SEDS) (2000); http://www.eia.doe.gov/emeu/states/_seds.html

Initial Vehicle Miles Traveled in the Year 2000:
UNIT: VMT/Vehicle
DESCRIPTION: The total of vehicle miles traveled in the state or region in the year 2000.
USE: Input an initial assumption for total VMT.
SUBSCRIPTS USED: Engine Fuel Type
DATA SOURCE: Energy Information Administration (EIA) Household Vehicles Energy Use: Latest Data and Trends (2001); http://www.eia.doe.gov/emeu/rtecs/nhts_survey/2001/; http://www.eia.doe.gov/emeu/rtecs/nhts_survey/2001/tablefiles/t0464(2005).pdf;

ELECTRICITY- PRICES

Electricity Demand Elasticity:
UNIT: Fraction
DESCRIPTION: Demand elasticity for electricity.
USE: Used to calculate the impact of price changes on consumer demand for electricity.
SUBSCRIPTS USED: N/A
DATA SOURCE: Modeling assumption
Electricity elasticity used to calculate feedback impacts on demand from price changes.

Initial Price of Electricity in the Year 2000:
UNIT: Dollar/KWh
DESCRIPTION: Price of electricity by sector in the year 2000.
USE: Used as a starting point for the calculation of the impact of prices on electricity demand and to calculate the percentage markup.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: Energy Information Administration (EIA) Average Retail Price of Electricity to Ultimate Customers by End-Use Sector (2000 data); http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html#_ftn1

ELECTRICITY- PRODUCTION

Life Cycle CO2e Emission Intensity:
UNIT: Metric Tons CO2e
DESCRIPTION: Life cycle CO2e emissions associated with the generation of electricity from various sources.
USE: Used in the functioning of various policies and the calculation of life cycle emissions from the electricity sector.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: Energy Protection Agency (EPA) eGRID2006 Version 2.1 (data from 2004), http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html; and US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009) http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
SNG assumed to be 70% of coal and the impact of CCS on IGCC is calculated with a different variable.

Combustion Carbon Intensity Emissions:
UNIT: Metric Tons CO2e

DESCRIPTION: Combustion CO_2e emissions associated with the generation electricity from various sources.
USE: Used in the functioning of various policies and the calculation of combustion emissions from the electricity sector.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE:
SNG: Coal with 30% CO_2e reduction
IGG/CCS: Coal with 70% CO_2e reduction
Existing Pulverized Coal: Energy Protection Agency (EPA) eGRID2006 Version 2.1(data from 2004); http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html
New Pulverized Coal: Energy Protection Agency (EPA) eGRID2006 Version 2.1 (data from 2004); http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html
Gas Electric: Natural gas chemical composition
Biomass: CH_4 and N_2O Wood/Waste, International Panel on Climate Change (IPCC) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, accessed 2008, http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html
Photovoltaic: Assumption
Wind Turbines: Assumption
Old Nuclear: Assumption
New Nuclear: Assumption
Hydroelectric: Assumption

Average Time to Construct Electricity Production Capacity:
UNIT: Years
DESCRIPTION: Average time it takes to construct capacity for electricity production.
USE: Used to calculate the construction completion rate of electricity production capacity.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: Expert consultation

Average Life of Electricity Production Capacity:
UNIT: Years
DESCRIPTION: Average life of capacity for electricity production.
USE: Used to calculate the decommission rate of electricity production capacity.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: Assumption

Excess Imports or Exports as a Fraction of Total Electricity Demand:
UNIT: Fraction (eg. 10% would be 0.10)
DESCRIPTION: Sets an upper or lower level ratio of export/import relative to the expansion or contraction of total electricity demand.
USE: Use this to establish state or region level of electricity exports/imports. Input a fraction to represent the excess electricity that is exported or imported as a percentage of total demand.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Annual Maximum Electricity Market Capture Rate:
UNIT: Fraction
DESCRIPTION: Maximum annual growth possible from one technology.
USE: Used to model technological limitations on capacity growth not extensively modeled.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: Assumption

Federal Renewable Portfolio Standard:
UNIT: Fraction
DESCRIPTION: Federal version of the NonFederal Renewable Portfolio Standard policy.
USE: Used in conjunction with its NonFederal version to determine the most restrictive renewable portfolio standard.

SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: Modeling assumption

Imported Electricity Price Relative to State or Region Prices:
UNIT: Fraction
DESCRIPTION: Expected price of electricity imported into the state relative to in state or region prices.
USE: Used to determine whether the electricity system is predisposed towards importing or exporting electricity.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption

Initial Electricity Production Capacity in 2000:
UNIT: TWh
DESCRIPTION: State or regional electricity production capacity of each generation technology (see subscripts) in the year 2000. This is the baseline electricity production of each generation technology (see subscripts) onto which new capacity is added.
USE: Input an initial electricity production capacity for each generation technology in TWh for the year 2000.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: Energy Information administration (EIA) State Energy Data System (SEDS) (2000); http://www.eia.doe.gov/emeu/states/_seds.html

Electricity Technology Availability Start Date:
UNIT: Year
DESCRIPTION: Date in which a particular electricity technology becomes available for construction.
USE: Used to limit electricity technologies so that they do not become available for construction until after the date set.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: ICF International (2008, August 22). Strawman Assumptions for Discussion Purposes Part II (Not for Distribution). Prepared for Modeling Subgroup, Midwest Greenhouse Gas Reduction Accord. http://www.icfi.com/default.asp

Expected Electricity Loss from Generation Transmission and Distribution:
UNIT: Fraction
DESCRIPTION: Expected electricity loss from generation, transmission, and distribution as a fraction of total electricity.
USE: Accounts for the disconnect between demand and production capacity needed to meet that demand from efficiency losses in generation, transmission, and distribution of electricity.
SUBSCRIPTS USED: N/A
DATA SOURCE: Energy Information Administration (EIA) Annual Energy Review (AER), accessed 2008; http://www.eia.doe.gov/emeu/aer/whatsnew.html

Electricity Carbon Capture and Storage Rate:
UNIT: Fraction
DESCRIPTION: The portion of combustion emissions being captured by CCS for use with IGCC.
USE: Used reduce the emissions from coal use in IGCC.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: Baseline values are zero or assumptions (SNG and ICGG + CCS).

Wind Capacity Limit Relative to Total Capacity:
UNIT: Fraction
DESCRIPTION: Maximum percentage of total capacity that can come from wind turbines
USE: Used to cap amount of electricity from wind turbines
SUBSCRIPTS USED: N/A
DATA SORCE: Generalized assumption

Minimum Natural Gas Needed as a Fraction of Wind:
UNIT: Fraction

DESCRIPTION: Minimum natural gas needed to supplement wind turbine use on the electricity grid. Used as a back-up electricity production capacity for when the wind is not blowing.
USE: Input the fraction of wind generation that needs to be backed up by natural gas generation.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption

Minimum Natural Gas for Peak Electricity Use:
UNIT: Fraction
DESCRIPTION: Minimum natural gas maintained to meet peak demand.
USE: Used to represent capacity needed on an incongruent time scale.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption

ELECTRICITY- COSTS AND PRICES

Electricity Investment Discount Rate:
UNIT: Fraction
DESCRIPTION: Discount rate used in the electricity sector.
USE: Used to calculate levelized average costs of particular electricity technologies in order to make decisions about construction.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: ICF International (2008, August 22). Strawman Assumptions for Discussion Purposes Part II (Not for Distribution). Prepared for Modeling Subgroup, Midwest Greenhouse Gas Reduction Accord. http://www.icfi.com/default.asp

Electricity Technology Construction Costs:
UNIT: Dollar/TWh
DESCRIPTION: Electricity technology construction costs.
USE: Used to calculate levelized average costs of electricity technologies.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: SNG: National Energy Technology Laboratory (NETL) (2007)
http://www.netl.doe.gov/technologies/coalpower/gasification/pubs/systems_analyses.html
Hydroelectric: Energy Information Administration (EIA) Annual Energy Outlook (AEO) (2008), converted to 2009 real dollars, http://www.eia.doe.gov/oiaf/aeo/index.html
Existing Pulverized Coal, New Pulverized Coal, Gas Electric, Biomass, Photovoltaic, Wind Turbines, Old Nuclear, New Nuclear: Assumptions based on data from the Energy Information Administration (EIA) National Energy Modeling System (NEMS) Electricity Market Module (EMM) (2008),
http://www.eia.doe.gov/oiaf/aeo/overview/electricity.html
Data appeared in ICF International (2008, August 22). Strawman Assumptions for Discussion Purposes Part II (Not for Distribution). Prepared for Modeling Subgroup, Midwest Greenhouse Gas Reduction Accord. http://www.icfi.com/default.asp
Data converted to 2009 real dollars.

Electricity Technology Operation and Maintenance Costs:
UNIT: Dollar/TWh
DESCRIPTION: Electricity technology operation and maintenance costs.
USE: Used to calculate levelized average costs for electricity technologies.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: SNG: National Energy Technology Laboratory (NETL) (2007)
http://www.netl.doe.gov/technologies/coalpower/gasification/pubs/systems_analyses.html
Hydroelectric: Energy Information Administration (EIA) Annual Energy Outlook (AEO) (2008), converted to 2009 real dollars, http://www.eia.doe.gov/oiaf/aeo/index.html
Existing Pulverized Coal, New Pulverized Coal, Gas Electric, Biomass, Photovoltaic, Wind Turbines, Old Nuclear, New Nuclear: ICF Assumptions based on data from the Energy Information Administration (EIA) National Energy Modeling System (NEMS) Electricity Market Module (EMM) (2008),
http://www.eia.doe.gov/oiaf/aeo/overview/electricity.html

Data appeared in ICF International (2008, August 22). Strawman Assumptions for Discussion Purposes Part II (Not for Distribution). Prepared for Modeling Subgroup, Midwest Greenhouse Gas Reduction Accord.
http://www.icfi.com/default.asp
Data converted to 2009 real dollars.

Carbon Capture and Storage Main Pipeline Costs:
UNIT: Dollars/KWh
DESCRIPTION: Costs incurred on the first 0.5 TWh required to build the main carbon capture and storage pipeline.
USE: Used to calculate levelized average electricity technology costs.
SUBSCRIPTS USED: N/A
DATA SOURCE: ICF International, Clean Air Task Force, http://www.icfi.com/default.asp.

Carbon Capture and Storage Costs:
UNIT: Dollars/KWh
DESCRIPTION: Costs incurred to develop carbon capture and storage technology on IGCC plants.
USE: Used to calculate levelized average electricity technology costs.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumptions based on data from the Energy Information Administration (EIA) National Energy Modeling System (NEMS) Electricity Market Module (EMM) (2008),
http://www.eia.doe.gov/oiaf/aeo/overview/electricity.html
Data appeared in ICF International (2008, August 22). Strawman Assumptions for Discussion Purposes Part II (Not for Distribution). Prepared for Modeling Subgroup, Midwest Greenhouse Gas Reduction Accord.
http://www.icfi.com/default.asp

Average Electricity Plant Size:
UNIT: TWh
DESCRIPTION: The average size of an electricity generating plant.
USE: Used to calculate the CCS production tax credit limit given a maximum tax credit assumed.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption

ELECTRICITY- LCFS CO2E CAP
ELECTRICITY- C&T CO2E CAP

Maximum Limit to Efficiency Improvements:
UNIT: Fraction
DESCRIPTION: Relative to what would happen without efficiency policy, this is the maximum fraction of that reference case that can be reduced through efficiency policy.
USE: Used to set the maximum amount of efficiency gains.
SUBSCRIPTS USED: N/A
DATA SOURCE: Generalized assumption

Initial Credits Available in the Credit Market in Year 2000:
UNIT: Metric Tons CO2e
DESCRIPTION: Amount of CO2 emissions used in credits to use in cap and trade system.
USE: Used as a first year pool of credits that can be used to meet cap and trade obligations.
SUBSCRIPTS USED: N/A
DATA SOURCE: Generalized Assumption

CO2e Credit Costs:
UNIT: Dollar/Metric Ton CO2e
DESCRIPTION: Cost of CO2e credits that can be purchased to meet the cap and trade policy.
USE: Used to set the cost of a CO2e credit for cap and trade.
SUBSCRIPTS USED: N/A
DATA SOURCE: Generalized Assumption

Initial Vehicle Availability in 2000:
UNIT: Vehicles/Year
DESCRIPTION: Theoretical constraint on particular vehicle types that can be purchased in a particular year. However, baseline data set to designed to be unrestrictive.
USE: Used to constrain the types of vehicles available for purchase in any particular year.
SUBSCRIPTS USED: Efficiency Level (high and low) and Engine Fuel Type
DATA SOURCE: Assumed to be high; unrestrictive

Average Vehicle Life:
UNIT: Year
DESCRIPTION: Average lifespan of a vehicle as a part of the fleet.
USE: Used to calculate the vehicle decommission rate.
SUBSCRIPTS USED: Engine Fuel Type
DATA SOURCE: Modeling default (13 years). Baseline Data: Espey, M. & S. Nair (2005). Automobile fuel economy: What is it worth? *Contemporary Economic Policy*, vol. 23, no. 3, July, pp. 317-323, http://www3.interscience.wiley.com/journal/120832563/abstract?CRETRY=1&SRETRY=0

Ecodriver Improvement Rate:
UNIT: Fraction
DESCRIPTION: Ecodriver Improvement rate is the fraction of fuel efficiency attributed to fuel efficient driving behavior.
USE: Used to estimated impact of ecodriving on vehicle fuel efficiency.
SUBSCRIPTS USED: N/A
DATA SOURCE: Consultation with Liz Marshall from World Resources Institute (2009).

Federal CAFE Passenger Vehicle Standards
UNIT: Miles/Gallon
DESCRIPTION: Federal version of the Corporate Average Fuel Economy (CAFE) standard policy.
USE: Used to improve the vehicle fuel efficiency of new passenger vehicles and therefore improving the average fleet vehicle efficiency.
SUBSCRIPTS USED: N/A
DATA SOURCE: National Highway Traffic Safety Administration (NHTSA) (2008), Federal CAFE Standard, http://www.nhtsa.gov/cars/rules/cafe/overview.htm. Baseline data from NHTSA 49 CFR Parts 523, 531, 533, 534, 536 and 537, [Docket No. NHTSA-2008 -0089], RIN 2127-AK29: Average Fuel Economy Standards, Passenger Cars and Light Trucks, Model Years 2011-2015.

Federal CAFE Truck Standards
UNIT: Miles/Gallon
DESCRIPTION: Federal version of the Corporate Average Fuel Economy (CAFE) standard policy.
USE: Used to improve the vehicle fuel efficiency of new trucks and therefore improving the average fleet vehicle efficiency.
SUBSCRIPTS USED: N/A
DATA SOURCE: National Highway Traffic Safety Administration (NHTSA) (2008), Federal CAFE Standard, http://www.nhtsa.gov/cars/rules/cafe/overview.htm. Baseline data from NHTSA 49 CFR Parts 523, 531, 533, 534, 536 and 537, [Docket No. NHTSA-2008 -0089], RIN 2127-AK29: Average Fuel Economy Standards, Passenger Cars and Light Trucks, Model Years 2011-2015.

Federal Clean Car Passenger Vehicle Standards
UNIT: Grams/Mile
DESCRIPTION: Federal version of the clean car standard policy.
USE: Used to improve the vehicle emission level of new vehicles and therefore improving the average fleet vehicle emissions.
SUBSCRIPTS USED: N/A

DATA SOURCE: Proposed Clean Car MPG equivalents and converted to g/mile using California Air Resources Board (CARB) data, http://www.arb.ca.gov/homepage.htm

Federal Clean Car Truck Standards
UNIT: Grams/Mile
DESCRIPTION: Federal version of the clean car standard policy.
USE: Used to improve the vehicle emission level of new vehicles and therefore improving the average fleet vehicle emissions.
SUBSCRIPTS USED: N/A
DATA SOURCE: Proposed Clean Car MPG equivalents and converted to g/mile using California Air Resources Board (CARB) data, http://www.arb.ca.gov/homepage.htm

Initial Vehicle Fuel Economy in 2000:
UNIT: Miles/Gallon
DESCRIPTION: Starting fuel economy if the current vehicle fleet.
USE: Used as a starting point for the average vehicle fuel economy of the vehicle fleet.
SUBSCRIPTS USED: Engine Fuel Type
DATA SOURCE: Gasoline and Diesel: Research and Innovative Technology Administration (RITA) Bureau of Transportation Statistics Table 4-23: Average Fuel Efficiency of U.S. Passenger Cars and Light Trucks, http://www.bts.gov/publications/national_transportation_statistics/html/table_04_23.html
Electric and Natural Gas: US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009) http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

Initial New Vehicle Fuel Efficiency in 2000:
UNIT: Miles/Gallon
DESCRIPTION: Actual average vehicle fuel economy of vehicles in the year 2000.
USE: Used as a starting point for actual new vehicle fuel economy and what new vehicle fuel economy would be if no policies were introduced.
SUBSCRIPTS USED: Engine Fuel Type
DATA SOURCE: Gasoline and Diesel: Research and Innovative Technology Administration (RITA) Bureau of Transportation Statistics Table 4-23: Average Fuel Efficiency of U.S. Passenger Cars and Light Trucks, http://www.bts.gov/publications/national_transportation_statistics/html/table_04_23.html
Electric and Natural Gas: US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009) http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

Annual Percent Change in Vehicle Fuel Efficiency from Improvements in Technology:
UNIT: Fraction
DESCRIPTION: Generated from historical data, this is the rate at which the average vehicle fuel economy of new vehicles increases ignoring the impacts of policy.
USE: Used to estimate growth in fuel economy not driven by policy.
SUBSCRIPTS USED: N/A
DATA SOURCE: Research and Innovative Technology Administration (RITA) Bureau of Transportation Statistics Table 4-23: Average Fuel Efficiency of U.S. Passenger Cars and Light Trucks, http://www.bts.gov/publications/national_transportation_statistics/html/table_04_23.html

TRANSPORTATION- VEHICLE COSTS AND PRICES

Vehicle Investment Discount Rate:
UNIT: Fraction
DESCRIPTION: The discount rate assumed for calculating the net present value of investing in a vehicle. Used to calculate the capital recovery factor which is used to calculate levelized average vehicle costs.
USE: Input a discount rate percentage as a fraction.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption based on expert consultation

Vehicle NonFuel Operation and Maintenance Costs:
UNIT: Dollar/vehicle
DESCRIPTION: Miscellaneous costs of operating and maintaining a vehicle not including fuel costs.
USE: Used to calculate levelized average vehicle costs.
SUBSCRIPTS USED: Fuel Type
DATA SOURCE: AAA (2007), Your Driving Costs 2007, http://www.aaaexchange.com/Assets/Files/20073261133460.YourDrivingCosts2007.pdf minus annual insurance costs

Vehicle Demand Elasticity:
UNIT: Fraction
DESCRIPTION: Vehicle demand elasticity in the vehicle sector.
USE: Used to calculate the impact of vehicle prices on vehicle demand.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption based on expert consultation (-0.3).

Vehicle Average Annual Insurance Cost:
UNIT: Dollar/ Vehicle
DESCRIPTION: Average annual insurance cost of vehicles.
USE: Used to calculate levelized average vehicle costs.
SUBSCRIPTS USED: Efficiency (high, low) and Engine Fuel Type
DATA SOURCE: AAA (2007), Your Driving Costs 2007, http://www.aaaexchange.com/Assets/Files/20073261133460.YourDrivingCosts2007.pdf, subtracted from Vehicle NonFuel O&M costs.

Pay as You Drive Insurance:
UNIT: Dollar/mile
DESCRIPTION: Cost of pay as you drive insurance which is applied on top of fuel prices.
USE: Input value in dollars per mile for additional costs of PAYD insurance
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Vehicle Prices:
UNIT: Dollar/Vehicle
DESCRIPTION: The average price of vehicles as seen by the consumer (i.e. also includes sales tax).
USE: Used to calculate levelized average vehicle cost.
SUBSCRIPTS USED: Efficiency (high, low) and Engine Fuel Type
DATA SOURCE: AAA Website accessed 2008, http://www.aaa.com/AAA_Travel/AutoBuying/car_buying_service.htm

Fuel Economy Range:
UNIT: Fraction
DESCRIPTION: Sets the efficiency level for the low and high fuel economy vehicle subscript. That is, if new vehicle efficiency is 10 and the range is 20%, low efficiency vehicles will be 8 and high efficiency vehicles will be 12.
USE: Used to establish a limit range of additional vehicle options for consumers.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption based on expert consultation

TRANSPORTATION- FUEL PRODUCTION INFRASTRUCTURE

Average Time to Build Fuel Production Capacity:
UNIT: Number of Years
DESCRIPTION: Time in years it takes to build out fuel production capacity.
USE: Used to determine construction completion rate for fuel production infrastructure.
SUBSCRIPTS USED: Transportation Technology

DATA SOURCE: Assumption based on expert consultation

Annual Maximum Fuel Market Capture Rate:
UNIT: Fraction
DESCRIPTION: Maximum Potential growth available for a particular fuel pathway in a given year. This variable is based on growth relative to all fuel production.
USE: Used to approximate the impact of more technology and financial specific related limitations on the growth in the industry.
SUBSCRIPTS USED: Fuel Pathways
DATA SOURCE: Assumption based on expert consultation

Excess Imports or Exports as a Fraction of Total Fuel Demand:
UNIT: Fraction (e.g. 10% would be 0.10)
DESCRIPTION: The maximum fraction of total demand that can be met by and the maximum fraction that state or region production will grow to produce exports. Sets an upper or lower level ratio of export/import relative to the expansion or contraction of total electricity demand.
USE: Used to limit the level of state or region demand that can be met by imports and limits the level of electricity production growth to supply exports. Input a fraction to represent the excess electricity that is exported or imported as a percentage of total demand. This variable does not impact what would occur if there is a temporary production shortfall because of unanticipated growth in demand.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input

Average Life of Fuel Production Capacity:
UNIT: Number of Years
DESCRIPTION: The average lifespan of a fuel production plant or refinery. Used to calculate the rate at which fuel production infrastructure is decommissioned and the capital recovery factor for fuel production technologies.
USE: Input an assumed average lifespan for each fuel type.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: Assumption based on expert consultation

Imported Fuel Price Relative to State or Region Prices:
UNIT: Fraction
DESCRIPTION: Percentage above or below in state or region import fuel prices are.
USE: Used to determine whether the system will import or export fuels up to the maximum fraction.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: Assumption based on expert consultation

Transportation Technology Availability Start Date:
UNIT: Year
DESCRIPTION: Date in which a particular transportation fuel technology becomes available.
USE: Transportation technologies do not become available for construction until after the date set.
SUBSCRIPTS USED: Fuel Pathways
DATA SOURCE: Assumption based on expert consultation.
Note: Oil Sands start date was set by the modeling team to limit the utilization of oil sand feedstocks in certain states to reflect reality.

Initial Fuel Production Capacity in 2000:
UNIT: Trillion BTUs
DESCRIPTION: Initial existing fuel production capacity needed to supply in state fuel demands.
USE: Used to set initial fuel production capacity.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: Coal to Liquids, Cellulosic Ethanol, Natural Gas, Adv Biodiesel values all 0. Refinery and Oil sands baseline data: Energy Information Administration (EIA) Annual Energy Outlook (AEO) accessed 2008, http://www.eia.doe.gov/oiaf/aeo/index.html

Corn Grain Ethanol baseline data: Minnesota data from Minnesota Department of Agriculture (MDA) Ethanol Program (2000 data), http://www.mda.state.mn.us/en/renewable/ethanol/about.aspx, other states baseline data based on the assumption that 2009 proportions of national ethanol production are the same as 2000.
Biodiesel: assumption- 10% of ethanol.

TRANSPORTATION- FUEL INFRASTRUCTURE COSTS

Transportation Technology Construction Costs:
UNIT: Dollar/Trillion BTU
DESCRIPTION: Transportation fuel technology construction costs.
USE: Used to calculate levelized average costs which are then used to make construction and blending decisions.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCES: Refinery, Oil Sands, Natural Gas: Assumptions
Coal to Liquid: National Energy Technology Laboratory (NETL) and US Department of Energy (DOE) (2009), Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass. DOE/NETL- 2009/1349.
http://www.netl.doe.gov/energy-analyses/pubs/CBTL%20Final%20Report.pdf
Corn Grain Ethanol, Cellulosic Ethanol: Tiffany, D. & Taff, S. J. (2009). Current and future ethanol production technologies: costs of production and Rates of Return on invested capital. Int. *J. Biotechnology. 11*(1/2):75-91.
Biodiesel: Paulson, N & Ginder, R (2007). The Growth and Direction of the Biodiesel Industry in the United States. Working Paper 07-WP 448. *Center for Agricultural and Rural Development, Iowa State University.*
http://www.agmrc.org/media/cms/CARD07PaulsonGinder_751A2F9827ABF.pdf
Adv. Biodiesel: None; value is 0
Transportation Investment Discount Rate
UNIT: Fraction
DESCRIPTION: Discount rate used in the transportation fuel sector.
USE: Used to calculate levelized average costs which influences construction and blending decisions.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: Assumption based on expert consultation (5%).

Transportation Technology Operation and Maintenance Costs:
UNIT: Dollar/Trillion BTU
DESCRIPTION: Transportation fuel technology operation and maintenance costs.
USE: Used to calculate levelized average costs which are then used to make construction and blending decisions.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: Refinery, Oil Sands: Assumptions
Coal to Liquid: National Energy Technology Laboratory (NETL) and US Department of Energy (DOE) (2009), Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass. DOE/NETL- 2009/1349.
http://www.netl.doe.gov/energy-analyses/pubs/CBTL%20Final%20Report.pdf Kreutz, et al. (2008). Fischer-Tropsch Fuels From Coal and Biomass. *Princeton Environmental Institute, Princeton University.*
http://web.mit.edu/mitei/docs/reports/kreutz-fischer-tropsch.pdf
Corn Grain Ethanol, Cellulosic Ethanol: Tiffany, D. & Taff, S. J. (2009). Current and future ethanol production technologies: costs of production and Rates of Return on invested capital. Int. *J. Biotechnology. 11*(1/2):75-91.
Biodiesel: Paulson, N & Ginder, R (2007). The Growth and Direction of the Biodiesel Industry in the United States. Working Paper 07-WP 448. *Center for Agricultural and Rural Development, Iowa State University.*
http://www.agmrc.org/media/cms/CARD07PaulsonGinder_751A2F9827ABF.pdf
Natural Gas: Expert consultation
Adv. Biodiesel: None; value is 0
Federal Fuel Feedstock Taxes or Subsidies
UNIT: Dollar/Trillion BTU
DESCRIPTION: Federal feedstock transportation fuel technology tax or subsidy policy.
USE: Used to calculate levelized average costs which influences construction and blending decisions.
SUBSCRIPTS USED: Fuel Pathways
DATA SOURCE: Policy input.
TRANSPORTATION- LIFE CYCLE EMISSIONS

Coal to Liquids Biomass Percentage:

UNIT: Fraction
DESCRIPTION: Percentage of biomass mixed into the production of coal to liquids fuels.
USE: This is used to decrease CTL life cycle emissions. Essentially applies a discount to Upstream Emissions and Emissions from Combustion based on the percentage of biomass assumed.
SUBSCRIPTS USED: Transportation Technology- Coal to Liquids only
DATA SOURCE: Input graph, assumed 30% initial value.

Coal to Liquids Carbon Capture and Storage:
UNIT: Fraction
DESCRIPTION: Percentage of emissions from the blender/refiner that are sequestered and stored.
USE: Used to reduce the emissions from the blender/refiner step in the production of coal to liquids fuel.
SUBSCRIPTS USED: Transportation Technology- Coal to Liquids only
DATA SOURCE: Input graph, assumed 50% initial value.

Emissions from Vehicle Construction:
UNIT: Metric Tons CO2e/Trillion BTU
DESCRIPTION: Emission intensity associated with the production of vehicles with particular engine types.
USE: Input an emission intensity to assume inclusion of vehicle construction in fuel life cycle assessment.
SUBSCRIPTS USED: Engine Fuel Type
DATA SOURCE: None

Indirect Land Use:
UNIT: Metric Ton CO2e/Trillion BTU
DESCRIPTION: Emissions associated with indirect land use changes that occur with the production of fuel feedstocks.
USE: Used to calculate full fuel cycle GHG emissions from fuels.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: User input.

Upstream Emissions Gasoline:
UNIT: Metric Tons CO2e/Trillion BTU
DESCRIPTION: Emission intensity associated with the extraction, growth, storage, and/or transportation of feedstocks used to produce fuels. Also includes the accounting of carbon uptake by plants from biofuels.
USE: Used to calculate non-combustion emissions associated with gasoline production process from each fuel pathway
SUBSCRIPTS USED: Fuel Pathways
DATA SOURCE: US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009)
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
Algae Biodiesel and Adv Biodiesel assumed same as Soybean Biodiesel.

Upstream Emissions Diesel:
UNIT: Metric Tons CO2e/Trillion BTU DESCRIPTION: Emission intensity associated with the extraction, growth, storage, and/or transportation of feedstocks used to produce fuels. Also includes the accounting of carbon uptake by plants from biofuels.
USE: Used to calculate non-combustion emissions associated with diesel production process from each fuel pathway
SUBSCRIPTS USED: Fuel Pathways
DATA SOURCE: US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009)
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
Algae Biodiesel and Adv Biodiesel assumed same as Soybean Biodiesel.

Emissions from Blender or Refiner Gasoline:
UNIT: Metric Tons CO2e/Trillion BTU
DESCRIPTION: Emission intensity associated with the blending and/or refining of fuels, marketing and distribution, and storage of gasoline fuel components.

USE: Used to calculate non-combustion emissions associated with gasoline blending, refining, marketing, distribution, and storage process from each fuel pathway
SUBSCRIPTS USED: Fuel Pathways
DATA SOURCE: US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009)
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
Algae Biodiesel and Adv Biodiesel assumed same as Soybean Biodiesel.

Emissions from Blender or Refiner Diesel:
UNIT: Metric Tons CO2e/Trillion BTU
DESCRIPTION: Emission intensity associated with the blending and/or refining of fuels, marketing and distribution, and storage of diesel fuel components.
USE: Used to calculate non-combustion emissions associated with diesel blending, refining, marketing, distribution, and storage process from each fuel pathway
SUBSCRIPTS USED: Fuel Pathways
DATA SOURCE: US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009)
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
Algae Biodiesel and Adv Biodiesel assumed same as Soybean Biodiesel.

Emissions from Combustion Diesel:
UNIT: Metric Tons CO2e/Trillion BTU
DESCRIPTION: Emission intensity associated with the operation and maintenance of vehicles using blended fuel components.
USE: Used to calculate combustion emissions associated with diesel fuels for each fuel pathway
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009)
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

Emissions from Combustion Gasoline:
UNIT: Metric Tons CO2e/Trillion BTU
DESCRIPTION: Emission intensity associated with the operation and maintenance of vehicles using blended fuel components.
USE: Used to calculate combustion emissions associated with diesel fuels for each fuel pathway
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: US Department of Energy Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009)
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

Drive Train Efficiency Adjustment Factor:
UNIT: Fraction
DESCRIPTION: Drive train related emission intensity adjustment factor to account for the different end fuel use vehicle drive train efficiency (Otherwise known as EER).
USE: Input a drive train efficiency adjustment based on the fuel efficiency of the engine used for each fuel type.
SUBSCRIPTS USED: Engine Fuel Type
DATA SOURCE: California Low Carbon Fuel Standard (LCFS),
http://www.energy.ca.gov/low_carbon_fuel_standard/index.html
Ferrel, A & Sperling, D. (2007), A Low-carbon Fuel Standard for California Part 1: Technical Analysis. Research report UCB-ITS-TSRC-RR-2007-2, *Institute of Transportation Studies, UC Berkley Transportation Sustainability Research Center,* http://www.energy.ca.gov/low_carbon_fuel_standard/UC_LCFS_study_Part_1-FINAL.pdf

TRANSPORTATION- FEDERAL RENEWABLE FUEL STANDARD

Federal Renewable Fuel Standard for Cellulosic Biofuel:
UNIT: Fraction

DESCRIPTION: Federal fuel standard for cellulosic biofuel as a fraction of total transportation fuel
USE: Used to mandate certain levels of cellulosic biofuel use.
SUBSCRIPTS USED: N/A
DATA SOURCE: Renewable Fuels Association (RFA) Renewable Fuel Standards (RFS) page, accessed 2009, http://www.ethanolrfa.org/resource/standard/

Federal Renewable Fuel Standard for Advanced Biofuel:
UNIT: Fraction
DESCRIPTION: Federal fuel standard for advanced biofuel as a fraction of total transportation fuel
USE: Used to mandate certain levels of advanced biofuel use.
SUBSCRIPTS USED: N/A
DATA SOURCE: Renewable Fuels Association (RFA) Renewable Fuel Standards (RFS) page, accessed 2009, http://www.ethanolrfa.org/resource/standard/

Federal Renewable Fuel Standard for Conventional Biofuel:
UNIT: Fraction
DESCRIPTION: Federal fuel standard for conventional biofuel as a fraction of total transportation fuel
USE: Used to mandate certain levels of conventional biofuel use.
SUBSCRIPTS USED: N/A
DATA SOURCE: Renewable Fuels Association (RFA) Renewable Fuel Standards (RFS) page, accessed 2009, http://www.ethanolrfa.org/resource/standard/

Federal Renewable Fuel Standard for Biomass Based Diesel:
UNIT: Fraction
DESCRIPTION: Federal fuel standard for biomass based diesel as a fraction of total transportation fuel
USE: Used to mandate certain levels of biomass based diesel use.
SUBSCRIPTS USED: N/A
DATA SOURCE: Renewable Fuels Association (RFA) Renewable Fuel Standards (RFS) page, accessed 2009, http://www.ethanolrfa.org/resource/standard/ .

Portion of the Vehicle Fleet Composed of Flex Fuel Vehicles:
UNIT: Fraction
DESCRIPTION: Assumption of what percentage of gasoline fuel demand is from flex fuel vehicles that can handle higher blends of ethanol.
USE: Input a trend for adoption of flex fuel vehicles as a percentage of the total passenger vehicle fleet.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption

TRANSPORTATION- CO2E CAP
TRANSPORTATION- FUEL PRICES

Impact of VMT Reducing Policy:
UNIT: Dollar/Mile
DESCRIPTION: How much a dollar of vehicle miles traveled (VMT) reduction spending will reduce per vehicle average VMT.
USE: Used to calculate per vehicle VMT given VMT reduction spending.
SUBSCRIPTS USED: VMT Reduction Policy
DATA SOURCE: Pansing, C., Schreffler, E.N. & Sillings, M.A. (2007). Comparative evaluation of the cost-effectiveness of 58 transportation control measures. *Transportation Research Record*, Vol. 1641, Paper No. 98-1100, http://trb.metapress.com/content/1388t6045gm523n7/

Federal Fuel Energy Based Taxes or Subsidies:
UNIT: Dollar/Trillion BTU
DESCRIPTION: Federal energy based taxes or subsidies on fuel.
USE: Used to calculate the price of consumer fuels.

SUBSCRIPTS USED: Liquid Fuels
DATA SOURCE: American Petroleum Institute (API) Motor Fuel Notes (2009), http://www.api.org/statistics/fueltaxes/index.cfm

Fuel Demand Elasticity:
UNIT: Fraction
DESCRIPTION: Demand elasticity used in the transportation fuel sector.
USE: Used to calculate the impact of prices on consumer vehicle miles traveled (VMT) from improving vehicle economy and VMT impact from changes in prices.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input, baseline value based on assumption

Initial Price of the Fuel Blend in the Year 2000:
UNIT: Dollars/Trillion BTU
DESCRIPTION: initial average price of fuel blends in the year 2000.
USE: Used to determine initial impacts of changing prices on vehicle miles traveled (VMT) and calculate a percentage markup for fuel prices.
SUBSCRIPTS USED: Engine Fuel Type
DATA SOURCE: Gasoline: Energy Information Administration (EIA) Retail Gasoline Historical Prices (2000), http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_history.html
Diesel: EIA Petroleum Navigator (2000), http://tonto.eia.doe.gov/dnav/pet/hist/ddr003m.htm
Electric: Energy Information Administration (EIA) Average Retail Price of Electricity to Ultimate Consumers by End-Use Sector (2000) http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html#_ftn1
Natural Gas: Energy Information Administration (EIA) Henry Hub price (2000)

NONELECTRIC BUILDING HEATING

Full Fuel Cycle Sector Facility Emissions:
UNIT: Metric Tons CO2e/Trillion BTU
DESCRIPTION: Emission intensity of nonelectric building heating on a full fuel life cycle basis.
USE: Input a life cycle emission intensity for nonelectric building heating source in metric tons CO2e per trillion BTUs.
SUBSCRIPTS USED: NonElectric Building Heating Technology and Primary Sector
DATA SOURCE: Environmental Protection Agency (EPA) eGRID2002 Version 2.01 (2000 Data), http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html

Average NonElectric Building Heating Capacity Life:
UNIT: Number of Years
DESCRIPTION: Life of nonelectric building heating capacity life.
USE:Used to calculate the decommission rate of nonelectric building heating capacity.
SUBSCRIPTS USED: NonElectric Building Heating Technology and Primary Sector
DATA SOURCE: Assumption based on expert consultation

Combustion Sector Facility Emissions:
UNIT: Metric Tons CO2e/Trillion BTU
DESCRIPTION: Emission intensity of nonelectric building heating on a combustion only basis.
USE: Input a combustion emission intensity for nonelectric building heating source in metric tons CO2e per trillion BTUs.
SUBSCRIPTS USED: NonElectric Building Heating Technology and Primary Sector
DATA SOURCE: Environmental Protection Agency (EPA) eGRID2002 Version 2.01 (2000 Data), http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html

NonElectric Building Heating Demand Elasticity:
UNIT: Fraction
DESCRIPTION: Demand elasticity used in the nonelectric building heating sector.
USE: Used to calculate the impacts of changing nonelectric building heating prices on demand.

SUBSCRIPTS USED: N/A
DATA SOURCE: Modeling assumption based on expert consultation (-0.10).

Average NonElectric Building Heating Capacity Construction Time:
UNIT: Number of Years
DESCRIPTION: Time required to construct additional nonelectric building heating capacity.
USE: Used to calculate the construction completion rate.
SUBSCRIPTS USED: NonElectric Building Heating Technology and Primary Sector
DATA SOURCE: Assumption
ENERGY EFFICIENCY- POLICY

Number of Years to Include in Average Building Demand:
UNIT: Number of Years
DESCRIPTION: Number of years used to include in the calculation of average building electricity demand.
USE: Used to calculate average demand as a part of the general efficiency mandate
SUBSCRIPTS USED: N/A
DATA SOURCE: None (3 year default)
Growth in Energy Demand from Construction by Sector:
UNIT: Fraction
DESCRIPTION: Growth in energy demand from new construction.
USE: Used to calculate how much energy demand growth is from construction.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis. Residential: EE6 line 48, Commercial: 66, Industrial: EE6 line 48, 66, and EE5 line 43. http://www.midwesterngovernors.org/energy.htm

Average Existing Public Building Electric Efficiency:
UNIT: Trillion BTU/Square Feet
DESCRIPTION: Average efficiency of existing public buildings in the electric sector.
USE: Used to calculate efficiency improvements required under efficiency policies.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Energy Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE6 Line 66. http://www.midwesterngovernors.org/energy.htm

Average Existing Public Building NonElectric Efficiency:
UNIT: Trillion BTU/Square Feet
DESCRIPTION: Average efficiency of existing public buildings in the nonelectric sector.
USE: Used to calculate efficiency improvements required under efficiency policies.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE6 Line 67. http://www.midwesterngovernors.org/energy.htm

Average New Public Building Electric Efficiency:
UNIT: Trillion BTU/Square Feet
DESCRIPTION: Average efficiency of new public buildings in the electric sector.
USE: Used to calculate efficiency improvements required under efficiency policies.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE6 Line 68. http://www.midwesterngovernors.org/energy.htm

Average New Public Building Non Electric Efficiency:
UNIT: Trillion BTU/Square Feet
DESCRIPTION: Average efficiency of new public buildings in the nonelectric sector.

USE: Used to calculate efficiency improvements required under efficiency policies.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE6 Line 69. http://www.midwesterngovernors.org/energy.htm

Existing Public Buildings:
UNIT: Square Feet
DESCRIPTION: Existing Public Buildings
USE: Used to calculate efficiency improvements in existing buildings in the nonelectric building heating and electric sector.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE6 Commercial Floorspace with Public Fraction. http://www.midwesterngovernors.org/energy.htm

New Public Buildings:
UNIT: Square Feet
DESCRIPTION: New public building annually.
USE: Used to calculate efficiency improvements in buildings in the nonelectric building heating and electric sector.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE6 Implied New Commercial Floorspace with Public Fraction (Line 66). http://www.midwesterngovernors.org/energy.htm

Rate of Compliance with Building Codes:
UNIT: Fraction
DESCRIPTION: Fraction of compliance with building codes
USE: Used to impact the potential impact of the building codes policy.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis. http://www.midwesterngovernors.org/energy.htm

Ratio of Space Conditioning to Total Electricity Demand:
UNIT: Fraction
DESCRIPTION: Portion of electricity demand devoted to building heating that is therefore reduced by new building codes.
USE: Portion of electricity demand devoted to building heating that is therefore reduced by new building codes.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis. http://www.midwesterngovernors.org/energy.htm

Ratio of Space Conditioning to Total NonElectric Building Heating Demand:
UNIT: Fraction
DESCRIPTION: Portion of electricity demand devoted to building heating that is therefore reduced by new building codes.
USE: Used to calculate the fraction of total electricity used for heating.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis. http://www.midwesterngovernors.org/energy.htm

Private Efficiency Improvements Beyond Code Compliance Rate:
UNIT: Fraction

DESCRIPTION: Assumed efficiency improvements in the private sector beyond what is required by policy.
USE: Input an efficiency improvement trend to assume additional private efficiency increases by a percentage amount.
SUBSCRIPTS USED: Primary Sector
DATA SOURCE: User input assumption, baseline data from MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis. http://www.midwesterngovernors.org/energy.htm

State/Provincial Local Fraction of Public Space:
UNIT: Fraction
DESCRIPTION: Portion of public buildings that are state or local buildings that can be governed by efficiency policy.
USE: Used to implement efficiency policy on state/local public buildings
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis. http://www.midwesterngovernors.org/energy.htm

NonElectric Building Heating Efficiency Mandate Overlap:
UNIT: Fraction
DESCRIPTION: Amount of overlap efficiency mandates have with efficiency investment.
USE: Used to calculate overlap between efficiency mandates and investment.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis. http://www.midwesterngovernors.org/energy.htm

Electricity Efficiency Mandate Overlap:
UNIT: Fraction
DESCRIPTION: Amount of overlap efficiency mandates have with efficiency investment.
USE: Used to calculate overlap between efficiency mandates and investment.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis. http://www.midwesterngovernors.org/energy.htm

Time Needed to Retrofit Existing Buildings:
UNIT: Number of Years
DESCRIPTION: Assumption of the number of years needed to retrofit existing buildings for efficiency improvements.
USE: Input the assumed number of years.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption based on consultation with Liz Marshall from World Resources Institute (2009).

ENERGY EFFICIENCY- SPENDING

Cost of Saving Energy from Appliance Standards:
UNIT: Dollar/Trillion BTUs
DESCRIPTION: Expected costs of implementing appliance standards and is used to calculate the economic impacts of the appliance standards policy.
USE: Input the appliance standards policy to change the costs of saving energy from appliances.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE5 Standards that Save Electricity

Cost of Saving Energy:
UNIT: Dollar/Trillion BTU
DESCRIPTION: Cost to save energy through efficiency improvements.
USE: Used to calculate the spending required to achieve energy efficiency and the cost of efficiency mandates.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE3 Levelized Incremental Cost of Electricity Efficiency. http://www.midwesterngovernors.org/energy.htm

Cost of Saving Energy from Building Codes:
UNIT: Dollar/Trillion BTU
DESCRIPTION: Cost of energy efficiency through building codes.
USE: Used to calculate how much must be spent to achieve a certain level of building efficiency.
SUBSCRIPTS USED: N/A
DATA SOURCE: MGA EEAG (2008), Estimate of Mitigation Option Costs and Benefits for Midwestern Governors' Association (MGA) Energy Efficiency Advisory Group (EEAG) GHG Analysis: EE6 Avoided Electricity Cost. http://www.midwesterngovernors.org/energy.htm

FEEDSTOCK- AVAILABILITY

Algae Availability:
UNIT: Trillion BTU
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Currently, there is no industrial fuel algae production.

Corn Grain Availability:
UNIT: Trillion BTU
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: National Agricultural Statistics Service (NASS) (2000 data), http://www.nass.usda.gov/Statistics_by_Subject/index.asp

Wind Electric Availability:
UNIT: TWh
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: American Wind Energy Association (AWEA) Top 20 States with Wind Energy Resource Potential (1991 data), http://www.awea.org/pubs/factsheets/Top_20_States.pdf

Coal Availability:
UNIT: Trillion BTUs
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Energy Information Administration (EIA) Table 7.2 Coal Production, 1949-2008 (2000 data), http://www.eia.doe.gov/emeu/aer/txt/ptb0702.html

Soybean Availability:
UNIT: Trillion BTUs
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A

DATA SOURCE: DATA SOURCE: National Agricultural Statistics Service (NASS) (2000 data), http://www.nass.usda.gov/Statistics_by_Subject/index.asp

EOR Oil Availability:
UNIT: Trillion BTUs
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumed no current or year 2000 utilization of EOR oil.

Oil Sands Availability:
UNIT: Trillion BTUs
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumption due to lack of data

North American Oil Availability:
UNIT: Trillion BTUs
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Energy Information Administration (EIA) International Petroleum Monthly, (2000), http://www.eia.doe.gov/ipm/supply.html

Foreign Oil Availability:
UNIT: Trillion BTUs
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Energy Information Administration (EIA) International Petroleum Monthly, (2000), http://www.eia.doe.gov/ipm/supply.html

Nuclear Fuel Availability:
UNIT: TWh
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: World Nuclear Association Uranium Production Figures 1998-2008 (2000 data), http://www.world-nuclear.org/info/uprod.html

Biogas Availability:
UNIT: TWh
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Energy Information Administration (EIA) State Energy Data System (SEDS) (2000), http://www.eia.doe.gov/emeu/states/_seds.html ([wood and waste]/2)

Natural Gas Availability:
UNIT: Trillion BTU
DESCRIPTION: Total system availability of energy from natural gas.
USE: Used as a maximum system cap for energy from one source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Energy Information Administration (EIA) Historical Natural Gas Annual 1930 Through 2000: Table 1. Quantity and Average Price of Natural Gas Production in the United States, 1930-2000 (2000 data),

http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/historical_natural_gas_annual/current/pdf/table_01.pdf

Biomass Availability:
UNIT: Trillion BTU
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: Biomass Feedstocks
DATA SOURCE: Grass: National Agricultural Statistics Service (NASS) (2000)
http://www.nass.usda.gov/Statistics_by_Subject/index.asp
Crop residue: Assumption; same as corn (1:1 corn to stover ratio)
Wood: Energy Information Administration (EIA) State Energy Data System (SEDS) (2000),
http://www.eia.doe.gov/emeu/states/_seds.html ([wood and waste]/2)

Sunlight Availability:
UNIT: TWh
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Minnesota Department of Commerce Average Solar Radiation in Minnesota (2002),
http://www.state.mn.us/mn/externalDocs/Commerce/MN_Solar_Map_110802025502_solarmap5.pdf

Hydro Availability:
UNIT: TWh
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Baseline data from Energy Information Administration (EIA) State Energy Data System (SEDS) (2000), http://www.eia.doe.gov/emeu/states/_seds.html, assumed capacity increase of 10%

Advanced Biodiesel Feedstock Availability:
UNIT: Trillion BTU
DESCRIPTION: Annually availability of feedstock for use in the state or region.
USE: Used as an absolute cap on fuel, electricity, or nonelectric building heating from this source.
SUBSCRIPTS USED: N/A
DATA SOURCE: Assumed zero in year 2000.

FEEDSTOCKS PRICES AND EMISSIONS

Biogas Prices:
UNIT: Dollars/TWh
DESCRIPTION: Feedstock costs for waste gas.
USE: Used in the calculation of levelized average costs of electricity productions.
SUBSCRIPTS USED: N/A
DATA SOURCE: None

Uranium Prices:
UNIT: Dollars/TWh
DESCRIPTION: Feedstock costs for uranium.
USE: Used in the calculation of levelized average costs of electricity productions.
SUBSCRIPTS USED: N/A
DATA SOURCE: None

Biogas Feedstock Emissions:
UNIT: Metric Tons CO2e/TWh
DESCRIPTION: Feedstock emissions associate with the upstream generation of waste gas.

USE: Used to calculate natural gas prices based on the proportion from recovered natural gas and waste gas.
SUBSCRIPTS USED: N/A
DATA SOURCE: Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, v. 1.8c.0 (2009)
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

Cost Curve Multiplier:
UNIT: Fraction
DESCRIPTION: Multiplier used for calculating the price effects based on a cost curve for each fuel pathway.
USE: Change the multiplier as appropriate for each fuel pathway.
SUBSCRIPTS USED: Fuel Pathways
DATA SOURCE: ICF International (2008, August 22). Integrated Planning Model (IPM) in Strawman Assumptions for Discussion Purposes Part II (Not for Distribution). Prepared for Modeling Subgroup, Midwest Greenhouse Gas Reduction Accord. http://www.icfi.com/default.asp

CO2E EMISSIONS CO2E BUYOUT

Percentage Below 1990 Emissions Levels:
UNIT: Fraction
DESCRIPTION: Emissions goal above or below the 1990 CO2e emission levels.
USE: Used to calculate policy goal line as a function of 1990 emission levels.
SUBSCRIPTS USED: N/A
DATA SOURCE: N/A; uses 1990 Emissions Levels

1990 CO2e Emissions Levels:
UNIT: Metric Tons CO2e
DESCRIPTION: 1990 CO2e levels of emissions.
USE: Used to generate a goal line for the user interface.
SUBSCRIPTS USED: N/A
DATA SOURCE: International Panel on Climate Change (IPCC), http://www.ipcc.ch/

Required Land Payment per Acre:
UNIT: Dollars/Acre
DESCRIPTION: On average how much it would cost to purchase an acre of land.
USE: Used for calculations involving land use changes.
SUBSCRIPTS USED: N/A
DATA SOURCE: User input, baseline value is an assumption based on expert consultation

CO2 Sequestration per Acre of Corn Converted to Grass:
UNIT: Metric Tons CO2e/Acre
DESCRIPTION: Annual carbon sequestration through the conversion of land being used for corn to grass.
USE: Used to calculate additional carbon sequestered in grass after conversion from corn crop land
SUBSCRIPTS USED: N/A
DATA SOURCE: User input, baseline value is an assumption based on expert consultation

ECONOMIC INDICATORS

Electricity Production Capacity Construction Jobs:
UNIT: Jobs/TWh
DESCRIPTION: Jobs generated from construction.
USE: Used to calculate jobs in the electricity sector.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: None; baseline value is 0

Electricity Production Capacity Operations and Maintenance Jobs:
UNIT: Jobs/TWh

DESCRIPTION: Jobs generated from operation and maintenance of electricity production capacity.
USE: Used to calculate jobs in the electricity sector.
SUBSCRIPTS USED: Electricity Technology
DATA SOURCE: None; baseline value is 0

Fuel Production Capacity Construction Jobs:
UNIT: Jobs/TWh
DESCRIPTION: Jobs generated from construction of fuel production capacity.
USE: Used to calculate jobs in the fuel sector.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: None; baseline value is 0

Fuel Production Capacity Operations and Maintenance Jobs:
UNIT: Jobs/TWh
DESCRIPTION: Jobs generated from operation and maintenance of fuel production capacity.
USE: Used to calculate jobs in the fuel sector.
SUBSCRIPTS USED: Transportation Technology
DATA SOURCE: None; baseline value is 0

Jobs from Demand Reduction Projects:
UNIT: Job/Trillion BTU
DESCRIPTION: Jobs generated through demand reduction in the electricity and nonelectric building heating sector.
USE: Tracking of jobs.
SUBSCRIPTS USED: N/A
DATA SOURCE: None, baseline value is 0

Description and sources of variables not in the user interface:

Fraction of Gasoline Vehicles: Graphical function variable that uses the relative levelized average cost difference between gasoline engines and all other engine types to determine the fraction of vehicles purchases that will be gasoline vehicles. This function assumes other factors in vehicle choice not explicitly modeled.
Baseline Data: none
Units: fraction

Fraction of Diesel Vehicles: Graphical function variable that uses the relative levelized average cost difference between diesel engines and all other engine types to determine the fraction of vehicles purchases that will be diesel vehicles. This function assumes other factors in vehicle choice not explicitly modeled.
Baseline Data: none
Units: fraction

Fraction of Electric Vehicles: Graphical function variable that uses the relative levelized average cost difference between electric engines and natural gas engine types to determine the fraction of vehicles purchases that will be electric vehicles. This function assumes other factors in vehicle choice not explicitly modeled.
Baseline Data: none
Units: fraction

Fraction of High Economy Vehicles by Engine Type: Graphical function variable that uses the relative levelized average cost difference between low efficiency and high efficiency vehicle types to determine the fraction of vehicles purchases that will be gasoline vehicles. This function assumes other factors in vehicle choice not explicitly modeled.
Baseline Data: none
Units: fraction

Cost of Vehicle Fuel Economy Standards: Uses comparison between actual vehicle fuel economy caused by policy to fuel economy without policy to calculate the additional cost of a vehicle.

Baseline Data: None/Calculated from reported cost of CAFÉ plus Clean car standard of 1300 dollars. http://emptywheel.firedoglake.com/2009/05/18/details-on-the-new-fuel-efficiency-standards/
Units: Dollar/Vehicle

Feedstock Costs: Costs associated with extracting, growing, and bringing the feedstock to the fuel production facility. Used to calculate the levelized average cost of fuel production.
Baseline Data: Petroleum and CTL: Energy Information Administration (EIA) Annual Energy Outlook (AEO) (2009), http://www.eia.doe.gov/oiaf/aeo/pdf/0383%282009%29.pdf
Corn Ethanol: Tiffany, D. & Taff, S. J. (2009). Current and future ethanol production technologies: costs of production and rates of return on invested capital. *Int. J. Biotechnology. 11*(1/2):75-91.
Soybean Biodiesel: Tiffany, D. & Taff, S. J. (2009). Current and future ethanol production technologies: costs of production and rates of return on invested capital. *Int. J. Biotechnology. 11*(1/2):75-91.
Paulson, N. & Ginder, R. (2007). The growth and direction of the biodiesel industry in the United States. Working Paper 07-WP 448. *Center for Agricultural and Rural Development, Iowa State University.* http://www.agmrc.org/media/cms/CARD07PaulsonGinder_751A2F9827ABF.pdf
Gas Natural Gas: Energy Information Administration (EIA) Annual Energy Outlook (AEO) (2009), http://www.eia.doe.gov/oiaf/aeo/pdf/0383%282009%29.pdf , plus 50 cents per mmBTU for transport from Henry Hub Algae Biodiesel, Feedstock Adv Biodiesel: None; values are 0
Units: Dollar/Trillion BTU

Life Cycle NonElectric Building Heating CO2e Emission Intensity: Emissions from the life cycle of fuels used in nonelectric building heating. Used to calculate total life cycle emission from nonelectric building heating.
Baseline Data: Oil Use: Fuel oil, diesel emissions
Solar Heating: None
Gas Use: Natural Gas
Nongrid Electricity: Environmental Protection Agency (EPA), eGRID2002 Version 2.01 (2000 Data), http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html
Units: Metric Tons CO2e/Trillion BTUs

Combustion NonElectric Building Heating CO2e Emission Intensity: Emission intensity from combustion of fuels in nonelectric building heating. Used to calculate total combustion emission from nonelectric building heating
Baseline Data: Oil Use: Fuel oil, diesel emissions
Solar Heating: None
Gas Use: Natural Gas
Nongrid Electricity: Environmental Protection Agency (EPA), eGRID2002 Version 2.01 (2000 Data), http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html
Units: Metric Tons CO2e/Trillion BTUs

Basic Feedstock Supply Curve: Biomass curves relating biomass demand to feedstock costs.
Baseline Data: Assumptions based on data from Energy Information Administration (EIA) Annual Energy Outlook (AEO) models (2008) appearing in ICF International (2008, August 22) Strawman Assumptions for Discussion Purposes Part II (Not for Distribution). Prepared for Modeling Subgroup, Midwest Greenhouse Gas Reduction Accord. http://www.icfi.com/default.asp
Units: Dollar/Trillion BTUs

Baseline Year CO2e Emissions for Use in a Electricity CO2e Cap: Emissions in the baseline year used to calculate as the CO2e cap's required reductions in emissions.
Baseline Data: none
Units: Metric Tons CO2e

Biomass Cost Curve Multiplier: Modifies biomass curve input to account for shifts in the biomass curves over time.
Baseline Data: ICF International (2008, August 22). Integrated Planning Model (IPM) in Strawman Assumptions for Discussion Purposes Part II (Not for Distribution). Prepared for Modeling Subgroup, Midwest Greenhouse Gas Reduction Accord. http://www.icfi.com/default.asp
Units: N/A

Minnesota
Low Carbon Fuels Standard Study

Economic Modeling

Contract No. B24112

University of Minnesota

Economic Modeling Research Team:

Jeffrey Apland, Department of Applied Economics, University of Minnesota (principal contact)

Jin-Young Moon, Department of Applied Economics, University of Minnesota

June 2011

Prepared for:

Minnesota Department of Commerce

Table of Contents

List of Figures

List of Tables

Overview

A low carbon fuels standard (LCFS) would require any person producing, refining, blending, or importing transportation fuels in Minnesota to reduce these fuels' average carbon intensity (AFCI), measured across the full fuel cycle: feedstock extraction, production, transport, storage, and use. An LCFS is expected to lower overall emissions from the transportation fleet.

Under a Department of Commerce contract, the University of Minnesota investigated and developed modeling and analytical frameworks with available data in order to compare the greenhouse gas, economic and environmental implications of various low carbon fuel standards policies for vehicles operated on Minnesota public roads. The present report provides findings of work performed for the economic modeling portion of the project. The economic model links Minnesota fuel markets, with demand levels from the policy model, to Minnesota-produced feedstock markets for ethanol and biodiesel fuel.

Our investigations revealed a wide range in data quality and availability. Certain data elements were found to be so uncertain—whether because there is no existing technology or because the policies are under active research—that they were not usefully examined in this section of the study. Both data and modeling will be improved over time through the efforts of current and subsequent researchers. Many of the data elements that are presently unknown or known only within extremely wide bounds will eventually be estimated with more certainty, at which time they might be usefully enfolded into modeling undertaken for this project.

Because of these substantial uncertainties, work reported here should be thought of as a tool for "policy exploration" and not for "policy guidance." We urge readers not to make policy decisions based upon the specific numbers developed in this report.

Economic Model Selection

Economic analyses of public policy changes of the type studies here might be accomplished with a variety of methodologies. Commonly used modeling frameworks include econometric simulation models, input-output analysis, and sector models. All of these frameworks offer potentially useful capabilities for the study of low carbon fuel policies. Input-output analysis relies on statistical data characterizing interactions between sectors of a national or regional economy to predict monetary impacts of external shocks to an economy, such as the construction of a large public works project or the occurrence of a natural disaster. Impact analysis models of this type focus on multiplier effects of these shocks on broad components of the economy, such as manufacturing or service sectors. Detailed changes in fuel technologies, such as those that accompany the development of biofuel markets, are not addressed. Econometric modeling relies on time series of data for relevant markets to develop mathematical estimates of supply and demand behavior for those markets. As such, econometric analysis is better suited to economic analyses that characterize past economic behavior, and are restricted to limitations of the time-series data, such as the aggregation of products, time and location. The sector modeling framework, while conceptually similar in many respects, provides a useful advantage through the use of quantitative models of production technologies, in this case production of biofuel feedstocks and the agricultural commodities with which they compete for land resources, and the fuel processing activities which use the feedstocks, with product demands and resource endowments. Important to the study of biofuels production, sector models may be spatially disaggregated to capture logistical costs. As such, a multi-region sector model was constructed for the study. A general sector model developed at the University of Minnesota, called MAGS for Minnesota Ag Sector model, was used to construct the sector model for the LCFS. MAGS uses the GAMS software package – a programming language for mathematical programming applications like MAGS.[1] Data requirements for the LCFS version of GAMS will now be discussed.

Data Inputs and Assumptions

Minnesota Department of Agriculture Statistics were augmented with crop budget data from the MnSCU Farm Business Management Program and the Minnesota Farm Business Farm Management Associations to construct crop production activities for the sector model. Crop production activities were constructed in the model for each county. Output coefficients for the crop production activities are from Minnesota Agricultural Statistics for each county. In order to represent production outcomes for a typical year, five year averages are used for crop yields. By using this approach, the model characterizes production possibilities that are representative, rather than better or worse than average, or, importantly, don't state relative outcomes that are outliers. The goal is to avoid over- or understating the opportunity costs associated with changes in production. Minnesota data on input requirements for crop production were used also, based on Lazarus and Goodkind, "Minnesota Crop Cost and Return Guide for 2010." Lazarus and Goodkind developed crop budgets for each of five production regions in Minnesota using production data from the FINBIN database. FINBIN data are from farm records for the MnSCU Farm Business Management Program and the Minnesota Farm Management Associations. Input requirements from these budgets for the corresponding budget region were used as input coefficients for the crop production activities in the sector model (see map in appendix). Input and commodity prices, also from Minnesota Agricultural Statistics, along with budget data, are reported in the appendix.

Summary of the Sector Analysis

The economic sector model was used to explore the capacity of the Minnesota economy to meet biofuel demand levels estimated with the policy model. The sector model is a multi-region production and market equilibrium model with crop, livestock and biofuel processing subsectors. For the sector analysis, state demand levels for gasoline, diesel fuel, biodiesel and ethanol are set at levels estimated with the policy model [Taff]. Predicted demands levels under reference and LCFP assumptions are used for 2010, 2020 and 2030. The estimated state-level demands are disaggregated spatially to the nine intra-state regions in the sector model based on relative population. Total demand is set to in-state demand for each policy scenario plus exports fixed at 2010 levels. Ethanol exports were computed as follows: the estimated in-state demand of 255.7 million gallons under the 2010 Reference policy scenario was subtracted from the 2010 ethanol production level of 1,117 million gallons [Minnesota Department of Agriculture]. So export of

---

[1] GAMS, the Generalized Algebraic Modeling System, is a widely used programming language for economic modeling [Rosenthal, 2007]. The GAMS program and input files for the economic sector model, as well as all of the output files for the analysis reported here, are available upon request. The GAMS software is required to run the sector model.

ethanol was fixed at 1,117.0 minus 255.7, or 861.3 million gallons. Biodiesel export is calculated in the same way. Using the Minnesota Department of Agriculture production level of 29.56 million gallons and assuming in-state consumption of 22.32 as estimated in the policy model, resulting in biodiesel exports for 2010 were estimated to be 7.24 million gallons. The exports of ethanol and biodiesel were assumed fixed over all policy scenarios, so changes in total demand for each policy scenario represent changes in in-state consumption. For the base case (scenario A), current technologies and market conditions are assumed for each of the six policy scenarios. Because policy-makers have a keen interest in competition for resources between food and fuel, a high food price scenario was analyzed. Scenario B was intended to bracket the state economy's capacity to meet biofuel demand levels while maintaining current grain export levels. Scenario B also reflects a high world food demand situation. The model allows flexibility in the sector's response to world markets. In scenario B, grain export prices are increased by 25%. Summaries of the sector model results appear in Tables A1, A2, B1 and B2.

Current market conditions are assumed in the results in Tables A1 and A2. Table A1 shows, for each of the six consumption scenarios, the levels of ethanol and biodiesel production and the corresponding feedstock use. Table A2 shows the corresponding levels of grain and corn stover production and acreages, and feedstock use as a percent of total production. All state and export ethanol demand is met with corn grain in 2010. In 2010 and in both the reference and LCFP cases, ethanol production uses about 403 million bushels of corn or about 36% of the state's 7.2 million acres of corn. In 2020 under the reference and LCFP cases, expanded ethanol demand is met with cellulosic ethanol production using corn stover – corn grain use remains at 403 million bushels. Expanded ethanol demand in 2020 and 2030 is met by cellulosic ethanol production using corn stover. This is notable because stover, as a by-product of corn grain production, does not compete directly with use of grain for food production. For the reference policy, 272 million gallons of ethanol are produced with corn stover in 2020 and 434 million gallons in 2030. Under the LCF policy, cellulosic ethanol production reaches 345 and 761 million gallons in 2020 and 2030, respectively. 761 million gallons of ethanol, if produced with corn grain, would have required 275 million bushels and increased total corn grain use for ethanol to over 60% of production. In policy scenarios where corn stover is used as an ethanol feedstock, the area of stover harvest ranges from 19% of total corn acreage in the 2020 reference case to 56% of total corn acreage under the LCF policy in 2030. The response of the Minnesota agriculture sector to expanded biodiesel demand is similar. Soybean acreage changes very little from 2010 to 2030. So, in order to meet higher biodiesel demand, soybean use increases from 18.7 million bushels in 2010 to 56.4 and 55.3 million bushels in 2030 for the reference and LCFP cases, respectively. Use of soybeans for biodiesel production increases from 5.8% of the acreage in 2010 (reference policy) to 17.7% and 17.3% of the acreage in 2030 under the reference and LCF policies, respectively.

Under scenario B, export prices for corn, soybeans and wheat are increased by 25% from the base, scenario A, levels. Thus high world demand for grain is modeled, while allowing state and export fuel demands are met with Minnesota-produced biofuel feedstocks. The results are summarized in Tables B1 and B2. Notably, with high opportunity costs, corn ethanol falls from current levels of about 1,117 million gallons to 596 million gallons in 2020 under the reference policy and 893 million gallons in 2030 under the LCF policy. Remaining demand is met with cellulosic ethanol produced with corn stover, a by-product of corn grain production. In the reference policy case, ethanol production increases from 272 million gallons a base grain prices to 794 million gallons with high grain prices. Ethanol production with corn stover reaches 985 million gallons in 2030 under the LCF policy – 29% higher than under current grain export prices. While total corn acreage increases somewhat under high grain export prices, the area of stover harvest increases significantly. In all policy scenarios, stover is harvested from over half of the corn acreage. Stover harvest as a percent of total corn acreage reaches 65% in 2030 under the LCF policy, suggesting the possibility of significant environmental impacts associated with the production of biofuel feedstock. Production of ethanol with cellulose has been estimated to decrease GHG emissions relative to corn ethanol or gasoline [Hill]. However, removal of crop residues lessens the environmental benefits they provide including control of crop nutrient runoff and water contamination [Mann, et al.] and protection of soil from wind and water erosion [Smil; Johnson, et al.]. As biodiesel is produced here using only soybean oil, soybean use for biodiesel does no change under high grain export prices. Use of soybeans for biodiesel as a percent of total production increases modestly as a result of a small decrease in soybean acreage under high export prices.

Table 1: Biofuel Feedstock Use by Policy Scenario.

	2010 Ref	2010 LCF	2020 Ref	2020 LCF	2030 Ref	2030 LCF
	—————— State-Level Demand, Million Gallons[a] ——————					
Diesel	639.9	662.2	757.8	749.7	896.8	899.7
Gasoline	2,559.5	2,557.6	2,099.4	1,981.6	2,099.3	1,578.0
Ethanol	255.7	255.5	527.9	601.0	690.0	1,016.7
Biodiesel	22.4	9.3	49.9	49.4	81.9	80.3
	—————— Ethanol Production, Million Gallons ——————					
Corn Ethanol	1,117.0	1,116.8	1,117.1	1,117.1	1,117.1	1,117.1
Cellulosic Ethanol – Crop	0.0	0.0	272.0	345.1	434.2	760.8
Cellulosic Ethanol – Wood	0.0	0.0	0.0	0.0	0.0	0.0
Total Ethanol	1,117.0	1,116.8	1,389.2	1,462.3	1,551.3	1,878.0
	—————— Ethanol Feedstock Use[b] ——————					
Corn Grain, Mil Bu	403.3	403.2	403.3	403.3	403.3	403.3
Corn Stover, 1000 T	0.0	0.0	3,325.2	4,219.2	5,307.7	9,301.3
Grass Use, 1000 T	0.0	0.0	0.0	0.0	0.0	0.0
Roundwood Use Use, 1000 T	0.0	0.0	0.0	0.0	0.0	0.0
Wood Residue Use Use, 1000 T	0.0	0.0	0.0	0.0	0.0	0.0
	—————— Biodiesel Production and Soybean Use[b] ——————					
Biodiesel Production, Mil Gal	29.6	16.6	57.1	56.7	89.2	87.5
Soybean Use, Mil Bu	18.7	10.5	36.1	35.8	56.4	55.3

[a] In-state fuel demand is fixed in the sector model at consumption levels estimated with the Policy Model. Total demand is set to in-state demand plus a fixed level of exports. Ethanol export is fixed at the 2010 production level of 1,117 million gallons [Minnesota Department of Agriculture], less the estimated in-state demand under the 2010 Reference policy scenario of 255.7 million gallons, or 861.3 million gallons. Biodiesel export is calculated in the same way, resulting in exports of 7.2 million gallons.
[b] Processing activities in the sector model assume yields of 2.77 gallons of ethanol per bushel of corn, and 1.58 gallons of biodiesel per bushel of soybeans.

Table 2: Grain and Stover Production and Use for Biofuels by Policy Scenario.

	2010 Ref	2010 LCF	2020 Ref	2020 LCF	2030 Ref	2030 LCF
	Thousand Acres					
Corn	7,206.1	7,206.1	7,146.4	7,131.6	7,006.2	7,103.1
Soybeans	7,315.8	7,315.8	7,329.4	7,329.4	7,329.2	7,292.6
Wheat	1,621.8	1,621.8	1,621.5	1,621.5	1,621.5	1,621.2
	Corn Grain Production and Use					
Production, Mil Bu	1,125.8	1,125.8	1,115.5	1,112.9	1,096.9	1,108.7
Use for Ethanol, Mil Bu	403.3	403.2	403.3	403.3	403.3	403.3
Use as Pct of Production	35.82%	35.81%	36.15%	36.24%	36.77%	36.37%
	Corn Stover Production and Use					
Production/Use, 1000 T	0.0	0.0	3,325.2	4,219.2	5,307.7	9,301.3
Production Area, 1000 Ac	0.0	0.0	1,358.4	1,727.9	2,211.0	3,975.7
Pct of Total Corn Area	0.0%	0.0%	19.0%	24.2%	31.6%	56.0%
	Soybean Production and Use					
Production, Mil Bu	321.6	321.6	322.3	322.3	322.3	320.4
Use for Biodiesel, Mil Bu	18.7	10.5	36.1	35.8	56.4	55.3
Use as Pct of Production	5.8%	3.3%	11.2%	11.1%	17.5%	17.3%

Table 3: Biofuel Feedstock Use With High Grain Export Prices by Policy Scenario.

	2020 Ref	2020 LCF	2030 Ref	2030 LCF
	——————State-Level Demand, Million Gallons[a] ———————			
Diesel	757.8	749.7	896.8	899.7
Gasoline	2,099.4	1,981.6	2,099.3	1,578.0
Ethanol	527.9	601.0	690.0	1,016.7
Biodiesel	49.9	49.4	81.9	80.3
	——————— Ethanol Production, Million Gallons ———————			
Corn Ethanol	595.5	634.4	695.1	892.8
Cellulosic Ethanol – Crop	793.6	827.9	856.2	985.2
Cellulosic Ethanol – Wood	0.0	0.0	0.0	0.0
Total Ethanol	1,389.2	1,462.3	1,551.3	1,878.0
	——————————— Ethanol Feedstock Use[b]————————————			
Corn Grain, Mil Bu	215.0	229.0	250.9	322.3
Corn Stover, 1000 T	9,702.1	10,121.0	10,467.3	12,044.0
Grass Use, 1000 T	0.0	0.0	0.0	0.0
Roundwood Use Use, 1000 T	0.0	0.0	0.0	0.0
Wood Residue Use Use, 1000 T	0.0	0.0	0.0	0.0
	—————— Biodiesel Production and Soybean Use[b]——————			
Biodiesel Production, Mil Gal	57.1	56.7	89.2	87.5
Soybean Use, Mil Bu	36.1	35.8	56.4	55.3

[a] In-state fuel demand is fixed in the sector model at consumption levels estimated with the Policy Model. Total demand is set to in-state demand plus a fixed level of exports. Ethanol export is fixed at the 2010 production level of 1,117 million gallons [Minnesota Department of Agriculture], less the estimated in-state demand under the 2010 Reference policy scenario of 255.7 million gallons, or 861.3 million gallons. Biodiesel export is calculated in the same way, resulting in exports of 7.2 million gallons.

[b] Processing activities in the sector model assume yields of 2.77 gallons of ethanol per bushel of corn, and 1.58 gallons of biodiesel per bushel of soybeans.

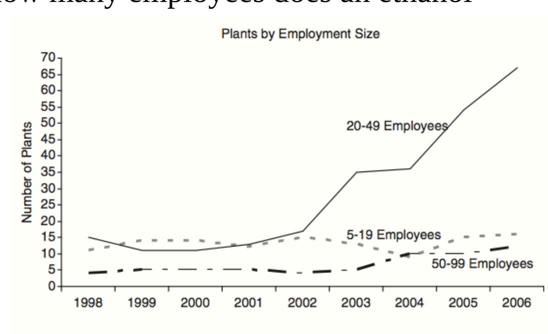
Table 4: Grain and Stover Production and Use for Biofuels with High Grain Export Prices by Policy Scenario.

	2020 Ref	2020 LCF	2030 Ref	2030 LCF
	Thousand Acres			
Corn	7,931.2	7,994.9	8,160.6	8,130.4
Soybeans	6,965.5	6,900.0	6,748.9	6,752.4
Wheat	1,576.1	1,576.1	1,568.6	1,568.6
	Corn Grain Production and Use			
Production, Mil Bu	1,217.3	1,227.7	1,254.2	1,249.5
Use for Ethanol, Mil Bu	215.0	229.0	250.9	322.3
Use as Pct of Production	17.66%	18.65%	20.01%	25.80%
	Corn Stover Production and Use			
Production/Use, 1000 T	9,702.1	10,121.0	10,467.3	12,044.0
Production Area, 1000 Ac	4,218.1	4,400.3	4,555.4	5,280.7
Pct of Total Corn Area	53.2%	55.0%	55.8%	65.0%
	Soybean Production and Use			
Production, Mil Bu	304.9	301.7	294.6	294.7
Use for Biodiesel, Mil Bu	36.1	35.8	56.4	55.3
Use as Pct of Production	11.8%	11.9%	19.1%	18.8%

In addition to regional production levels, sector models of the type used in this study can provide estimates of resource and input use under various market, policy and technological scenarios. Land use, as summarized in Tables A1, A2, B1 and B2, are of particular interest as is labor. Importantly, there is direct labor use required for the production and processing of biofuel feedstocks. However, the overall change in labor use is influenced by indirect effects in other parts of the sector. For example, the policy scenarios studied here involve increased processing of grain and cellulosic ethanol, but labor use for this processing will be offset in part by decreased petroleum processing. In this study, crop production patterns remained relatively stable over various policy scenarios, thus labor use in agriculture would remain relatively stable. A notable exception would involve expanded corn stover production, which involves additional field operations and handling of the stover, and therefore additional farm labor use. Cellulosic ethanol production involves increased shipping as well. Labor use is included in operating costs for production and processing in the current sector model, so explicit results pertaining to labor use are not possible. Additional data on labor requirements will be necessary to predict the impacts of low carbon fuel policies on labor markets. A few observations on the employment effects of biofuel production can be made, however.

The employment effects of an ethanol or other biofuel plant are either *direct*, such as when a plant hires additional labor; *indirect*, such as when suppliers of the plant employ more people; or *induced*, such as when newly-hired employees spend their wages in the local economy and create new demand for local services.

Direct employment effects are fairly straightforward – how many employees does an ethanol plant require? A rule of thumb in the industry used to be "*one direct employee per Million gallons per year (MGY).*" In those days, however, plants rarely exceeded a capacity of 50 MGY. With capacities now in the range of 100 MGY, significant industrial economies of scale are bringing that figure down. For ethanol plants with a capacity between 50-100 MGY, the direct employment requirement is more in the range of 0.4–0.7 jobs/MGY. Larger plants have lower direct employment needs per MGY.



Source: Authors' calculations from annual *County Business Patterns* files (U.S. Bureau of the Census, 2008a).
Note: These data are for NAICS 325193, Ethyl Alcohol Manufacturing, an industry primarily engaged in manufacturing nonpotable ethyl alcohol, including but not limited to ethanol for fuel. The spectacular increase in the number of establishments results from the expansion of ethanol production.

Figure 1: Source: Low (2009)

Estimating indirect and induced jobs effects necessitates some economic assumptions. Variations in these assumptions can lead to very different figures. One prevailing assumption regards the nature of the supply industry, especially the corn (or other biofuel) industry. In the past, some researchers have made the mistake of counting locally-sourced grain as additional or *new* production that would not have occurred without the existence of the plant. In reality, locally-sourced grain rarely represents new production. It is more likely to be production that has been taken away from its next-best use or production that has been shifted away from other crops. Counting it as new production exaggerates the jobs impact of an ethanol plant by at least an order of magnitude. In the chart below, several authors (Petersan, Swenson, and Low) correct for this error by explicitly assuming that no additional jobs are created by the agricultural production.

Another assumption involves the size and diversity of the economy within the study area. Larger and more diverse study areas will have greater indirect and induced jobs effects because the plants will source more of their supplies locally, and employees will spend more of their wages locally. Similarly, whether or not to include employment effects from plant construction may also complicate the analysis. Swenson [2006] estimates that up to 60 local jobs may be created during the 18-month construction period. But this is a short-term impact, and there are very few firms in the United States that have the experience necessary to build a specialized plant for ethanol or other biofuels. It is therefore unlikely that all construction jobs will be sourced from the local economy or that those jobs will have significant indirect or induced employment effects. Therefore, Swenson and Low [2009] justify ignoring the construction employment effects in their analyses. If they were included, or if it were known that the plant's construction company were located within the study area, then the total employment effect would be greater.

If there is capacity for additional livestock feeding operations in the region around an ethanol plant, the livestock feeding industry may benefit from the relatively less expensive wet spent grain that is a byproduct from the plant. This is primarily a relationship seen in the cattle and dairy feeding industry, though there is some potential in the swine and poultry feeding industries as well. The wet spent grain has a shelf-life of about a week, is costly to transport (maxing-out at about a 50 mile radius), and may only constitute a portion of the animals' diets. But in locations where an ethanol plant/feed lot relationship is feasible, additional employment may be created in a relatively more efficient livestock feeding industry. A 100-MGY ethanol plant produces enough spent grain to feed two cohorts of 100,000 head of cattle each year (Pierce, et al 2006). Where additional livestock feeding capacity exists, its employment effects should be taken into consideration – but that may require the modeler to make additional changes to the input-output coefficients for the livestock sector of the model. Low [2009] did not integrate changes to the livestock feeding coefficients in the model, but found that tripling the feedlot output of Hamilton County, Illinois uses only a small portion of the ethanol plant's wet spent grain, and creates 59 additional jobs.

Future Work

The sector modeling framework used in the economic analysis for the LCFP study might be extended in a variety of ways as technical and economic data are developed to model the economic and environmental impacts of alternative energy sources. For example, research on energy crop production systems could support development of new crop production alternatives that might compete with existing crops for land resources. As broad based estimates of the impacts of feedstock production of water quality become available, use of the feedstocks for energy production can be evaluated in the context related water policies. For instance, the rate of stover removal might depend on slope and soil characteristics that influence the impacts of the removal on effluent levels. Perennial energy crops may be more economical as energy feedstocks when their environmental benefits are considered. Regional, sub-state level economic models would be useful for developing insights about the efficient organization of the biofuel industry, such as the optimal size and location of processing facilities and supporting infrastructure. Technical and economic detail on other biofuels, such as forest resources and industrial byproducts could be used to extend the sources of feedstock supply, also. Economic analyses of this type might be used to evaluate existing and newly available energy sources and technologies, and could also be used to set targets for future research.

Table 5: Employment Effects of Ethanol Plants.

Year	Author	Study Area	Total Plant Size, MGY	Direct Jobs	Indirect & Induced Jobs	Direct Jobs per MGY	I&I Jobs per MGY	Total Jobs per MGY	Jobs Multiplier (Direct→ Total)
2002	Petersan	Revenna, NE	80	48	163	0.6	2.04	2.64	4.4
2005	Urbanchuck Cited in Swenson	US	-	3,500 to 4,000	114,844	-	-	-	29.7 to 33.8
2005	Stuefen	SD	-	473	2,972	-	-	-	7.3
2006	Daschle Speech Cited in Swenson	US	3,100	200,000		-	-	64.52	-
2006	Imerman & Otto	IA	800	-	-	-	-	3.00	-
2006	Swenson	TriCo, IA	50	35	98	0.70	1.96	2.66	3.8
2008	Ye	MN	670	1,445	2,861	2.16	4.27	6.43	3.0
2009	Low and Isserman	Kankakee Cty, IL	100	39	211	.39	2.11	2.50	6.4
		Coles Cty, IL	60	35	117	.58	1.95	2.53	4.3
		Hamilton Cty, IL*	100	39	114	.39	1.14	1.53	3.9
		Harlan Cty, NE	60	35	65	.58	1.08	1.64	2.9

* Low & Isserman (2009) note that using less than 10% of the ethanol plant's distillers' grain byproduct as feed in adjacent cattle feedlots could create 59 additional jobs. This would make (Ye) Total Jobs per MGY 2.12, and the Jobs Multiplier 5.43.

References

2010 Minnesota Agricutural Statistics. Minnesota Department of Agriculture, USDA, National Agricultural Statistics Service. 2010.

Low, Sarah A. and Andrew M. Isserman. "Ethanol and the Local Economy: Industry Trends, Location Factor, Economic Impacts, and Risks." Economic Development Quarterly 23: 71-88. 2009.

Hill J., S. Polasky, E. Nelson, D. Tilman, H. Huo, L. Ludwing, J. Neumann, H. Zheng and D. Bonta. "Climate change and health costs of air emissions from biofuels and gasoline." *Proceedings of the National Academy of Sciences*. 106(6): 2077-2082. 2009.

Johnson J., D. Reicosky, R. Almaras, D.Archer, and W. Wilhelm. "A Matter of Balance: Conservation and Renewable Energy." *Journal of Soil Water Conservation*. 61(4): 121A–125A. 2006.

Mann, L., V. Tolbert and J. Cushman. "Potential Environmental Effects of Corn (Zea Mays L.) Stover Removal with Emphasis on Soil Organic Matter and Erosion. *Agriculture, Ecosystems and Environment*. 89:149-166. 2002.

Otto, Daniel, and Mark D. Imerman. Analysis of Energy Supply and Usage in the Iowa Economy. Working Paper. Iowa State University. Ames, IA: Iowa State University. 2006.

Petersan, Donis N. Estimated Economic Effects for the Nordic Biofuels Ethanol Plant in Ravenna, Nebraska. Nebraska Public Power District. Columbus, NE: Nebraska Public Power District. 2002.

Smil V. "Crop residues: agriculture's largest harvest." *BioScience*. 49(4): 299–308. 1999.

Stuefen, Randall. The Economic Impact of Ethanol Plants in South Dakota. Stuefen Research, LLC. Vermillion, SD: Stuefen Research, LLC. 2005.

Swenson, Dave. "Input-Outrageous: The Economic Impacts of Modern Biofuels Production." Iowa State University. 2006.

Ye, Su. "Economic Impact of the Corn and Ethanol Industry in Minnesota." Minnesota Department of Agriculture. 2008.

Appendix A: The Economic Sector Model

An economic sector model was used to study the capacity of the state to meet biofuel demand levels predicted by the policy model. Sector modeling, a widely used economic modeling technique, is useful for studying the economic impacts of changes in public policies, technologies and general economic conditions by capturing the economic behavior of producers in a sector, the consumers of its products, the suppliers of inputs to the sector, and trade with other sectors. By expressing the market equilibrium as an optimization problem, these models typically integrate the behavior of consumers of the sector's products through the use of exogenous demand functions, supply of inputs to the sector through exogenous input supply functions, demand for exports, supply of imports, and an endogenous expression of product supply and input demand through the construction of aggregate production processes and functions for the sector. It is this later characteristic that makes sector models widely useful as well as challenging to build. Production activities in a sector model must be adapted to reflect the practices and technologies that are relevant to a particular economic problem. A general sector model called MAGS (Minnesota Ag Sector model) was adapted for use in this study. The MAGS model was designed for a wide range of economic applications, particularly applications to environmental and energy problems. The model was constructed using the Generalized Algebraic Modeling System software (GAMS). For the Low Carbon Fuel Policy Study, the sector model includes crop, livestock, forest feedstock and fuel processing sub-sectors. In this appendix, the structure and assumptions of the computer programs, input files and output files will be explained, and the economic sector model will be presented, following a brief general discuss of sector models.

Structure GAMS Program, Data Files and Output Files

GAMS is a programming language that is widely used in economic analyses. MAGS, a Minnesota Ag Sector model, is a general sector model designed to analyze the economic behavior of economic sectors with particular spatial detail. MAGS was constructed using the GAMS programming language. GAMS programs are written in text files which are executed by the GAMS program, which creates a new file with results. The input file generally has .gms as an extension − GAMS creates an output file with the same name and .lst as the extension. The output, or list file, begins with a listing of the input file, so the list file provides a comprehensive description of any GAMS run. Price, cost and technical coefficients for the sector model may be included directly in the GAMS program (.gms) file. However, large data tables may be read from other text files referred to as include (.inc) files. The application of MAGS used in this study uses several include files. The .inc files are often created in Excel, which provides a convenient way to prepare problem data. MAGS was run ten times for this study and the results are summarized in the economic section of the project report. All related GAMS program files (.gms files), include files (.inc files), and output files (.lst files), have been provided to the Department of Commerce, Office of Energy Security, and are available to others upon request. Details of the input, data and output files are provided in Table 1.

General Structure of the Minnesota Ag Sector Model

MAGS is a multi-regional, endogenous supply sector model. While it can be applied broadly to many different sectors, the model includes feature that are especially useful for modeling agricultural production and related environmental and energy policy and technology issues. Mathematical programming techniques are used to construct the model and solve it. Exogenous, price responsive, demands for the sector's products and supplies for the sectors inputs are included for each region. Exports and imports capture demands and supplies from outside the sector. The sectors product supply, and its derived demand for inputs are endogenous through the mathematical model of production within the sector. Currently, linear programming production activities are used, however, GAMS can be used with other mathematical forms, too. Product demand and input supply functions are currently linear in price, however, this assumption may be relaxed in GAMS, too. Figure n.1 shows a general mathematical programming sector model similar to the MAGS model. For simplification, exports and imports are not included here. In this mathematical programming problem, the market equilibrium is found by maximizing producer and consumer surplus subject to market clearing constrains for the sector's products and inputs. The optimal solution provides equilibrium quantities for the sector's products (Y) and inputs (Z) in each region. The economic behavior of producers in the sector is expressed in the solution values to the production activities X. Constraints in each region limit consumption of each product to no more than production plus shipments from other regions less shipments to other regions. Similarly, use of each input plus shipments to other regions cannot exceed supply plus in-shipments. The dual variables associated with the market clearing constraints, also part of the optimal solution, represent the regional market prices for the products and inputs.

Table 6: GAMS Files Used for the Economic Sector Analysis.

Policy Scenario	Year Scenario		
	2010	**2020**	**2030**
Reference	GAMS Program File		
	MAGS-LCFS 2010-REF.GMS	MAGS-LCFS 2020-REF.GMS*	MAGS-LCFS 2030-REF.GMS*
	External Data Files		
	LCFS-AC.INC LCFS-AL.INC LCFS-ARP.INC LCFS-CSR.INC LCFS-2010-REF-CDR.INC LCFS-2010-REF-CXMR.INC	LCFS-AC.INC LCFS-AL.INC LCFS-ARP.INC LCFS-CSR.INC LCFS-2020-REF-CDR.INC LCFS-2020-REF-CXMR.INC	LCF-AC.INC LCF-AL.INC LCF-ARP.INC LCF-CSR.INC LCF-2030-REF-CDR.INC LCF-2030-REF-CXMR.INC
	GAMS Output File		
	MAGS-LCFS 2010-REF.LST	MAGS-LCFS 2020-REF.LST*	MAGS-LCFS 2030-REF.LST*
Low Carbon Fuel	GAMS Program File		
	MAGS-LCFS 2010-LCF.GMS	MAGS-LCFS 2020-LCF.GMS*	MAGS-LCFS 2030-LCF.GMS*
	External Data Files		
	LCFS-AC.INC	LCFS-AC.INC	LCF-AC.INC
	LCFS-AL.INC	LCFS-AL.INC	LCF-AL.INC
	LCFS-ARP.INC	LCFS-ARP.INC	LCF-ARP.INC
	LCFS-CSR.INC	LCFS-CSR.INC	LCF-CSR.INC
	LCFS-2010-LCF-CDR.INC	LCFS-2020-LCF-CDR.INC	LCF-2030-LCF-CDR.INC
	LCFS-2010-LCF-CXMR.INC	LCFS-2020-LCF-CXMR.INC	LCF-2030-LCF-CXMR.INC
	GAMS Output File		
	MAGS-LCFS 2010-LCF.LST	MAGS-LCFS 2020-LCF.LST*	MAGS-LCFS 2030-LCF.LST*

* Parameter changes for the high grain export price case were made in the .gms files for the 2020 and 2030 policy scenarios. Input and output files for these four runs are the same as those above, with HXP added to the file name (e.g. MAGS-LCFS 2020-REF HXP.GMS).

The MAGS models differs from the mathematical programming problem in Figure n.1 in the following ways. In addition to inter-regional trade, goods may exported and/or imported.[2] Also, when spatial aspects of production and consumption are not critical, some products and inputs may be identified as non-regional, so supply and demand are balanced without considering the region. This option allows a means of managing model size for markets in which location is not economically significant to the problem being studied. Table 2 illustrates the general structure of MAGS in tableau format for a two-region case.

The Crop Subsector

Crop production activities were constructed using 2010 crop enterprise budgets developed by Lazarus and Goodkind. State-wide, crop activities included corn grain, corn silage, corn grain with stove harvest, soybeans, wheat, alfalfa hay, other hay/grass, sugar beets and other crops. Operating input requirements for specific budget regions as well as labor and machinery requirements were taken directly from enterprise budgets [Lazarus and Goodkind]. Crop yields were disaggregated further to the county level – five year average yields were used as output coefficients for crop activities in each county. This was accomplished by including for each of the nine regions in the sector model, crop activities so derived for each county in that region. Counties were treated as "crop land types" in MAGS. Crop land types are used as a devise for disaggregating crop production activities in MAGS by specifying unique input output coefficients for each crop land type and constructing crop land input constraints for each land type in the region.

[2] Currently, the "small country assumption" is employed in MAGS, so import and export prices are assumed exogenous. Again, this assumption may be relaxed in GAMS.

Figure 2: A General, Multi-Region, Mathematical programming Sector Model.

Maximize:
$\mathbf{X}, \mathbf{Y}, \mathbf{Z}, \mathbf{T}$

$$\sum_{g=1}^{r}\sum_{i=1}^{n}\left[\mathbf{a}_{gi}\mathbf{Y}_{gi} + \mathbf{0.5b}_{gi}\mathbf{Y}_{gi}^{\mathbf{2}}\right] - \sum_{g=1}^{r}\sum_{k=1}^{m}\left[\mathbf{c}_{gk}\mathbf{Z}_{gk} + \mathbf{0.5d}_{gk}\mathbf{Z}_{gk}^{\mathbf{2}}\right] - \mathbf{F}$$
$$- \sum_{g=1}^{r}\sum_{h=1}^{r,h\neq g}\sum_{i=1}^{n}\mathbf{t}_{ghi}\,\mathbf{T}_{ghi}$$

Subject to:

$$\mathbf{Y}_{gi} - \sum_{j=1}^{s}\mathbf{e}_{gij}\,\mathbf{X}_{gj} - \sum_{h=1}^{r,h\neq g}\mathbf{T}_{hgi} + \sum_{h=1}^{r,h\neq g}\mathbf{T}_{ghi} \leq \mathbf{0} \qquad g = 1 \ldots r,\ \ i = 1 \ldots n$$

$$\sum_{j=1}^{s}\mathbf{e}_{gkj}\,\mathbf{X}_{gj} - \mathbf{Z}_{\boldsymbol{gk}} \leq \mathbf{0} \qquad g = 1 \ldots r,\ \ k = 1 \ldots m$$

$$\sum_{j=1}^{s}\mathbf{w}_{glj}\,\mathbf{X}_{gj} \leq \mathbf{Q}_{gl} \qquad g = 1 \ldots r,\ \ l = 1 \ldots q$$

$$\mathbf{Y}_{gi}, \mathbf{Y}_{gi}, \mathbf{Y}_{gi}, \mathbf{Y}_{gi} \leq \mathbf{0} \qquad g = 1 \ldots r;\ \ h = 1 \ldots r, h \neq g;\ \ i = 1 \ldots n;\ \ j = 1 \ldots s;\ \ k = 1 \ldots m$$

Where: g is the region

Y_{gi} it the quantity demanded of product i

Z_{gk} is the quantity supplied of input k

X_{gj} is the level of production activity j

Q_{gl} is the supply of fixed input l

T_{ghi} is the quantity of product I shipped from region g to region h

References

Rosenthal, Richard E. *A GAMS Tutorial*. GAMS Development Corporation. Washington, DC, USA. 2008.

Apland, Jeffrey and Hans Andersson. "Optimal Location of Processing Plants: Sector Modeling Considerations and an Example." *Review of Agricultural Economics*. September 1996.

Apland, Jeffrey, Bo Öhlmér and Lars Jonasson. "Economic Analysis of Agricultural Technologies and Policies: The Sector Modeling Approach". Report 71. Department of Economics, Swedish University of Agricultural Sciences. Uppsala, Sweden. 1994.

Coble, Keith H., Ching-Cheng Chang, Bruce A. McCarl and Bobby R. Eddleman. "Assessing Economic Implications of New Technology: the Case of Cornstarch-Based Biodegradable Plastics." *Review of Agricultural Economics*. January 1992, pp. 31-43.

Hamilton, Scott A., Bruce A. McCarl and Richard M. Adams. "The Effect of Aggregate Assumptions on Environmental Impact Analyses." *American J of Agricultural Economics*. May 1985, pp. 407-413.

Howitt, Richard E. "Positive Mathematical Programming." *American Journal of Agricultural Economics*. May 1995, pp. 329-342.

Jonasson, Lars and Jeffrey Apland. "Frontier Technologies and Inefficiencies in Programming Sector Models: An Application to Swedish Agriculture." *European Rev of Agr Econ*. 24(1997): 109-131.

Lazarus, W., and Goodkind, A. "Minnesota Crop Cost and Return Guide for 2010." University of Minnesota Extension, 2009.

Magrath, William B. and Loren W. Tauer. "New York Milk Supply with Bovine Growth Hormone." *North Central Journal of Agricultural Economics*. July 1988, pp. 233-241.

McCarl, Bruce A. "Cropping Activities in Agricultural Sector Models: A Methodological Proposal." *American Journal of Agricultural Economics*. November 1982, pp. 768-772.

McCarl, Bruce A. and Thomas H. Spreen. "Price Endogenous Mathematical Programming as a Tool for Sector Analysis." *American Journal of Agricultural Economics*. February 1980, pp. 87-102.

Setia, Parveen and Steven Piper. "Effects of Soil and Agricultural Chemicals Management on Farm Returns and Ground Water Quality." *Review of Agricultural Economics*. January 1992, pp. 65-80.

US Department of Agriculture – Agricultural Marketing Service. "Ethanol Transportation Backgrounder" 2007.

US Department of Agriculture – Agricultural Marketing Service, "Truck Transportation"

http://www.ams.usda.gov/AMSv1.0/ams.fetchTemplateData.do?template=TemplateA&navID=AgriculturalTransportation&leftNav=AgriculturalTransportation&page=ATQuarterlyUpdates&description=Quarterly%20Updates&acct=graintransrpt accessed August 2009.

Table 7: Tableau Illustrating the General Structure of MAGS.[1]

	Prod & Proc	Input Supply	Product Demand	Inter-Reg Transport[2]	Import[2]	Export[2]	Prod & Proc	Input Supply	Product Demand	Inter-Reg Transport[2]	Import[2]	Export[2]	Prod & Proc	Input Supply	Product Demand	Import[2]	Export[2]	
Maximize: Objective		-[3]	+[3]	-	-	+		-[3]	+[3]	-	-	+		-[3]	+[3]	-	+	RHS
Region One																		
Input Constraints	+/-	-1		1	-1	1				-1	-1	1						= 0
Output Constraints	+/-		1	1	-1	1				-1	-1	1						= 0
Other Constraints	+/-																	≤ +
Region Two																		
Input Constraints				-1			+/-			1								= 0
Output Constraints				-1			+/-			1								= 0
Other Constraints							+/-											≤ +
Non-Regional																		
Input Constraints													+/-	-1		-1	1	= 0
Output Constraints													+/-		1	-1	1	= 0
Other Constraints													+/-					≤ +
Lower Bound	0	+[4]	+[4]	0	0	0	0	+[4]	+[4]	0	0	0	0	+[4]	+[4]	0	0	
Upper Bound	∞	+[4]	+[4]	∞	∞	∞	∞	+[4]	+[4]	∞	∞	∞	∞	+[4]	+[4]	∞	∞	

[1] This is a schematic of the sector model tableau in which the rows and columns represent sets of constraints and activities, respectively. Thus, each cell is a matrix. The + and - symbols indicate the signs of non-zero elements in the corresponding matrix. A 1 or -1 indicates that non-zero elements of that cell are 1 or -1, that is, that activity and the corresponding constraint are in the same units. The model is a nonlinear program, so the coefficients in some cells are functions of endogenous variables. The symbols in brackets are the variable, equation and parameter names used in the GAMS model.

[2] Regional import and export activities represent trade of inputs and products outside the sector. Inter-regional trade within the sector is accomplished with inter-regional transportation activities.

[3] The objective function is consumer plus producer surplus so the objective function entries on supply activities are minus the supply function integrals and the the objective function entries on the demand activities are the demand function integrals. Inputs and products in MAGS-LCFPS are assumed to have infinitely elastic, or constant price, supply and demand functions, with the exception of crop land, livestock facilities and some processing capacity.

[4] Lower and upper bounds on input supply and product demand activities allow for fixed minimum and or maximum levels for supply and demand.

Table 8: Partial Tableau Illustrating the Structure of Crop Production Activities for a Representative Land Type.

	Corn	Silage	Soybeans	Beets	Alfalfa	Other Hay	Other Crops	Mix 2004	Mix 2005	Mix 2006	Mix 2007	Input Supply	Product Demand	
Objective												-[b]	+[c]	
Corn Land	1	1						-[a]	-[a]	-[a]	-[a]			≤ 0
Soybean Land			1					-[a]	-[a]	-[a]	-[a]			≤ 0
Sugar Beet Land				1				-[a]	-[a]	-[a]	-[a]			≤ 0
Alfalfa Land					1			-[a]	-[a]	-[a]	-[a]			≤ 0
Other Hay Land						1		-[a]	-[a]	-[a]	-[a]			≤ 0
Other Crop Land							1	-[a]	-[a]	-[a]	-[a]			≤ 0
Total Crop Land	1	1	1	1	1	1	1	-[a]	-[a]	-[a]	-[a]			≤ 0
Crop Mix Convexity								1	1	1	1			= 1
Input Balance	+	+	+	+	+	+	+					-1		= 0
Output Balance	-	-	-	-	-	-	-						1	= 0
Lower Bound	0	0	0	0	0	0	0	0	0	0	0	+[b]	+[c]	
Upper Bound	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	+[b]	+[c]	

[a] The coefficient for a crop mix activity (Mix 2004 – Mix 2007 here) on the land constraint for a specific crop is minus the area of the crop for that observation, or mix. The coefficients for the total land constraint are the total crop areas for the crop mix observations, entered as negative values. By the approach to modeling crop production, the equilibrium crop mix must be a convex combination of the Mix activities.

Table 9: Partial Tableau Illustrating Crop Land Transfer Activities.

	Corn	Corn 2	Soybeans	Alfalfa	Other Crops	Transfer Soybean	Transfer Alfalfa	Transfer Other	Mix 2004	. . .	Mix 2007	
Objective												
Corn Land	1								-	. . .	-	≤ 0
Transferred Corn Land		1				-1	-1	-1	-	. . .	-	≤ 0
Soybean Land			1			1			-	. . .	-	≤ 0
Alfalfa Land				1			1		-	. . .	-	≤ 0
Other Crop Land					1			1	-	. . .	-	≤ 0
Total Crop Land	1	1	1	1	1				-	. . .	-	≤ 0
Crop Mix Convexity									1	. . .	1	= 1
Input Balance	+	+[b]	+	+	+							= 0
Output Balance	-	-	-	-	-							= 0
Lower Bound	0	0	0	0	0	0	0	0	0		0	
Upper Bound	∞	∞	∞	∞	∞	+[a]	+[a]	+[a]	∞		∞	

[a] Upper bounds on the transfer activities were set to .

[b] Production of corn on transferred crop land was assumed to have yields xx% of base corn yields.

Table 10: Crop Enterprise Budgets – Corn Grain and Corn Silage.*

		Corn									Silage								
Input	Units	NW	NC	NE	WC	C	EC	SW	SC	SE	NW	NC	NE	WC	C	EC	SW	SC	SE
Corn Seed	bg	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
Nitrogen	lb	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00	140.00
Phosphorus (P_2O_5, Dry)	lb	40.00	30.00	20.00	35.00	25.00	20.00	30.00	30.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Potash (K_2O)	lb	15.00	30.00	45.00	30.00	35.00	45.00	45.00	50.00	50.00	0.00	2.50	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Ammonium Sulfate	gal	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Glysophate	gal	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Lubrication	usd	0.83	0.83	0.83	0.91	0.90	0.83	0.95	0.97	0.95	0.61	0.61	0.60	0.71	0.69	0.69	0.75	0.78	0.75
Custom Hire	usd	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00	17.00
Crop Insurance	usd	30.75	26.86	22.96	28.24	30.33	22.96	23.30	29.43	35.21	30.75	26.86	22.96	28.24	30.33	30.33	23.30	27.09	27.97
Labor For Field Operations	usd	5.99	5.95	5.91	6.50	6.42	5.91	6.77	6.90	6.76	5.70	5.62	5.54	6.87	6.68	6.68	7.49	7.79	7.47
Non-Field Operation Labor & Mgmt	usd	40.47	44.78	49.09	37.73	48.25	49.09	41.60	43.30	48.36	4.91	18.90	32.88	35.21	33.96	33.96	10.83	14.65	23.52
Other Variable Or Operating Cost	usd	63.86	55.30	46.73	64.68	66.29	46.73	54.04	68.29	72.27	20.36	20.08	19.79	24.54	23.87	23.87	26.76	27.82	26.70
Variable Machine Cost Exc Fuel & Lubr	usd	30.99	30.78	30.57	33.99	33.53	30.57	35.60	36.37	35.58	28.11	27.71	27.31	34.07	33.12	33.12	37.24	38.74	37.15
Fixed Machinery Cost	usd	16.34	16.25	16.16	17.62	17.41	16.16	18.29	18.62	18.28	18.37	18.10	17.82	22.39	21.75	21.75	24.52	25.54	24.47
Other Fixed Or Overhead Cost	usd	8.43	8.48	8.53	8.59	8.65	8.53	8.66	8.90	8.81	8.36	8.28	8.19	8.38	8.45	8.45	8.20	8.34	8.37
Miscellaneous	usd	11.57	9.15	6.72	11.55	14.90	6.72	13.87	14.29	15.21	11.57	9.15	6.72	11.55	14.90	14.90	13.87	14.29	15.21
Diesel Fuel	gal	3.71	3.69	3.67	4.04	3.98	3.67	4.21	4.29	4.20	2.73	2.70	2.67	3.14	3.07	3.07	3.35	3.46	3.35

* Minnesota Crop Reporting Districts Regions are used. Because of data availability, budget for NC region is averaging of NW & NE and EC Budget is assumed to have same budget with C.

Soybeans, Wheat and Sugar Beet Budgets*

		B-SOYBEANS									B-WHEAT					B-BEET	
Input	Units	NW	NC	NE	WC	C	EC	SW	SC	SE	NW	NE	WC	SW	S	NW	WC
SOYBEAN SEED	BU-S	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00							
NITROGEN	LB										115.00	140.00	115.00	115.00	130.00	115.00	115.00
PHOSPHORUS FERTILIZER (P2O5, DRY)	LB	25.00	25.00	25.00	15.00	0.00	0.00	0.00	0.00	0.00	30.00	50.00			35.00	40.00	40.00
POTASH FERTILIZER (K2O)	LB									5.00	20.00	20.00	25.00	20.00	22.50	60.00	60.00
AMMONIUM SULFATE	GAL	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75						0.75	2.00
GLYPHOSATE	GAL	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38						1.00	1.00
LUBRICATION COST	USD	0.80	0.80	0.80	0.86	0.88	0.88	0.91	0.92	0.92	0.68	0.91	0.68	0.85	0.91	4.00	3.90
CUSTOM HIRE	USD	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	31.00	10.51	31.00	4.22	13.08	17.08	29.37
CROP INSURANCE	USD	25.00	25.00	25.00	23.01	26.85	26.85	24.62	28.06	30.84	13.26	11.29	8.66	6.63	2.78	19.43	23.12
LABOR FOR FIELD OPERATIONS	USD	5.01	5.01	5.01	5.31	5.43	5.43	5.58	5.66	5.64	4.32	4.93	4.32	3.62	5.42	61.86	59.65
NON-FIELD OPERATION LABOR & MGMT	USD	21.57	21.57	21.57	31.60	37.26	37.26	31.96	34.72	40.22	21.60	16.85	17.49	25.60	23.00	83.32	66.83
OTHER VARIABLE OR OPERATING COST	USD	15.46	15.46	15.46	16.22	16.74	16.74	17.52	17.92	17.81	38.11	32.42	69.21	23.99	21.13	211.94	141.29
VARIABLE MACHINE COST EXC FUEL & LUBR	USD	23.53	23.53	23.53	25.06	25.67	25.67	26.45	26.84	26.74	36.24	5.38	36.29	5.05	15.76	75.88	71.20
FIXED MACHINERY COST	USD	12.99	12.99	12.99	13.62	13.86	13.86	14.18	14.34	14.30	10.37	17.37	10.28	17.61	20.61	68.85	64.16
OTHER FIXED OR OVERHEAD COST	USD	4.16	4.16	4.16	3.97	3.93	3.93	3.85	3.97	4.17	8.85	17.87	7.87	17.58	9.04	52.69	46.92
MISCELLANEOUS	USD	9.06	9.06	9.06	9.74	11.15	11.15	10.29	11.17	10.58	6.35	1.80	4.72	2.89	3.84	2.01	23.20
DIESEL FUEL	GAL	3.56	3.56	3.56	3.82	3.92	3.92	4.04	4.11	4.09	3.02	4.05	3.02	3.79	4.05	17.77	17.35

*Because of data availability, Soybean budget region is based on Minnesota Crop Reporting Districts. Budgets for NC & NE are assumed to be same as NW. EC budget is assumed to be same as C. Wheat and sugar beet budget region is based on the Minnesota State Colleges and Universities Farm Business Management Program Region.

Alfalfa Hay Establishment (B-HAY-A-EST) and Mature Budgets (B-HAY-A-MAT)*

		B-HAY-A-EST									B-HAY-A-MAT								
Input	Units	NW	NC	NE	WC	C	EC	SW	SC	SE	NW	NC	NE	WC	C	EC	SW	SC	SE
PHOSPHORUS FERTILIZER (P2O5, DRY)	LB	50.00	50.00	50.00	30.00	15.00	15.00	20.00	15.00	0.00	30.00	30.00	30.00	25.00	15.00	15.00	20.00	15.00	0.00
POTASH FERTILIZER (K2O)	LB		0.00	0.00	15.00	45.00	45.00	50.00	50.00	55.00	10.00	10.00	10.00	25.00	35.00	35.00	50.00	50.00	60.00
LUBRICATION COST	USD	0.44	0.44	0.44	0.45	0.45	0.45	0.46	0.46	0.46	0.51	0.51	0.51	0.56	0.58	0.58	0.62	0.62	0.63
CROP INSURANCE	USD	1.93	1.93	1.93	0.42	2.92	2.92	1.38	0.87	0.90	1.93	1.93	1.93	0.42	2.92	2.92	1.38	0.87	0.90
LABOR FOR FIELD OPERATIONS	USD	7.19	7.19	7.19	7.37	7.41	7.41	7.56	7.58		11.62	11.62	11.62	12.68	12.97	12.97	13.83	13.96	14.13
NON-FIELD OPERATION LABOR & MGMT	USD	31.99	31.99	31.99	35.81	44.81	44.81	50.80	39.33		26.48	26.48	26.48	29.16	39.78	39.78	42.19	33.27	51.49
OTHER VARIABLE OR OPERATING COST	USD	1.63	1.63	1.63	2.08	2.20	2.20	2.57	2.62	2.70	3.26	3.26	3.26	4.16	4.41	4.41	5.14	5.25	5.40
VARIABLE MACHINE COST EXC FUEL & LUBR	USD	16.18	16.18	16.18	16.61	16.72	16.72	17.08	17.11	17.20	27.35	27.35	27.35	29.96	30.65	30.65	32.77	33.08	33.52
FIXED MACHINERY COST	USD	11.24	11.24	11.24	11.45	11.51	11.51	11.68	11.70	11.74	17.44	17.44	17.44	18.69	19.03	19.03	20.06	20.20	20.41
OTHER FIXED OR OVERHEAD COST	USD	3.80	3.80	3.80	3.82	4.04	4.04	4.15	4.07	4.00	0.95	0.95	0.95	1.15	1.33	1.33	1.64	1.56	1.59
MISCELLANEOUS	USD	10.52	10.52	10.52	8.64	10.31	10.31	11.40	10.34	10.61	10.52	10.52	10.52	8.64	10.31	10.31	11.40	10.34	10.61
DIESEL FUEL	GAL	1.97	1.97	1.97	2.01	2.02	2.02	2.05	2.06	2.06	2.28	2.28	2.28	2.50	2.56	2.56	2.75	2.77	2.81
RAPTOR HERBICIDE	GAL	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04									
WARRIOR HERBICIDE	GAL	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
ALFALFA SEED –PROPRIETARY	LB	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00									

* Minnesota Crop Reporting Districts Regions are used. Budgets for NC & NE are assumed to be same as NW. EC budget is assumed to be same as C

Hay Other Establishment (B-HAY-O-EST), Mature Year 1 to3 (B-HAY-O-MAT1~3), and Harvest (B-HAY-O-HAV) Budgets*

Input	Units	B-HAY-O-EST	B-HAY-O-MAT1	B-HAY-O-MAT2	B-HAY-O-MAT3	B-HAY-O-HAV
NITROGEN	LB	0.00	0.00	10.00	20.00	60.00
PHOSPHORUS FERTILIZER (P2O5, DRY)	LB	0.00	0.00	10.00	20.00	60.00
POTASH FERTILIZER (K2O)	LB	0.00	0.00	10.00	20.00	60.00
AMMONIUM SULFATE	GAL	0.38	0.00	0.00	0.00	0.00
GLYPHOSATE	GAL	0.17	0.00	0.00	0.00	0.00
LUBRICATION COST	USD	0.11	0.03	0.00	0.14	0.15
LABOR FOR FIELD OPERATIONS	USD	1.68	0.50	0.08	3.21	3.42
NON-FIELD OPERATION LABOR & MGMT	USD	17.50	17.50	17.50	17.50	17.50
VARIABLE MACHINE COST EXC FUEL & LUBR	USD	7.37	2.21	0.38	7.50	8.01
FIXED MACHINERY COST	USD	5.56	1.67	0.28	5.03	5.27
OTHER FIXED OR OVERHEAD COST	USD	3.05	0.00	0.47	0.95	2.85
MISCELLANEOUS	USD	0.00	0.00	0.00	0.00	0.00
DIESEL FUEL	GAL	0.47	0.14	0.02	0.62	0.66
PRAIRIE SEED	LB	8.50	0.00	0.00	0.00	0.00

*Minnesota State Budget is used

Table 11: Livestock Enterprise Budgets.*

	UNIT	B-SW-LITTER	B-SW-FINISH	B-BF-STR-H	B-BF-STR-S	B-BF-HFR-H	B-BF-HFR-S	B-BF-COW	B-DAIRY
MISCELLANEOUS IN FEED COST	USD	10.35	19.23	83.80	83.80	81.53	121.53	154.90	325.43
LIVESTOCK FACILITIES AND EQUIPMENT COST	USD	66.15	11.28	21.00	21.00	25.33	17.87	65.10	520.00
OTHER FIXED COST - LIVESTOCK	USD	62.86						163.48	239.00
OTHER VARIABLE COST - LIVESTOCK	USD	92.22	33.79	178.53	175.59	185.39	175.18	205.94	1720.04
DRIED DISTILLERS GRAINS AND SOLUABLES	LB		32.00						
SOYBEAN MEAL	LB	149.00	119.00						
CORN	Bushel	17.10	9.80	52.00	38.00	68.00	41.00	4.00	104.00
CORN SILAGE	US Ton				1.70		1.10		8.00
ALFALFA HAY	US Ton								6.10
HAY-OTHER	US Ton			0.40		0.58		2.10	
HEIFER CALF - 500 LB	Head					1.00	1.00	-0.26	
STEER CALF - 550 LB	Head			1.00	1.00			-0.46	-0.51
CULL COW - 1350 LB	CWT							-13.50	-13.50
CULL SOWS	CWT	-1.00							
FARM MILK	CWT								-200.00
MARKET STEERS AND HEIFERS	CWT			-11.50	-11.50	-11.00	-11.00		
MARKET HOGS	CWT		-2.60						
FEEDER PIGS - 12 LB	Head	-9.00	1.00						
DAIRY REPLACEMENT HEIFER	Head								-0.18
SWINE FARROWING CAPACITY		1.00							
SWINE FINISHING CAPACITY			1.00						
BEEF FINISHING CAPACITY				1.00	1.00	1.00	1.00		
BEEF COW-CALF CAPACITY								1.00	
DAIRY CAPACITY									1.00

*Source: Iowa State University, University Extension "Livestock Enterprise Budgets for Iowa 2009" 2009.

Budget Label	Descriptions
B-SW-LITTER	ONE LITTER(9HEAD) PRODUCING WEANED 12LBS PIGS, TOTAL CONFINEMENT
B-SW-FINISH	FINSING WEANED PIG(12LB)-ONE PIG
B-BF-STR-H	FINISHING STEER CALVES, CORN AND HAY RATION
B-BF-STR-S	FINISHING STEER CALVES, CORN AND SILAGE RATION
B-BF-HFR-H	FINISHING HEIFER CALVES, CORN AND HAY RATION*
B-BF-HFR-S	FINISHING HEIFER CALVES, CORN AND SILAGE RATION*
B-BF-COW	COW-CALF, CALVES SOLD
B-DY-COW	GRADE A DAIRY-20000LB OF MILK PER COW

* Combined budgets of Finishing Yearling Heifers & Backgrounding Steer Calves are applied.

Table 12: Transportation Cost Data.
-Distance in Miles between Regions*

	NW	NC	NE	WC	C	EC	SW	SC	SE
NW	0.0	119.4	273.3	208.4	263.9	258.3	369.8	400.8	449.0
NC	119.4	0.0	153.8	228.1	234.0	183.0	374.9	368.5	387.6
NE	273.3	153.8	0.0	322.0	275.6	177.7	429.9	378.4	351.5
WC	208.4	228.1	322.0	0.0	102.1	180.2	161.5	211.9	291.5
C	263.9	234.0	275.6	102.1	0.0	103.2	154.4	138.3	194.9
EC	258.3	183.0	177.7	180.2	103.2	0.0	254.7	203.9	204.8
SW	369.8	374.9	429.9	161.5	154.4	254.7	0.0	119.9	231.1
SC	400.8	368.5	378.4	211.9	138.3	203.9	119.9	0.0	111.4
SE	449.0	387.6	351.5	291.5	194.9	204.8	231.1	111.4	0.0

*Straight distance is adjusted by 1.4 Augmentation factor

It is assumed that transportation of inputs and products is carried by semi truck. USDA publishes quarterly grain truck transportation cost (USDA 2009). Also it is assumed that grain truck transportation costs are same as other liquids and cellulosic feedstock transportation cost. $2.91 per mile truck cost is derived by averaging from 4th quarter, 2007 to 3rd quarter, 2008 truck cost for 25 to 100 mileage distance. Semi trailer has cargo capacity of 26 ton in weight or 7,865 gallons in volumes (USDA 2007). Unit cost per mile is derived by $2.91/7,865 gallon (in volume) and $2.91/26 ton (in weight). Because corn stover and hay-other are harvested as bales, their transportation costs are separately derived. Lazarus (2009) is based on round bale with 5 feet wide by 6 feet diameter (1470.6 lbs/bale) for cellulosic feed stock production. If the semi trailer has 9' x 9' x 48' of cargo space, 30 round bales can be loaded. That makes 22.06 ton per load and unit costs per mile in cellulosic feedstock is derived by $2.91/20.01 MT.

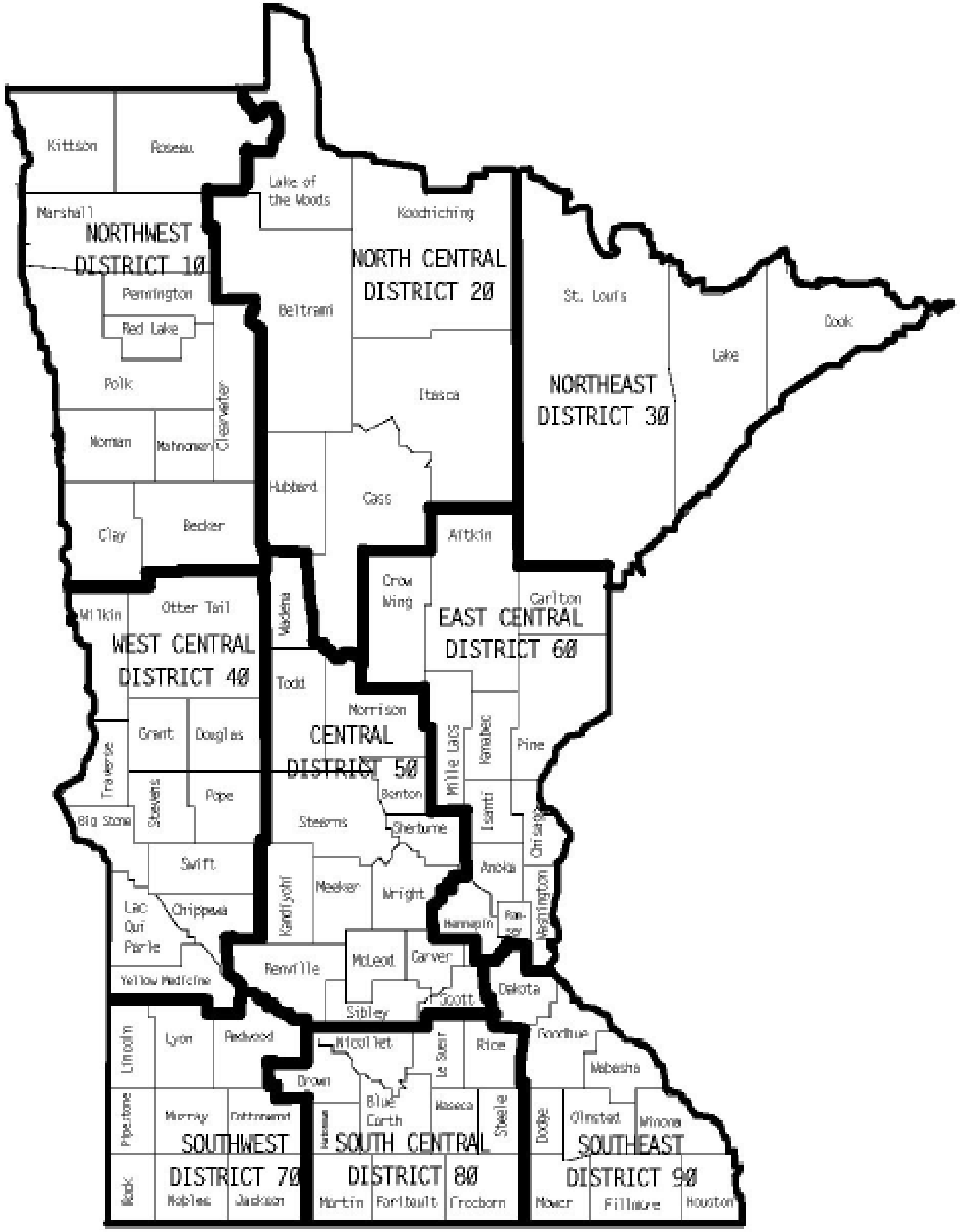
Table 13: Input and Product Prices.

Input & Product	Unit	Price	Source
CORN SEED			
SOYBEAN SEED	BAGS	250	1
NITROGEN	BUSHEL	40	1
PHOSPHORUS FERTILIZER (P2O5, DRY)	LB	0.26	1
POTASH FERTILIZER (K2O)	LB	0.33	1
AMMONIUM SULFATE	LB	0.58	1
GLYPHOSATE	GAL	6.85	1
DIESEL FUEL	GAL	75	1
RAPTOR HERBICIDE	GAL	2.25	1
WARRIOR HERBICIDE	GAL	635	1
ALFALFA SEED -PROPRIETARY	GAL	768	1
PRAIRIE SEED	LB	3.79	1
DIESEL	LB	8.24	1
DRIED DISTILLERS GRAINS AND	GAL	2.25	1
SOLUABLES	LB	0.06	2
FEEDER PIGS - 12 LB	HD	32.00	2
HEIFER CALF - 500 LB	HD	560.00	3
STEER CALF - 550 LB	HD	616.00	3
CULL COW - 1350 LB	CWT	54.60	3
CULL SOWS	CWT	28.20	3
FARM MILK	CWT	19.05	3
MARKET STEERS AND HEIFERS	CWT	90.20	3
MARKET HOGS	CWT	48.90	3
DAIRY REPLACEMENT HEIFER	HD	992.20	3
SOYBEAN MEAL	LB	0.12	4
SOY-OIL	LB	0.36	4
CRUDE	barrel	77.15	5
OIL-SANDS	barrel	63.96	5
BIODIESEL	GAL	3.06	5
CORN	bushel	4.00	6
SOYBEANS	bushel	10.00	6
WHEAT	bushel	7.50	6

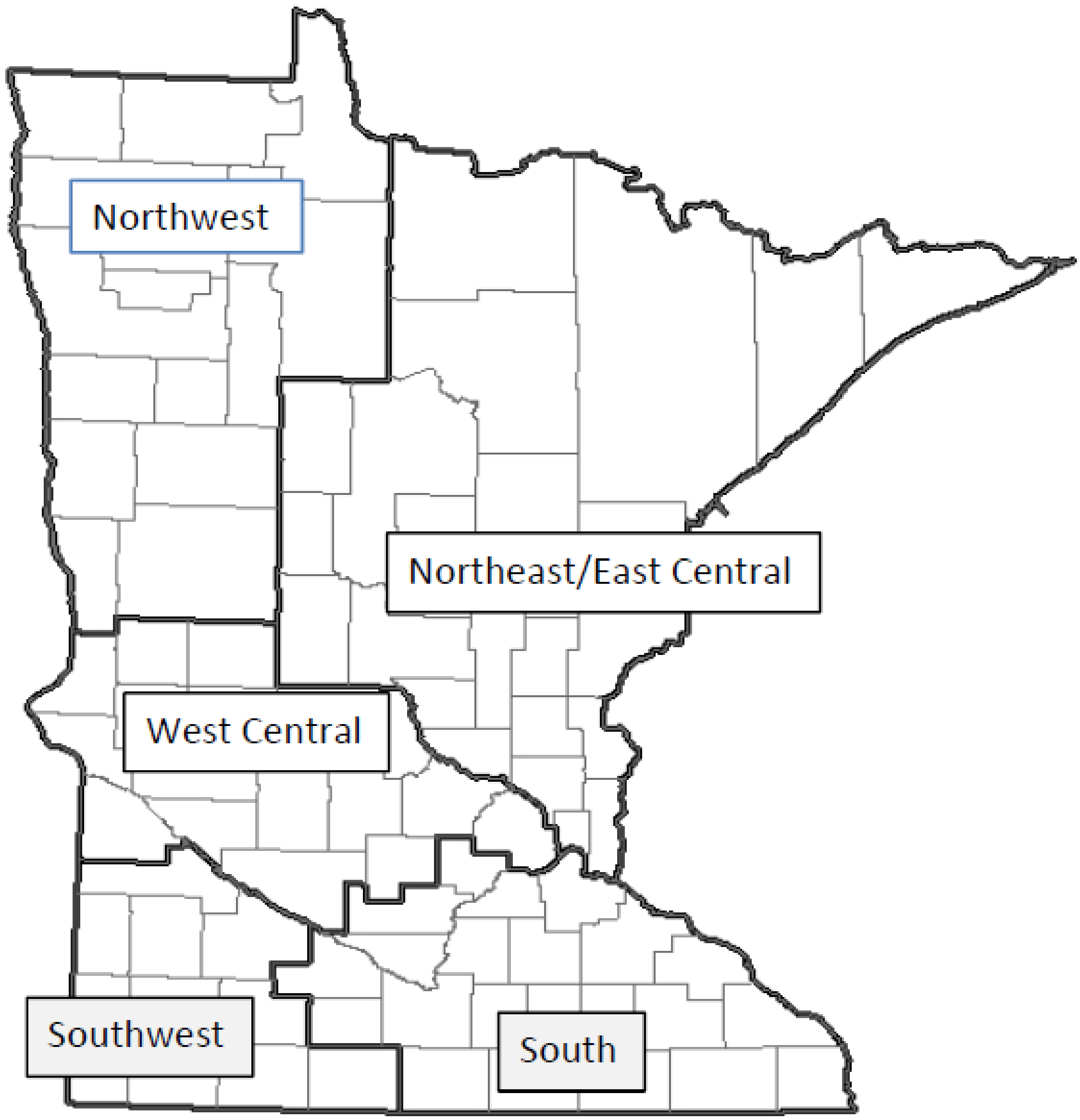
Source: 1. Lazarus, W.F. and Goodkind, A. "Minnesota Crop Cost & Return Guide for 2010" University of Minnesota Extension, 2009.
2: Iowa State University, University Extension "Livestock Enterprise Budgets for Iowa 2009" 2009.
3. U.S. Department of Agriculture- National Agricultural Statistics Service, "Agricultural Prices", 2009 Feb.
4. U.S. Department of Agriculture- Agricultural Marketing Service, "National Monthly Feedstuff Prices", monthly average price (2006~2008)
http://www.ams.usda.gov/AMSv1.0/ams.fetchTemplateData.do?startIndex=1&template=TemplateW&navID=RN2L1Feedstuffs&rightNav1=RN2L1Feedstuffs&topNav=&leftNav=MarketNewsAndTransportationData&page=SearchFeedstuffsReports&resultType=&acct=lsmn
5. Steve Taff Model data
6. U.S. Department of Agriculture- National Agricultural Statistics Service, "Agricultural Prices", 2007 & 2008 Marketing Year Average, Wheat is draft price
http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1002

Crop budget input price is cited from Lazarus Enterprise budget (Lazarus 2009). Most livestock product price cited from NASS, USDA is 2008 marketing year average price received in the Minnesota State. Using AMS, USDA feedstuff price report, central Illinois Soybean meal and soy-oil monthly price is average from 2006 to 2008. Crude, oil-sands and biodiesel price is from Steve Taff model data.

Minnesota Crop Reporting Districts



MnSCU Farm Business Management Program Regions



Minnesota
Low Carbon Fuels Standard Study

Comparative Assessment of Environmental Implications

Contract No. B24112

University of Minnesota

Environmental Implications Research Team:

Timothy M. Smith, Bioproducts & Biosystems Engineering, University of Minnesota (principal contact)

Junghan Bae, Bioproducts & Biosystems Engineering, University of Minnesota

Kristell Miller, Natural Resources Science & Management, University of Minnesota

June 2011

Prepared for:

Minnesota Department of Commerce

Table of Contents

List of Tables

List of Figures

Overview

As a whole, this project has investigated and developed modeling analytical frameworks with available data in order to compare the greenhouse gas, economic and environmental implications of various low carbon fuel standards (LCFS) policies for vehicles operated on Minnesota public roads. This section of the final report provides findings of work performed for the modeling analytical framework investigated and developed for the environmental portion of the project. Environmental impacts are identified as environmental and health impacts, including global warming potential related to greenhouse gas emissions (GHGs), but not limited to that category. Therefore, this section largely compliments our report's prior section addressing the Minnesota-specific greenhouse gas impact assessment. Specifically, it provides a broader assessment of select non-carbon environmental impact of various alternative fuel sources currently in production within the state and likely to be called upon in the future under a variety of economic and policy scenarios. The fuels incorporated into the analytical framework presented in this section are limited by the availability of data and the complexity associated with assessing multiple environmental impacts across multiple fuel types.

Two methods of review and assessment were performed to provide an evaluation of the possible environmental impacts associated with select, and likely, fuel pathways associated with the implementation of a Low Carbon Fuel Standard within the state of Minnesota. First, we review the existing literature of life cycle based studies examining alternative transportation fuels, whereby environmental impacts, beyond those of GHGs, were assessed. This effort attempts to determine the current state of knowledge concerning the broader environmental impacts of fuel pathways across their entire life cycle (i.e. resource extraction, production, and use/combustion). Second, a Life Cycle Assessment (LCA), including a Life Cycle Impact Assessment (LCIA) was undertaken for fuel pathways currently in use within the state and where adequate life cycle inventory data is available. The steps that were followed for this analysis are delineated within the International Standards of Organization for Environmental Management and Life Cycle Assessment (ISO 14040 series).

While fourteen fuel pathways were analyzed in the GHG-LCA portion of this study, significantly less research has been conducted in the U.S. regarding the non-carbon environmental impacts of transport fuels on a life cycle basis. Due to the lack of data consistency and differences in approach across prior studies, these pathways were compressed to seven generalized fuel types are explored within the literature review that follows. We restrict our analysis to peer-reviewed life cycle based studies, whose impacts are reported vis-à-vis their appropriate fuel baselines of gasoline or petro diesel. In addition, four generalized fuel pathways were chosen for further study using Life Cycle Impact Assessment (LCIA). This detailed LCIA framework is restricted to corn ethanol, soy biodiesel, gasoline and petro diesel based on the availability of externally developed life cycle inventory (LCI) databases. Where data was available the LCIA framework included environmental aspects, from raw material acquisition to final disposal (i.e. from "cradle to grave"). Material and energy inputs, as well as emissions to soil, water and air – some virtually without temporal boundaries - are accounted for through life cycle inventories assembled by commercial and governmental research labs.

While additional discussion of LCI database and LCIA characterization tool selection is provided in subsequent sections of this report, it is important to note that findings reported from this LCIA represent inventory data selected from the commercial ecoinvent database and the US EPA LCIA tool known as the Tool for the Reduction and Assessment of Chemical and other environmental Impacts or TRACI. Therefore, our results reflect the assumptions incorporated in the development of these data by their creators. The system boundaries chosen for this LCIA of four fuel pathways are "well to wheel", including mineral extraction (energy crop cultivation), mass transportation (truck/rail/pipeline), regional storage, fuel pumping station and fuel combustion in vehicle operation. It is important to note that this system boundary is different from the analysis conducted in the prior GHG-LCA study presented earlier in the GHG section of this report, in that ecoinvent includes "upstream impacts" not generally included within the GREET model employed in this study's previous GHG assessment. For example, , GREET identifies a system that only includes direct air emissions associated with fuel combustion of the tractor or emissions to water related to fertilizer and pesticide application solely due to cultivation of corn for ethanol. Ecoinvent, in addition to these inputs and emissions, also attempts to include the upstream materials, energy and emissions associated with the manufacture of fertilizers, pesticides, and farm equipment used in the production of corn, a portion of which is used for ethanol. While it makes it difficult to compare these approaches directly, the GHG results reported in this section of the report are reasonably consistent with previous studies and with results reported earlier in this report, with the caveat of Minnesota-specific assessments of fossil fuel baselines. Gasoline and diesel consumed in Minnesota are markedly more carbon intense due to greater percentages of heavy crude from Canadian tar sands than the national average.

With regard to non-carbon environmental impacts, our results indicate that each fuel pathway examined in the literature and through LCIA create impacts of higher magnitude in some categories and lower magnitude in others. Significant research has been conducted on environmental and health impacts within various life cycle stages of fuel production and use (i.e. oil extraction, refining, combustion, etc.), as well as within the many facets of agricultural and mining systems that may be implicated in the development of new fuel pathways in the future (i.e. corn/soy production, mountain-top removal coal extraction, international land-use change, etc.). However, to be consistent with the approach taken in most GHG-LCA assessments of alternative fuels and to avoid significant issues associated with impact trade-offs (GHG vs. eutrophication vs. ecotoxicity) or impact shifting (combustion in-use to production or end-of-life phases), our focus is restricted to literature and tools consistent with a more holistic approach of LCA. This is important because if we were to, for example, overemphasize impacts of tailpipe emissions - given the vast amount of regulatory-based research in this area - a reader might form incorrect or incomplete conclusions.

While significant life cycle based research has been conducted to assess energy content and GHG emissions, little work has been done to explore non-carbon impacts of transport fuels that encompass many other environmental impacts of fuels across production, refining and use. Therefore, it is important to recognize that the state of LCA science is nascent, both in terms of the databases comprising inventories of inputs and emissions (particularly with regard to U.S. specific data) as well as tools for the characterization of these inventory data across multiple impacts (e.g. spatially- and temporally-specific consideration). The information provided below is, thus, reported under conditions of uncertainty, and we encourage readers to take appropriate caution when drawing direct conclusions from our findings. We feel the results presented are important to our growing understanding of the broader impacts of emerging policies addressing alternative fuels, that they reflect the sound application of relevant data and impact assessment tools and that they are useful to the deliberations necessary for the development of effective public policy influencing the transport fuel mix. However, these results are also heavily influenced by the assumptions inherent in the data sets and tools used by authors of previous studies included in our review, as well as in the assumptions and data employed by our LCIA developed in this report. There is little agreement within the LCA academic and practitioner community as to standardization or harmonization across approaches, though many are working toward this end.

Our findings suggest significant environmental and health impacts associated with the current use of large amounts of tar sand refinery fuels in Minnesota. The majority of studies examined approach this fuel pathway as a future alternative fuel with large carbon and land use impacts, however, significant volumes are currently in use within the state (upwards to 90% of Minnesota's current fuel mix). Therefore, the environmental and health impacts of "conventional gasoline" or "conventional diesel" found in subsequent analyses of this report are significantly underestimated for the Minnesota context. In addition, we report significant anticipated environmental and health impacts associated with increased volumes of coal-to-liquid fuels anticipated to play a much larger role in the Minnesota transport fuel mix in the absence of policies explored in earlier sections of this report. The non-carbon life cycle impacts of these fuels are largely unexplored. Improved environmental and health impacts are suggested for many emerging transport fuel alternatives, from cellulosic biofuels to plug-in electric powered vehicles to natural gas, although significantly more research is needed to explore non-carbon impacts of these technologies. Our quantitative life cycle impact assessments comparing alternative first generation biofuels to conventional petroleum fuels indicate carbon reductions similar to previous studies employing similar systems boundary conditions. In addition, similar to previous studies, our assessment of these fuels find increased eutrophication impacts relative to conventional petro fuels. We highlight biodiesel's potential to reduce photochemical smog, and results from the modeling analytical framework also suggest potentially greater impacts associated with photochemical smog and human health (cancer and non-cancer) throughout the life cycle of producing and using first generation corn ethanol. However, these results are presented under significant uncertainty. Interpretation of findings represents a framework for assessing non-carbon environmental and health impacts of a low carbon fuel standard, as opposed to purporting any specific number for shaping policy

Particularly with regard to non-carbon environmental assessments of alternative transport fuels, many data elements utilized in these analyses were found to be highly variable—whether because the data is based upon modeled future technologies or because the methods of measurement and characterization are under active and developing research. Findings reported here provide specific examples of uncertainties and reveal focused areas of research needed to reduce them. We urge readers not to make policy decisions based upon the specific numbers reported, but rather use findings to enable more informed discussions on the topic.

Literature Review to Determine Current State of Knowledge

A literature review was undertaken to determine the current state of knowledge regarding environmental impacts of fuels commonly affected by low carbon fuel standard policies. The following summaries are provided for a gasoline/diesel baseline, corn ethanol, biodiesel, cellulosic ethanol, and coal-to-liquid fuels. Only those fuel types for which assessments have been conducted across the entire life cycle, and which are anticipated to play a significant role in the MN production transportation fuel mix under the business as usual or the basic low carbon fuel policy scenario through 2030 have been included for broader environmental impact evaluation.[1]

Given the priorities outlined at the outset of this project, environmental impact categories investigated in the literature for each fuel, referred to as category indicators in life cycle analysis, were: global warming potential, acidification, eutrophication, photochemical oxidation (smog formation), and human respiratory impacts, land use and water use. Many of these impacts are interrelated as acidification and eutrophication inherently affect water and air quality, and land-use demands directly impact wildlife health and biodiversity. A growing sub-field of life cycle assessment, often referred to as "consequential LCA," attempts to address the impacts of these types of system changes over time. Land-use change and indirect land-use change across geographies and land-use application is a central topic in this field, as a few square miles of tropical forests may contain more above-ground species than all of North America. Expanding fuel crops onto previously forested land in the tropics or into wetlands is likely to exact a high price in terms of wild species displaced or lost (Huston 1994). While this report provides a cursory review of land and water use impacts directly attributed to fuel pathway production and consumption, we do not address indirect land-use impacts (or any other indirect impacts) in this report.

A difficulty associated with attempting to address the literature related to environmental impacts of fuel pathways is that many different fields of study, from ecology, biology and agricultural sciences to chemistry, engineering and public health have each explored in depth components of fuel extraction, production and combustion impacts. This work has largely followed societies lead by informing media-specific (i.e. land, water, air) and source-specific (i.e. stationary or mobile) regulatory and policy efforts addressing the environment. While this body of knowledge is incredibly informative to our understanding of risk to environmental and human health, and largely informs the life cycle data and tools used to assess fuel systems, our examination of the literature attempts to only address impact categories assessed across the fuels life cycle (i.e. extraction, production, transport, combustion). In this way, impact categories examined and the system boundaries of analysis are non-standard and vary study by study, but attempt to capture a more holistic picture of impacts of the fuel. Thus, wildlife is affected by poor water and air quality, land-use change and toxic releases to the environment, for example. Sedimentation is related to water use and land-use. Land use has implications on global warming potential, etc. It is outside of the scope of this report to review the decades of research addressing the underlying data used in life cycle models of fuel systems. Rather, in this section we focus on life cycle studies addressing transport fuels where insights from previous research are available to inform an assessment of a low carbon fuel standard.

[1] Significant portion of the MN production transportation fuel mix is defined as comprising more than 1% of the estimated transportation fuels produced by Minnesota firms to meet both in-state demand and exports in 2020 or 2030 across either policy scenario, as determined in the Policy Interactions Modeling section of this report.

Table 1: Assignment of fuel pathways to reporting categories for environmental assessment.

	"Fuel Pathway"	"Transportation Technologies"	"Transportation Fuels"	Fuel as Assessed for Non-Carbon Env. Impact
B	North American Refinery	Refinery	Gasoline/Diesel	Gasoline/Diesel Baseline
	Foreign Refinery	Refinery	Gasoline/Diesel	Gasoline/Diesel Baseline
	EOR Refinery	Refinery	Gasoline/Diesel	Gasoline/Diesel Baseline
1G1	Corn Ethanol	Corn Grain Ethanol	Ethanol	Corn Ethanol
1G2	Soybean Biodiesel	Biodiesel	Biodiesel	Biodiesel
2G1	Grass Ethanol	Cellulosic Ethanol	Ethanol	Cellulosic Ethanol
	Crop Residue Ethanol	Cellulosic Ethanol	Ethanol	Cellulosic Ethanol
	Wood Ethanol	Cellulosic Ethanol	Ethanol	Cellulosic Ethanol
2G2	Tar Sands Refinery	Oil Sands	Gasoline/Diesel	Oil Sands Gasoline/Diesel
2G3	Coal CTL	Coal to Liquids	Gasoline/Diesel	CTL Gasoline/Diesel
2G4	Natural Gas	Natural Gas	Natural Gas	Not Assessed
2G5	SNG	electricity	electricity	Not Assessed
	IGCC and CCS	electricity	electricity	Not Assessed
	Existing Pulverized Coal	electricity	electricity	Not Assessed
	New Pulverized Coal	electricity	electricity	Not Assessed
	Gas Electric	electricity	electricity	Not Assessed
	Biomass	electricity	electricity	Not Assessed
	Photovoltaic	electricity	electricity	Not Assessed
	Wind Turbines	electricity	electricity	Not Assessed
	Old Nuclear	electricity	electricity	Not Assessed
	New Nuclear	electricity	electricity	Not Assessed
	Hydroelectric	electricity	electricity	Not Assessed
NA	Algae Biodiesel	Biodiesel	Biodiesel	Not Assessed

The category indicators examined through a review of the literature include: global warming potential, acidification potential, eutrophication potential, photochemical oxidation (smog) potential, land use, water use, and human health impact potential (specifically respiratory). The following discussion provides background and definitional information associated with each category.

Global Warming is defined as an accumulation of atmospheric gases such as carbon dioxide, methane and nitrous oxide which slow the passage of re-radiated heat through the Earth's atmosphere and cause an increase in the temperature of the Earth's troposphere. This "greenhouse effect" can lead to increased droughts, floods, sea-level rise, change in wind and ocean patterns, extreme weather events and other environmental effects. A Global warming potential (GWP) is defined as a measure of the potency of a greenhouse gas (GHG) relative to the same mass of CO_2 (whose GWP is assigned a value of 1) as proposed by the International Panel on Climate Change (IPCC,1996). GWP is based on the chemical's radiative forcing and lifetime and is calculated over a specific time interval. The value of this must be stated whenever a GWP is quoted. The final sum is the emission's global warming index and this indicates the emission's potential contribution to global warming. It is calculated as:

Global Warming Index = $\Sigma_i\, e_i$ X GWP_i (where e_i is the emission (in kilograms) of substance *i* and GWP_i is the global warming potential of substance *i*) (Bare, 2003).

Acidification is caused when the acidity (hydrogen ion concentration, [H+]) of water or soils increases which in turn causes the pH of the affected aquatic or terrestrial system to decrease. The effects of acid deposition on aquatic systems depend chiefly upon the ability of the ecosystem to neutralize the additional acid. Acidification has been shown to have adverse effects on forests, freshwaters, soils, aquatic and insect life-forms as well as causing damage to buildings, monuments and other historical artifacts. Deposition occurs via wet or dry methods. Wet deposition of acid occurs when any form of precipitation (rain, snow, sleet, etc.) removes acids from the atmosphere and delivers it to the Earth's surface. Dry deposition occurs when particles and gases stick to leaves, soil or other surfaces. According to the US EPA, lower pH concentrations resulting from acidification make it difficult for some fish and other aquatic organisms to survive, grow, and reproduce (EPA (g), 2007). The responses of forest trees to acid precipitation include accelerated weathering of leaf surfaces, increased permeability of leaf surfaces to toxic materials, water, and disease agents; increased leaching of nutrients from foliage; and altered reproductive processes which can weaken trees so that they are more susceptible to other stressors such as extreme weather, pests and pathogens. The deposition of sulfates and nitrates on manmade materials can hasten natural weathering processes by accelerating the corrosion of metals, degrading paints, and deteriorating building materials (such as concrete, limestone and marble) and culturally important items such as statues and works of art.

Acidification potential is expressed as the terrestrial deposition of expected H+ equivalents (in moles per kilogram) (Norris, 2002).

Eutrophication is caused when a nutrient that was previously scarce (limited) is provided to a water body such as a lake, estuary or slow-moving stream. Once this occurs, previously restricted photosynthetic plant life is allowed to proliferate which can lead to an overabundance of algae and aquatic weeds (USGS, 2008). As this dead plant matter decomposes, it reduces the amount of dissolved oxygen in the water which can cause the death of aquatic marine life, reduced biodiversity, a foul odor or appearance and toxic chemical build-up. The most common cause of eutrophication in surface waters is excessive inputs of phosphorus (P) and nitrogen (N) (Howarth/Pearl, 2008).

Severe eutrophication can directly affect human activities by causing fish and shellfish kills due to low oxygen levels, declining tourism due to noxious odors and unfavorable aesthetic conditions, and risks to human health due to build up of toxins in edible fish (Shumway 1990). According to a National Oceanic and Atmospheric Administration report, more than half of the nation's estuaries have moderate to high manifestations of at least one of these symptoms - indicating advanced eutrophication (Clement et.al,2001). Some algal blooms are toxic to plants and animals. A common example of algal toxins working their way into humans is the case of shellfish poisoning. Biotoxins created during algal blooms are taken up by shellfish (mussels, oysters), leading to these foods acquiring toxicity. When consumed by humans this causes health risk.

Eutrophication potential is a product of the amount of limiting nutrient provided to an ecosystem (nutrient factor) and a transport factor and is expressed relative to 1 kg. N discharged directly to surface waters.

Photochemical Oxidation (smog): Ground level ozone, or tropospheric ozone, is formed in the atmosphere when sunlight causes complex photochemical reactions involving nitrogen oxides (NO and NO2 known collectively as NOx), volatile organic hydrocarbons (VOCs) and carbon monoxide (CO). Contrary to the protective ozone that exists in the stratosphere, tropospheric ozone (smog) is detrimental to human health and ecosystems and can lead to respiratory ailments and plant mortality. Ozone is a highly reactive substance that can react directly with, and have a destructive effect on, cells lining the lungs of humans and the leaves of plants. High ozone concentrations can lead to respiratory symptoms, illness or disease, and may also be associated with increased mortality (EPA (r), 2009). US studies have found surface ozone concentrations to be strongly correlated with ambient NOx concentrations (Wang, et.al., 2007. While the immediate impacts of NOx emissions are generally local, the products formed by NOx may travel long distances. NOx, VOCs and CO are emitted into the atmosphere primarily via combustion processes. However, VOCs are also produced from biological sources such as trees (Hess et. al., 2008). Anthropogenic sources of NOx include the use of fertilizers and the resulting biogenic soil activity.

The potential to create photochemical smog is expressed in kilograms of NOx equivalents (Bare et. al. 2003).

Land Use: Land uses, such as agricultural production, mineral extraction, and human settlements and infrastructures, have a number of physical impacts on flora, fauna, soil, and soil surface, which are often neglected in product life cycle assessment (LCA) because of lack of adequate impact indicators. This metric is often described in terms of indicators for ecosystem productivity and biodiversity. With regard to ecosystem productivity, indicators for the impact on biotic resources, the potential for agriculture, and most of the life-support functions of natural systems are usually accounted for. For biodiversity, indicators associated with species richness, inherent ecosystem scarcity (expressed as the inverse of the potential ecosystem area that could be occupied by the ecosystem if left undisturbed by human activities), and ecosystem vulnerability (indicating the relative number of species affected by a change in the ecosystem area, as expressed by the species-area relationship). The metric chosen for this study was the amount of land used in the production of fuel or feedstock. This metric is more readily quantifiable when analyzing the production of feedstocks necessary for biofuels and also for oil sands gasoline obtained through strip mining. It is less quantifiable when the fuel is obtained through drilling, as is the case for domestic sweet crude and in situ oil sands extraction.

Land Use impacts are expressed in hectares required to fuel one car (HA/car/year), global cropland hectares ecological footprint (Vos,2007) and Eco-Indicator points (Uihlein,2009)

Water Use: When assessing the environmental performance of a product by means of LCA, attention is usually drawn on the energy consumed along a product's lifespan or on the emission of greenhouse gases and toxic substances. In contrast, the use of freshwater throughout a product's life cycle is often neglected. The review of research articles dealing with assessment of water use in LCA or case studies revealed a lack of a consistent terminology. In order to provide consistent wording throughout this article, the terminology proposed by the UNEP/SETAC Life Cycle Initiative has been adopted. In general, the total input of freshwater into a product system is referred to as "water use." As parts of the water input is released from the product system as waste water, the remaining part which has become unavailable due to evaporation or product integration is referred to as "water consumption." Accounting and assessing water use in LCA specifies the entire amount of freshwater required to produce a product. This comprises the water use in the manufacturing process as well as water used in background processes such as the mining of raw materials, the production of materials and semi-finished products, or the generation of electricity. Furthermore, the water used during the product's use, disposal, or recycling is taken into account. Water inventories can be established by means of LCA databases like ecoinvent and GaBi, or the WBCSD Global Water Tool. Depending on the database, tool, or framework the information content of the inventory can differ considerably. LCA databases usually only classify the input and output fluxes according to the watercourses from which the water is withdrawn and to which it is released (ground-, surface-, seawater, etc.).

Water use impacts are reported as volume of water use per volume of fuel production (g/g or l/l)

Human Health Impacts/Respiratory Effects: Fine particulate matter (PM) is a mixture of extremely small particles and liquid droplets made up of a number of components, including acids, organic chemicals, metals or dust. Particles that range in size from 10 micrometers in diameter or smaller can be inhaled and affect the lungs and heart causing serious health issues.

Ambient particulate concentrations are measured by the amount of total suspended particulates which includes PM less than 10 μm in diameter (PM 10), PM less than 2.5μm in diameter (PM 2.5) and emissions of SO2 and NOx (which cause the formation of secondary particulates sulfate and nitrate). The smaller size of PM 2.5 means that it may be transported longer distances and may present a greater health hazard by penetrating deep into the lungs. Fine PM is primarily generated through combustion by direct release of smoke or by chemical reactions of gaseous combustion emissions (i.e. NOx, SO2, VOCs). The possible respiratory health effects of PM2.5 exposure include: decreased lung function, irregular heartbeat, onset of asthma, chronic bronchitis, non-fatal heart attacks and premature death in people with lung or heart disease (EPA (h), 2008).

Human health and respiratory impacts are expressed in PM 2.5 equivalents

Literature Review Findings

The results of the literature review are first summarized in tabular form and are divided into sections reflecting the stage of product development and the bulk of information known about the environmental implications of the fuel pathways[2]. As some alternative fuel pathways are in relatively nascent stages of production, referred to as 2nd Generation fuels, few full LCIA studies or other assessments have been preformed to analyze the environmental effects of these fuels. They, in many ways, cannot be considered on the same scale as those more thoroughly researched technologies (called 1st Generation fuels) and therefore have been separated into different charts in this review. Also, the reader must be aware that available information regarding possible impacts for these new technologies are limited to those areas in which multi-category LCIA's have been performed and therefore may not reflect all possible impacts or place each 2nd generation fuel on a level playing field. Obviously, much further research in these areas is needed.

1st Generation Fuels

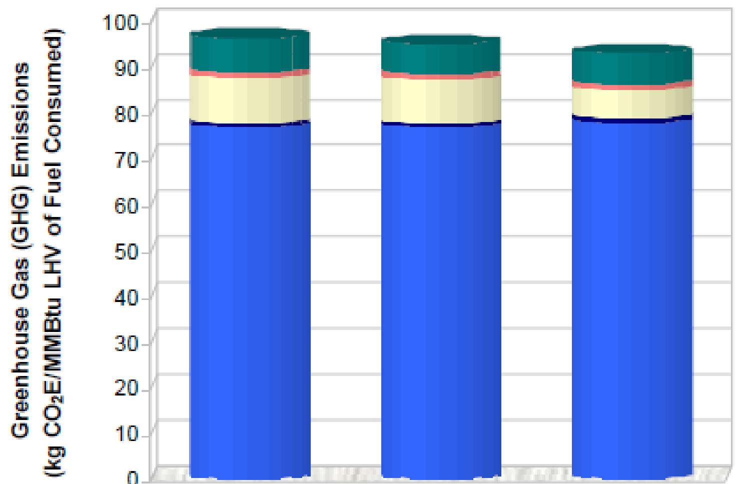
<u>Gasoline/Diesel – Baseline</u>

Studies assessing impacts of renewable fuels were found to be much more available to the public than those for fossil fuels. Some specific limitations on data available for fossil fuels are included in this section.

For comparison purposes, light crude refinery gasoline or diesel served as the baseline to which substitute fuels were compared in summary Tables 1 and 2. With regard to the reviewed literature, the "baseline" used in each LCA study varied. There is no consistent baseline that is agreed upon by industry when conducting fuel type comparisons. The baselines used in the studies included in our analysis varied from 92 – 96.9 gCO2 eq/MJ.

Global Warming: Standard values used by several life cycle models to compare alternative fuels, measured in grams of CO2 equivalent emissions per megajoule (MJ) of gasoline fuel consumed, are as follows: .92 - .94 kg CO2 equiv. per MJ (Arons, 2007, Liska,2008, Farrell,2006); 95.2gCO2eq./ MJ (Unnasch,2009); 95.86 g CO2 eq./MJ(CARB,2009) and 96.9 gCO2 eq./MJ (Hill,2006). An uncertainty band of +/- 1 to 2 g CO2eq/MJ is typically reported (Unnasch, 2009). Results of research for the GHG section of this report determined that Minnesota refining of its current oil sands and sweet crude mix result in 105 gCO2e/MJ. According to Sheehan 1998, CO_2 emitted from the tailpipe represents 86.54% of the total CO_2 emitted across the entire life cycle of the fuel. Most remaining CO_2 comes from emissions at the oil refinery, which contribute 9.6% of the total CO_2 emissions. Net CO_2 for petroleum diesel is estimated at gCO_2/bhp-h 633.28. Minnesota has a higher baseline due to the high percentage oil sands gasoline used within the state.

[2] As the summary tables are presented in summary form and in a very dense format. It is expected that the reader will make use of the explanatory footnotes referenced within each cell.



Key	Life Cycle Stage	Conventional Gasoline		Conventional Diesel		Kerosene-Based Jet Fuel	
	#1: RMA	7.3	8%	6.6	7%	6.8	7%
	#2: RMT	1.4	1%	1.3	1%	1.3	1%
	#3: LFP	9.8	10%	9.5	10%	6.0	6%
	#4: PTR	1.1	1%	0.9	1%	1.0	1%
	#5: Use	76.6	80%	76.7	81%	77.7	84%
	Total:WTT	19.6	20%	18.4	19%	15.1	16%
	Total:WTW	96.3	100%	95.0	100%	92.9	100%

Figure 1: Baseline 2005 life cycle greenhouse gas emissions for petroleum transportation fuels sold/distributed in U.S. (kg CO2E/MMBtu LHV of fuel consumed) (NETL 2008).

Although the range of emissions reported herein fall within a fairly consistent range, there is definite variation amongst reported baseline petroleum values. This is because there is no uniform standard of what is considered "conventional petroleum." There are inherent difficulties in providing accurate comparisons of alternative technologies to petroleum fuels if the "baseline" is different depending on who is doing the study and the value they use as a baseline. If average petroleum emission values are used, baseline values are dependent upon the particular fuel mix of the region. What method of refining, type of feedstock, and source of crude should then be considered "conventional"? With every source of crude, from low-sulfur, light domestic, to high-sulfur, heavy foreign to Canadian oil sands crude to crude from Iraq, the inputs required change. These differing inputs include extraction technologies, refining methods, venting and flaring, transportation, and military protection of supply. The energy requirements of, and GHG emissions associated with, each can vary considerably.

According to a comparative petroleum analysis performed by Life Cycle Associates, when tertiary extraction technologies, resources and heavy forms of crude oil (all of which can contribute over 10% of current supplies) and indirect effects such as military activities to protect Middle Eastern oil supplies are included, the range in emissions is considerably greater. When the above are included, the GHG impact of petroleum ranges from 90 to 120 g CO2e/MJ (grams of CO2 equivalent emissions per megajoule (MJ) of gasoline fuel consumed) (Unnasch, 2009).

Land Use: Information addressing this impact category from studies employing life cycle based methodologies where not found. This metric is more readily quantifiable when analyzing the production of feedstocks necessary for biofuels and also for oil sands gasoline obtained through strip mining. It is less quantifiable when the fuel is obtained through drilling, as is the case for domestic sweet crude and in situ oil sands extraction. In many of these cases, other land uses occur up to and around the drill site. Studies assessing the amount of acreage set aside strictly for drilling, and the impacts to that acreage, were not found.

Water Use: The water needs for the refining phase of petroleum gasoline amount to 1 – 2.5 gallons of water per gallon of fuel produced (US DOE, 2006). In order to compare across fuel types, the only metric that applied to all fuel types that was addressed in Life Cycle Assessments was the amount of water used for fuel refining, production and feedstock production. Therefore, this was the metric chosen for comparison. Significant research has been done with regard to toxic and hazardous substance release due to petroleum extraction, processing and spills to both land and water. While this information is incorporated into the ecotoxicity impact category explored subsequently in the LCIA portion of this report, no study was identified that reported life cycle impacts of these impacts across the fuel life cycle.

A problem encountered when analyzing petroleum baseline impacts is that very few multi impact category LCAs could be found that address non-carbon environmental impacts. In addition, those that address broader environmental impacts often present comparative data, vis-à-vis alternative transport fuels, without disclosing nominal impact category values – disclosing only percent increases and/or reductions. For this reason, much of the following discussion, as well as reported data within Tables 1 and 2, is presented with regard to the subject fuel relative to the appropriate petroleum baseline.

Corn Ethanol

Global Warming: Much disagreement exists regarding the methods, assumptions, and system boundaries necessary in order to accurately quantify the total amount of GHG's emitted during the production and use of corn ethanol. During the growth phase, corn acts as a carbon sink and CO2 is sequestered, not emitted. However, N_2O emissions from nitrification and denitrification of nitrogen fertilizer in corn fields (producing CO2 equivalents) are a significant GHG emission source during the growth phase (Wang, 2007). Differences in modeling the various components of the ethanol pathway, land use changes and upstream processes as well as differences in evaluation measures and time horizons account for the wide range of results. Current LCA studies, using a variety of models, have determined the following GHG intensities for corn ethanol, measured in grams of CO2 equivalent emissions per megajoule (MJ) of fuel consumed, to be: 38-48 g CO2eq./MJ (Liska, 2008);77 gCO2eq./MJ(Farrell et al, 2006); 84.9 gCO2 eq./MJ (Hill et. al,2009) and, measured as the percentage GHG emissions are reduced compared to reported value of CPB, as: 18% (Farrell et al, 2006);<20% (Sagar/Kartha, 2007); 20% (Searchinger et.al, 2008); 22% (EPA (g), 2007); 19%-39% (Wang et.al, 2007); 53% (Liska, 2008);and 48%-59% (Kim/Dale, 2008).

There are several ways in which modeled emission amounts can vary. The refining process is especially sensitive to the method used to power the refining plant (e.g. coal vs. natural gas) as well as the milling method used (wet or dry milling). A 52 -54% reduction as compared to baseline has been reported for a biomass-fired dry mill plant to a reported 3- 4 % increase as compared to baseline for a coal-fired wet mill plant (Wang,2007;EPA (g),2007). During the production of ethanol, important and useful co-products such as dried distiller grains with solubles (DDGS - used for animal feed), corn syrup and corn oil are produced as well. If the energy inputs used to produce these products are not allocated to them, as has occurred with some studies, data will vary accordingly (Farrell, 2006). Some models include land use change when calculating GHGs, others don't. How land use is handled within models varies as well.

If potential advances in production efficiency at the farm and refinery are assumed, GHG emissions from corn ethanol produced by using natural gas are lower than those of baseline gasoline, even with land-use change included (Hill, 2006). This as is further supported in recent EPA RFSII analysis which concludes that corn ethanol produced under new technology assumptions and using natural gas energy inputs satisfy the 20% GHG reductions over conventional fuels required by the policy. Results of research for the GHG section of this report determined that Minnesota corn ethanol plants average 63 gCO2e/MJ. Minnesota GHG emissions of corn ethanol hold potential for significantly lower emissions. That section of this report estimates that if best practices currently in use for some of Minnesota's plants and corn growers were adopted, emissions would be 50 gCO2e/MJ.

Land Use: There are several different ways in which the growth of corn ethanol has been shown to impact land use. One study looked at the amount of hectares required to fuel one car for a year and determined that it was 1.1 hectares for corn ethanol (Farrell, 2006). Another study looked at what researchers termed the "*ecological footprint,*" defined as being the amount of land needed out of all land area the earth has available for generating renewable resources, and determined the cropland footprint of corn ethanol to be 2.43 global hectares (Vos, 2007)[3]. Other researchers used different measurements of land use such as the yield per acre of cropland (370 gallons ethanol/acre (Curran, 2008). When looking specifically at the state of Minnesota, the yield of corn ethanol per unit area was determined to be between 41.4 and 46.4 GJ ha-1 (Liska et al. 2008).

From 1980 to 2006, corn ethanol production increased 30 fold despite the fact that the number of acres in corn production held steady at about 80 million acres (Wang et.al, 2007). The increase in per acre corn yield before the 1970's occurred because of the application of fertilizers. Since 1970, increased yields are due to improved seed varieties, farming practices and other agricultural improvements (Wang et.al, 2007). If corn yields continue to increase at present rate (1.8 bushels per acre per year) production could increase by more than 3.1 billion bushels (29%) by 2030 with no additional acreage (EIA, 2007). However, there are uncertainties about the future potential for yield increases for food and energy crops. There are prospects for biotechnology-driven improvements in crop characteristics and yet the possibility of yield declines due to the long-term impacts of intensive agriculture (Sagar, 2007).

Water Use: When looked at from a life cycle perspective, there is great disparity nationwide regarding the amount of water needed for corn ethanol production. Beginning with water needs for the growth phase of corn, 96 % of corn grown nationwide and used for ethanol is not irrigated. However, when ethanol corn crops are irrigated, the nationwide average is 785 gallons water/gallon of ethanol eventually produced (Aden, 2007). Irrigating states require much more

[3] Note: the vehicle is a typical North American passenger vehicle assumed to have an annual mileage of 24,000 km (15,000miles) and a fuel economy of approximately 10 km/liter or 23 miles per gallon. 1 hectare = 2.47 acre.

water than refining states. For example, Nebraska, an irrigating state, uses 2,100 gallons of water/bushel X 1 bushel/2.7 gallons of ethanol = 780 gallons water per gallon of ethanol (WSTB, 2008).

The refining process for ethanol typically requires 3-4 gallons (for dry grind) with current best practice less than 3 gallons (Aden, 2007). Consumptive water use by ethanol plants mainly comes from evaporation during cooling and wastewater discharge. Ethanol plants are designed to recycle water within the plant and the process is one that does not require potable water. Modern ethanol plants have sophisticated water treatment techniques to enable recycling of water to boilers. These treatment techniques also enable ethanol plants to use lower quality water such as sewage treatment plant effluents and possibly even water recycled from animal feedlots (Keeney, 2006). 68% of fresh water for refining is used in cooling tower and 32% is used in boiler process (Aden, 2007). Virtually all process water is recycled through a series of evaporators, centrifuges, and anaerobic digesters (called net zero discharge) (Aden, 2007) The water needs of coal fired plants are higher with 0.6 gallons water per kilowatt hour required for a coal-fired power plant which equals 15 gallons of water per gallon of ethanol equivalent energy (Aden, 2007).

Specifically for the state of Minnesota, from a recent study looking at the full life cycle water from field to pump needs of ethanol production, the embodied water in ethanol (i.e. corn farm to fuel pump) equaled 5gals./gal. ethanol (19 liters/L ethanol) with approx 4 gallons (16L) coming from groundwater and 1 gal. (3 L.) coming from surface water (Chiu et.al., 2009). The refining process within the state of Minnesota required 4 gallons on average (Keeney, 2006). Minnesota has published information regarding the water requirements of each individual ethanol plant and is the only state in the nation to do so (Keeney, 2006).

Acidification: Related to the application of fertilizer, category indicators show the acidification potential of corn ethanol emissions is increased in comparison to those of conventional gasoline (Hess, 2008; Kim/Dale, 2005; 2008). The use of fertilizer to enhance the growth of corn causes an increase in NOx emissions during the initial production of fertilizer and also via field emissions of ammonia and NOx when fertilizer is applied. Both of these contribute to acid rain through aerosol formation (Hess, 2008).

Eutrophication: Category indicators show eutrophication potential is increased for corn ethanol as compared to conventional crude (Curran, 2008; Kim/Dale, 2005; Carpenter, 2005; Zah, 2007; Simpson, 2008). Several studies showed a significant increase, up to 500% (Zah, 2007), over conventional crude due to the leaching of nitrogen and phosphorus into surrounding water systems from over-fertilized fields (Curran, 2008; Carpenter, 2005).

Photochemical Oxidation: Category indicators show the potential for photochemical oxidation (or ground-level smog) generally increases relative to conventional gasoline (WI DNR, 2005; Zah, 2007; Curran, 2008; Kim/Dale, 2008; EPA (i), 2009; Sagar/Kartha, 2007). Contributing factors to the increase in smog potential include emissions from the production of fertilizer as well as field emissions (Hess, 2008), VOC’s and NOx produced during ethanol refining (Brady/Pratt, 2007) and increased transportation emissions (WI DNR, 2005). Although ethanol has a very low vapor pressure – around 2 psi at 100F, there is an increase in emissions due to higher volatility of gasoline/ethanol blends compared to gasoline. The increase in vapor pressure due to ethanol blending can be compensated by adjusting the vapor pressure of the base gasoline by a similar amount. This is frequently practiced in reformulated gasoline or vapor pressure controlled regions by blending with a Reformulated Blendstock for Oxygenate Blending gasoline at slightly less than 6.0 psi as opposed to 7.0 psi vapor pressure (Furey).

As commonly formulated there tends to be an increase in emissions during the use phase (transportation emissions) of volatile organic compounds in ethanol/gasoline blends (Sagar/Kartha, 2007). Twelve Minnesota ethanol plants, under direction of the US EPA, were required to install Best Available Control Technology (BACT) using a thermal oxidizer to achieve a reduction in emissions at the refinery (EPA (i), 2009). Initial studies, post installment, have shown the efficiency of scrubbers to be in the range of 60 – 90% ethanol plant emissions captured, although considerable variability exists amongst plants tested (Brady/Pratt, 2007). A preliminary LCA has computed E85's affect as being an increase in ozone-related mortality, hospitalization and asthma by about 4% in the US as a whole relative to gasoline (Curran, 2008).

Health Effects: The impact category of human health/respiratory effects, related to PM 2.5 has generally been shown to increase relative to conventional gasoline (Hill, 2009; Hess, 2008; EPA (i), 2009; Jacobson, 2007). Production of PM 2.5 occurs in the use phase via fuel combustion and indirectly through atmospheric reactions involving Sox, NOx, NH3 and VOCs emitted from stationary, mobile and area sources (Hill, 2006). It has been stated that corn ethanol has higher PM 2.5 emissions no matter what process heat source (natural gas, coal or corn stover) is used in the refinery and further that, even if improvements in ethanol technology over the next decade are assumed, costs due to PM 2.5 could become approximately equal to, but unlikely less than, those of conventional gasoline (Hill, 2009). Other studies have reported that ethanol degrades air quality (Hess, 2008) and that respiratory deaths would increase (Jacobson, 2007) relative to conventional gasoline.

Overall: Analysis of the environmental impacts of corn ethanol production reveals that agricultural practices are a major contributor to the production of emissions leading to increased acidification, eutrophication, etc. Reducing environmental externalities by using less disruptive agricultural practices (such as conservation tillage, reduced fertilizer use) may greatly improve the environmental performance of this fuel pathway (Hill et. al, 2006, Kim/Dale, 2005, Tegtmeier/Duffy, 2004). As stated by Von Blottnitz and Curran (2007), "Numerous studies have been done in recent years evaluating the life cycle impacts of bio-ethanol, and there is now strong evidence that all bio-ethanol production is mildly to strongly beneficial from a climate protection and a fossil fuel conservation perspective. Fuel ethanol produced from sugar crops in tropical settings appears by far the most efficient in these categories from a land-use perspective. However, whilst over 40 studies have been life cycle based, only seven were identified which could be said to approach life cycle assessments. These studies do not, of course, cover the full range of possible feedstocks and geographies, and their results in the standard impact categories diverge. Further assessments should thus, take energy and carbon performances as understood, work on the less studied but highly promising feedstocks and locations outside Europe and North America, and pay more attention to the safeguard subjects of human and ecological health."

Soy Biodiesel

Global Warming: Studies vary. In general, biodiesel does lower GHGs significantly in comparison to petroleum diesel. In soy biodiesel, values range from a 78.45% reduction

(Sheehan, 1998) to a 50% (EPA (g), 2007) & 40% (Hill, 2006) [42% for B100 (Fang, 2008)] reduction, to an *increase* in CO2 emissions vs. petroleum diesel (Delucchi, 2006). In the study showing a comparative increase in CO_2, the system boundary was expanded to include life cycle emissions of N_2O from nitrogen fixation by soybeans. When the boundary is expanded CO_2 emissions of soy biodiesel may be *higher* than that of conventional diesel. According to the author, the IPCC has identified and quantified these emissions but, to date, they have not been included in any other biodiesel LCA (Delucchi, 2006). In 2006 the Intergovernmental Panel on Climate Change (IPCC) released their 2006 Guidelines for National Greenhouse Gas Inventories. In Volume 4, Section 11.2 it is stated that:

> "Biological nitrogen fixation has been removed as a direct source of N2O because of the lack of evidence of significant emissions arising from the fixation process itself (Rochette and Janzen, 2005). These authors concluded that the N2O emissions induced by the growth of legume crops/forages may be estimated solely as a function of the above-ground and below-ground nitrogen inputs from crop/forage residue (the nitrogen residue from forages is only accounted for during pasture renewal). Conversely, the release of N by mineralization of soil organic matter as a result of change of land use or management is now included as an additional source. These are significant adjustments to the methodology previously described in the 1996 IPCC Guidelines." (IPCC, 2006)

The majority (85%) of CO_2 in soy biodiesel production comes from the fuel combustion phase with the remaining coming from the refining process (Sheehan, 1998). More recently the US EPA concluded that biodiesel directly reduces GHGs by 85-86% compared to average 2005 petroleum (EPA (d); EPA (e)). In 2008, Argonne National Laboratory published a report 3 that concluded all soybean oil derived fuels achieve a significant reduction in fossil energy use. Quantified reductions are provided for several different allocation methods. Using a hybrid approach of allocation methods, Argonne National Laboratory concluded that soybean oil-based biodiesel reduces well-to-wheels GHG emissions by 94 percent relative to petroleum diesel (Argonne National Laboratory, 2008). Argonne National Laboratory subsequently updated the GREET model in July 2010 to include this revised data on soybean oil-based biodiesel. Argonne National Laboratory currently quantifies biodiesel's well to wheel GHG benefit being as high as 122 percent compared to average petroleum diesel (Intergovernmental Panel on Climate Change, 2006).

Land Use: The production of soy beans has a high land requirement. No crops are planted in Minnesota for the sole purpose of producing soy oil for biodiesel. Soy bean oil is a co-product of soybean processing including products such as soybean flour, fiber, meal, roasted bean products and industrial and food grade oils. Research shows displacing one vehicle's carbon emissions with soy biodiesel would require more than 10 hectares of land (assuming a 40% reduction in carbon emissions as compared to petro diesel) (Sagar/Kartha, 2007). 4.3 hectares required to fuel one car with soy biodiesel (Hill, 2006). Ecological footprint of 2.78 global hectares with 100% soy biodiesel (as compared to 1.6 global hectares for conventional gasoline) (Vos 2007). More energy is required to grow soy than corn because the biodiesel yields per acre for soy are much less than the ethanol yields per acre for corn (Hess, 2008). Soy biodiesel yield is 56 gallons per acre (DOE) while 370 gallons ethanol per acre for corn (ERG/Curran, 2008). Potential for increased soybean farming efficiency: 0.5 bushels soybean/year for an increase of 1 billion bushel increase by 2030 (EIA, 2007).

Water Use: The refining of biodiesel is a relatively efficient process with average plant refining requirements being 1 gallon water per gallon of biodiesel produced. If soybeans are irrigated, overall water requirements become much higher, with the US average being 239 gal. H20/gal. biodiesel (USDA, 2003). Only a very small percentage of soy across the nation is irrigated (Harto et.al, 2007). In Minnesota, 102,854 acres planted in soybeans were irrigated as compared to 208,560 non-irrigated in 2003 (USDA, 2003). Minnesota-specific USDA data indicates approximately 9.6 gallons of irrigated water is used per gallon for Minnesota biodiesel (National Agriculture Statistics Service, 2008).

Acidification: Nitrogen fertilizer is not needed on soybean feedstock and today's high yielding varieties typically remove more soil nitrogen than they fix, thereby depleting the soil organic matter (Keeney, 2000). NOx emissions are higher for soy biodiesel than conventional diesel. The percentage NOx is increased, as compared to conventional diesel, ranges from approximately 10% higher for B100 (EPA (s)), 13% higher (Sheehan, 1998), 15% (Fang, 2008) to a 30% increase (NREL) to an unspecified increase (EPA (b),2002; Lane, 2007). The increase in NOx occurs at the tailpipe and is due to a higher temperature of combustion (Sheehan,1998; Fang, 2008; Dincer, 2008). Higher NOx emissions lead to a higher acidification potential.

Eutrophication: The increase in NOx also affects soy biodiesel's eutrophication potential. An LCA specifically measuring the eutrophication potential of soy biodiesel found it to have a increased potential of 500% as compared to petro diesel (Zah, 2007).

Photochemical Oxidation: Increased NOx emissions react with other chemicals to create ground level ozone, increasing smog potential with biodiesel as compared to conventional diesel. Emissions during the refining process of soy biodiesel are considered to be significant. Biodiesel fuel production occurs mostly in Midwest states and ozone nonattainment areas are located mostly in California or the Northeast (Fang, 2008). NOx Emissions are 10% higher than conventional diesel for B100 (EPA (f), 2006). The extraction of vegetable oil to create biodiesel in large chemical processing plants is typically achieved using hexane-a VOC. Although tailpipe emissions are lower, large amounts of VOCs are released during fuel production and from volatilization of agrochemicals applied on the farm causing total well-to-wheels release of VOCs to be higher than conventional diesel (Hess, 2008; Sheehan, 1998). One study found 100% soy biodiesel to have 200% the potential for smog as compared to fossil reference (Zah, 2007) however, a contrary study found the ozone-forming potential of biodiesel to be 50% less than that of conventional diesel (Dincer, 2008). Analysis conducted by the United Soybean Board describing biodiesel lifecycle NOx emissions developed using the U.S. Lifecycle Inventory (USLCI) database compiled by the National Renewable Energy Laboratory, shows emissions of NOx to have significantly decreased in the soybean farming, soybean crushing and refining, and in the biodiesel production phases of the lifecycle. This study estimates N2O emissions to be 85 percent less than the data contained in the previous USLCI database for these phases (United Soybean Board, 2010; United Soybean Board, 2010)

Human Health Effects: Large reduction in PM 2.5 emissions (-47%) occur with biodiesel, as well as a reduction in CO (-48%), sulfates (-100%), air toxins and polycyclic aromatic hydrocarbons (-80%) (EPA (f), 2006; Fang, 2008). From an air quality perspective, the emissions associated with the feedstock stage of the soy biodiesel life cycle have the largest impact (Hess, 2008). Sulfur emissions are essentially eliminated with B100 (Dincer, 2008). In an LCA study using GREET, air quality improvements in comparison with conventional diesel were shown with allowances for large co-product credits – PM 2.5 emissions were shown to be 0.04 g/L less than baseline (Hess, 13).

Overall: Fuel life cycle emissions most frequently occur in a rural air basin, whereas tailpipe emissions most frequently occur in urban areas. The air quality benefits of biodiesel will depend on the geographic locations of the fuel production and of the vehicles consuming the fuel and on prevailing baseline air quality conditions (Fang, 2008). Some phases of the biodiesel have higher emissions and some have lower as compared to conventional diesel so it depends where in the life cycle you look at the emission profile to see where greatest impacts would occur.

Table 2: Summary of life-cycle literature impacts for select first generation biofuels (directional comparisons to baseline petroleum fuels vary across individual studies).

Fuels	Global Warming Potential	Acidification	Eutrophication	Photochem. Ox. (Smog)	Health Effects/Resp.	Land Use	Water Use
Corn Ethanol	38-48;77; 84.9 gCO2 eq./MJ. 18%,<20%, 20%,22%,28%-39%, 53%,48%-59% ↓ compared to gasoline [1]	NOx ↑ (0.43 moles H+ equiv. kg-1) [3]	Up to 500% ↑ [5]	↑in smog potential (120%) and ozone formation [7]	PM 2.5 ↑ CO ↓ [9]	1.1 - 2.43 global HA/car/year 370 gal/acre [11]	MN Refining Ave: 4 gal./gal. Total life cycle↑: 19L/L ethanol; US irrigated ave: 780gal/gal [13]
Soy Biodiesel	41%,50%,68%, 78% ↓compared to diesel. Possible ↑ [2].	NOx: 13% -15% ↑ NOx and HC: 100% ↑ [4]	Up to 500% ↑ [6]	VOC, CO and SOx ↓ [8]	PM: 32%-47%↓ CO: 35% - 48%↓ sulfates: 100%↓ HC: 65% - 80%↓ [10]	2.1 - 4.3, global HA/car/year 56 gal./ acre [12]	Refining: 1 gal./gal. US irrigated avg: 239 gal/gal. [14] MN irrigated ave 9.6 gal/gal

1. Reported LCA results of GHG intensity for corn ethanol measured in grams of CO2 equiv./MJ: Liska, 2008; Farrell, 2006; Hill, 2006. Results measured as % GHG's are reduced as compared to CPB: Farrell, 2006; Sagar/Kartha, 2007; Searchinger, 2008;EPA (g), 2007;Wang, 2007;.Liska, 2008; Kim/Dale, 2008
2. Reported LCA results of studies measuring GHG intensity for Soy Biodiesel (B100) as compared to CP diesel: Hill, 2006; EPA (g), 2007; Sheehan, 1998/// Possible increase in CO2 equiv. as compared to CP Diesel if nitrogen fixation by soybeans is included in LCA (Delucchi, 2006).
3. (Hill et al., 2009)//NOx emissions increase due to prod. of fertilizer and field emissions. These contribute to acid rain through aerosol formation (Hess et al. 2008). Utilization of biomass for biofuels would increase acidification because of N and P related burdens from the soil during cultivation (Kim/Dale 2005).
4. 5. A great portion of the N (per NEB: 7.0 g/MJ) and P (per NEB: 2.6 g/MJ per NEB) fertilizer is transported to the surface, ground and coastal waters causing eutrophication (Hill,2006). Biomass for biofuels would increase eutrophication because of N and P related burdens released from the soil during cultivation (Kim/Dale,2005). 100% blend of US Soy biodiesel leads to 500% increase in eutrophication potential as compared to fossil ref.(Zah,2007). Even with recommended fertilizer and land conservation measures, corn acreage can be a major source of N loss to water (Simpson,2008). Also: (Curran, 2008)
6. 100% blend of US Soy biodiesel leads to 500% increase in eutrophication potential (Zah, 2007); (Kim /Dale, 2005); (Hess, 2008)
7. E10 mandate in WI will increase O3 by 1-2 ppbv on a typical summer day (WI DNR, 2005). Smog potential is 125% that of fossil ref.(Zah,2007).NOx emission result is high (Hess, 2008). 12 MN ethanol plants installed (BACT) to achieve at least 95% reduction in emissions. Considerable variability exists amongst plants tested (Brady/Pratt,2007).E85 may increase ozone-related mortality, hospitalization and asthma by about 4% in the US as a whole relative to gasoline(Curran,2008). Also: (Kim/Dale, 2008);(EPA (i),2009);(Sagar/Kartha,2007).
8. Decreased emissions relative to petro. diesel (Sheehan,1998)(Hill,2006). Biodiesel VOCs reduced -63% compared to conv. Diesel (Dincer,2008).
9. Corn ethanol has higher PM2.5 than gasoline regardless of whether biorefinery uses process heat from natural gas, coal, or corn stover (Hill, 2008). "Corn Ethanol degrades air quality emissions. We believe this is a robust conclusion" (Hess, 2008). "If every vehicle in the US ran on ethanol instead of pure gasoline, respiratory deaths would increase" (Jacobson, 2007).
10. Reductions in PM 2.5, CO, Sulfates and HC compared to CP diesel as reported by: EPA (f),2006; Dincer,2008; Hess, 2008; Sagar/Kartha, 2007.
11. 1.1 hectares required to fuel one car- [yield per hectare(gal. fuel /ha) = 915 (3,463 liters)] therefore 1006.5 gal. to fuel 1 car(Farrell,2006). 2.43 global hectares needed for corn ethanol prod.-50% greater than gasoline - Ecological Footprint (Vos, 2007). Yield=370 gallons/acre cropland (ERG). Increase at present rate (1.8 bu./acre/ yr), could increase production by more than 3.1 billion bushels (29%) by 2030 with no additional acreage (EIA, 2007).
12. 2.11 global cropland hectares (Vos, 2007); 4.3 hectares required to fuel one car (Hill,2006);4.33 hectares (Tilman,2006); Yield = 56 gal/acre (US DOE,2009); Soy production could increase at the rate of 0.5 bu/ac/yr for an increase of 1 bill.bushels by 2030 with no additional acreage (EIA,2007).
13. Refinery Ave.: 3-4 gallons (dry grind) best practice <3 gal. Ethanol does not require potable water (Aden, 2007); MN refining ave.= 4 gal. -MN is the only state to have individual plant data (Keeney/Muller, 2006). Water from "farm to pump" in MN = 19 liters/L ethanol (Chiu,2009). 96 % of corn used for ethanol is not irrigated. When irrigated, US ave. is 785 gal. (WSTB,2008).
14. Refining: 1 gal. fresh water per gallon (Pate.WSTB, 2008); Biodiesel life cycle wastewater flows are almost 80% lower than those of petro diesel. (Sheehan, 1998). US irrigation average is 239 gal/gal.(USDA,2003). MN 2003 report: 102,854 acres irrigated/208,560 acres non-irrigated (USDA, 2003).

2nd Generation Fuels

Cellulosic Ethanol

Global Warming: Reported values of LCA studies measuring GHG intensity for cellulosic ethanol vary from a 70% reduction (Searchinger, 2008) as compared to the conventional petroleum baseline (CPB) to a high of a 106 % reduction (US NREL, 2008). Others reported values in between as follows: 86% reduction (Wang, 2007); -88% (Farrell, 2006); -91% (EPA (g), 2007); and -100% (Range Fuels). Another LCA gave the GHG intensity as measured in grams of CO2 equivalent emissions per megajoule (MJ) as compared to reference value of 94 gCO2eq/MJ for gasoline) 11 gCO2 eq/MJ (Farrell, 2006). Other methods have reported total life cycle measurements of 24.3 grams of CO2 equiv. per mile for cellulosic ethanol compared to 384.7 grams of CO2 equiv. per mile for conventional gasoline (Cleary, 2008). Many researchers found the GHG intensity of cellulosic ethanol to be dependent on feedstock. Some analysis has found corn stover and diverse prairie grass to be better than switchgrass from a GHG perspective (Hill et.al, 2009). It was stated that this is because corn stover or perennial crops require less inputs and have lower emissions at the biorefinery. Also, lignin combustion provides process heat and power which is then able to displace fossil fuel inputs and electricity production. When looking at cellulosic ethanol production from forest residues, the range of life cycle CO2 produced can vary widely based upon simple production processing choices. For example, it has been shown that by simply increasing the diameter of the material chipped from 4 to 16 cm, the CO2 emissions per MWh of biofuel produced is decreased by a factor of 7 (Van Belle, 2006). Biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural lands planted with perennials are often preferred in models as they have been shown to incur little or no carbon debt and can offer immediate and sustained GHG advantages (Fargione, 2008).

Land Use: Compared to other fuel types, cellulosic ethanol appears to have reduced land area needs: 0.7 hectares is required to fuel one car (Farrell, 2006) and 0.97 global cropland acres is needed when it is viewed from an "ecological footprint" perspective (Vos, 2007). However, there appear to be uncertainties regarding the availability of excess, abandoned agricultural lands, which are many times listed as the main source of land for cellulosic crop production. Also, marginal and degraded lands may not be suitable for production or free of other claims (Sagar/Kartha, 2007). It is thought that cellulosic ethanol production processes that use a variety of feedstocks could be beneficial to the ecosystem by increasing diversity in agricultural landscapes and enhancing insect related ecosystem services (Landis, 2008).

Water Use: As commercial cellulosic production facilities are not currently in operation, it is difficult to accurately determine all water needs. However, from conceptual cellulosic refining models, it has been estimated that 1.9 gallons will be needed for thermochemical production and 6 gallons will be needed for biochemical production (Aden, 2007). When breaking down conceptual water needs for cellulosic production further, it is expected that 71% of refining water needs for biochemical cellulosic (from models) is for cooling tower and 29% for the boiler process.

Acidification: Results of LCA studies regarding acidification are mixed and appear to be feedstock specific. In general, it appears that nitrogen oxide emissions (measured in grams NO2 per mile) are higher with cellulosic ethanol than gasoline. An NREL study reported values that are twelve times that of gasoline (1.854 vs. 0.149) (Cleary, 2008). However, a separate study showed that using straw to produce lignocellulosic resulted in a measurement of 5 Eco-Indicator 99 points- which is considered low (Uihlein,2009). In the case of corn stover, it appears that treatment with sulfuric acid results in increased acidification potential (Kim/Dale, 2005).

Eutrophication: As with acidification, it appears that LCA results regarding indicators of eutrophication potential are dependent upon the feedstock as well as the production process. The use of switchgrass as a feedstock source seems to have a beneficial effect as its extensive root network reduces problems from fertilizer runoff, erosion, and associated nitrogen and phosphorus loss (Simpson, 2008).

The eutrophication profile of corn stover appears dependent upon the cultivation system used. A continuous corn production system, with stover collection for ethanol, increases the eutrophication potential by almost a factor of three versus corn-soybean rotation with conventional till according to an NREL study (Powers, 2005). It has been stated that the harvest of corn stover for cellulosic ethanol production would likely increase erosion (sedimentation) and nutrient loads, which would adversely affect nutrient-stressed waters (Simpson, 2008). However, other research has found that corn stover removal can improve the eutrophication profile of the continuous corn cultivation systems because there are less nitrogen burdens from the soil and higher ethanol production per hectare (Kim/Dale, 2005). They caution though that corn stover pretreatment by sulfuric acid significantly adds to eutrophication potential.

Blanco-Canqui and Lal caution that "economic incentives for producers due to increased demand for crop biomass may increase the land area under monocrops and reduce the land enrollment in conservation programs which would result in increased soil erosion and fertilizer input. Reduced crop diversification would cause the degradation of soil and water quality through eutrophication of downstream water bodies" (Blanco-Canqui/Lal 2009).

Photochemical Oxidation: An LCA study has shown that while the GREET model suggests a decrease in upstream emissions of VOCs for cellulosic ethanol production, downstream emissions are increased which leads to an overall increase in VOCs over gasoline (0.21 g/L for E10 cellulosic)(Hess, 2008). Forest residues that are commonly used as feedstocks (such as poplar) are considered to be significant isoprene emitters, a biogenic VOC (Wiedinmyer et.al, 2006). This can have the effect of increasing the formation of smog but the net effect of tree plantations on trophospheric ozone formation is reliant upon the ambient atmospheric concentrations of other necessary chemicals, mainly NOx (Hess, 2008).

Human Health Effects: Again, results appear to depend upon the feedstock used and the production process. LCA study reports have found cellulosic ethanol to have the lowest PM 2.5 emissions of all fuels types analyzed due to lower life cycle emissions of sulfur (an important precursor of aerosols), lower agricultural inputs and excess electricity generation during the refining process which then displaces the emissions caused by the combustion of coal (which would otherwise be used as a source of electricity) (Hill et.al, 2009). In this same study, it is found that, within this category and from a PM 2.5 perspective, diverse prairie grass is best, then switchgrass, then corn stover. Depending upon feedstock, other LCAs have shown low emissions from feedstock production but very high emissions from fuel production process from feedstock (Hess, 2008).

Overall: Some have proposed that although the production of cellulosic ethanol from feedstocks like perennial prairie grass face limitations, accelerating the development of this fuel type has the potential to reduce dependence on grain fuel-stocks and therefore provide water quality and other environmental benefits (Simpson, 2008). However, no commercial scale cellulosic production facilities currently exist and further research is needed in order to develop a viable technology for fuel conversion of this feedstock source. Also, cellulosic feedstock materials tend to be bulky and not very dense. Shipping from field to refinery requires significant transportation costs making smaller scale production facilities, located near feedstock sources, possibly a more environmentally sustainable method of production rather than large plants.

Oil Sands Gasoline/Diesel

Although we estimate that 83% of MN gasoline and diesel fuel originates from oil sand fuel production in the Athabasca river region located in the province of Alberta, Canada, we describe the environmental impacts of this extraction process separately for a number of reasons. First, the majority of the life cycle literature distinguishes conventional petroleum-based fuels from emerging petroleum extraction technologies (EOL, Shale, Oil Sands, CTL, etc.). Second, our current estimates of MN fuel mix are subject to change based on crude oil prices and the policy landscape regarding carbon.

Oil sands are grains of sand that are covered by a layer of water that is covered by a layer of bitumen (a tar substance that can be converted to oil) (Czarnecki et al. 2005). Together, oil sands are 85% sand, clay and silt; 5% water; and 10% crude bitumen. Bitumen is a very heavy and viscous form of crude oil that will not flow unless it is heated or diluted. In comparison to conventional light crude oil, bitumen is tar like with a density greater than 960 kg/m3 whereas light crude is pourable and has a density as low as 793 kg/m3(Patel, 2007). Two different methods are used to extract oil sands: surface mining which can reach deposits less than 250 ft below the surface and in-situ extraction used to reach deposits located 250 ft. or farther under the surface (Patel, 2007). According to Alberta's 2008 ERCB report, 40% of bitumen was extracted via in-situ mining in 2007 while the other 60% was produced with surface mining. It is currently estimated that 82% of recoverable bitumen deposits will be extracted using *in situ* technologies in the future (Jordaan, 2009).

Global Warming: When looking at the refining process alone, LCA results show the carbon intensity of blended diesel from oil sands to be: 591 tons CO2 equiv/1000 barrels diesel for high sulfur-very heavy crude (Alberta oil sands); compared to conventional diesel: 526 tons CO2 equiv/1000 barrels diesel for low sulfur- light crude (Texas or Louisiana light) (Marano, 2009). This is mainly a result of the larger amount of natural gas that is needed for the extraction and refining of bitumen as compared to conventional oil extraction and refining (Brandt /Farrell, 2007). It is expected that a shift from crude oil to oil sands technology will greatly increase GHG emissions unless it is accompanied by simultaneous breakthroughs in carbon abatement technology (Hill et.al, 2009). Results of research for the GHG section of this report determined that Minnesota refining of its current oil sands and sweet crude mix to produce diesel and gasoline are 105 gCO2e/MJ.

Land Use: In order to produce one barrel of crude oil, two tons of oil sand must be mined (Patel, 2007). Strip mining leaves behind open pits and overburden pile in which the surface and subsurface hydrology has been disrupted (Elshorbagy, 2005). Both methods create tailings ponds filled with toxic effluent (Clemente and Fedorak, 2005; Elshorbagy, 2005; Woynillowicz, 2007). The government of Alberta enacted the *Environmental Protection and Enhancement Act* in September of 1993. This act requires operators of heavy oil processing plants (oil sands companies) to remediate and reclaim land so that it can be productive again (Alberta Gov.,2008). In order to be issued a reclamation certificate, reclaimed land in Alberta must be able to support a range of activities similar to its previous use (Alberta, 2008). Extensive reclamation work is needed in order to reestablish various elements of the hydrological cycle and surface landscapes (Elshorbagy, 2005). Alberta just issued its first reclamation certificate, in March of 2008 (Alberta, 2008). Syncrude Canada received certification for a 104-hectare parcel of land known as Gateway Hill. The time needed for reclamation of this property has taken over 25 years as Syncrude stopped production at this location and began to replace topsoil and plant trees and shrubs back in the early 1980's (Alberta, 2008).

Presently, oil sands production is rapidly increasing. In 2003, 160 sq. miles had been mined for oil sands. By 2006, 772 sq. miles had been mined – a five-fold increase. Currently approved projects allow for 1,312 more miles to be strip mined (Thomas-Muller, 2008)

Also of concern is landscape fragmentation (Jordaan, 2005; Unnasch, 2009). Fragmentation is a process in which a large expanse of habitat is broken down into smaller patches of total area, isolated from each other by a matrix of habitats unlike the original (Wilcove et al. 1986). It has been determined that both methods of oil sands mining cause fragmentation and studies conducted in the boreal forest of Alberta confirm that fragmentation can significantly affect the occurrence and behavior of wildlife (Jordaan, 2009).

Water Use: The mining of oil sands requires 2 – 4.5 barrels of water per barrel of oil sands oil produced (Thomas-Muller, 2005). 82 % of the water used for bitumen extraction in Alberta comes from the Athabasca River (Thomas-Muller, 2005). In both methods, excess water (from the hot water used to release bitumen from the sand in surface mining and the steam condensed into water from in-situ mining) is collected in on-site reservoirs called tailings ponds. According to Syncrude Canada, 88% of the water required for extraction has been recycled (Mintz-Testa, 2008). In-situ extraction poses possible groundwater contamination problems due to leakage of diluting materials (Patel, 2007).

Naphthenic acids occur naturally in oil sands bitumen and are believed to be some of the most toxic components of oils sands tailings waters (Schramm et al., 2000; Madill et al., 2001). Naphthenic acids are soluble in neutral or slightly alkaline waters and are known to be acutely toxic to a range of organisms (Clemente/Fedorak, 2005). About 200 mg of naphthenic acids are present in each kg of oil sands ore (Scott et al. 2007) and naphthenic acids concentrations greater than 2.5–5 mg l 1 in refinery effluent have been found to be toxic to fish (Dorn et al. 1993.

Acidification: Compared to petroleum diesel, emissions of NO_x and SO_2 are significantly increased (Hazewinkel, 2008). However, current lake studies have not shown increased acidification. Research is suggesting that the lakes in this region differ from other lakes in Northern Europe and Eastern North America with regard to the limiting nutrients. It appears that Phosporus loading will persist until sediment and groundwater is overwhelmed, and then acidification will occur (Hazewinkel, 2008). Acidification can occur in soil, water and air. Similar to conventional fuels, ocean acidification (the net change in ocean pH levels due to fluxes of carbon dioxide between the oceans, terrestrial biosphere, lithosphere and the atmosphere) has increased in "acidity" (ion concentration) relative pre-industrial levels by approximately 30 percent. Increased CO_2 associated with oil sand fuels is expected to increasingly contribute to this impact. In addition, high temperatures created by the combustion of petroleum cause nitrogen gas in the surrounding air to oxidize, creating nitrous oxides. Nitrous oxides, along with sulfur dioxide from the sulfur in the oil, combine with water in the atmosphere to create acid rain. These may also end up deposited into the soil. It is unclear whether these impacts may be more or less affected by the combustion of oil sand fuels.

Eutrophication: Information addressing this impact category from studies employing life cycle based methodologies where not found.

Photochemical Oxidation: Information addressing this impact category from studies employing life cycle based methodologies where not found[4]

Respiratory Health Effects: Information addressing this impact category from studies employing life cycle based methodologies where not found.

<u>Coal-to-Liquid (CTL) Gasoline/Diesel</u>

Life cycle of Fischer-Tropsch (FT) fuels produced from coal includes coal mining, transportation of coal, processing via gasification to syngas (CO & H2) and then FT processing to synthetic crude which is refined to diesel and gasoline. Transportation from CTL plant to fueling stations and use in vehicle are also included.

Global Warming: Without carbon sequestration an LCA study reported a value of: 153 - 179 gCO2eq./MJ (Brandt/Farrell, 2007). Other LCAs have reported values of the GHG intensity of coal-to- liquid without sequestration, as an increase relative to conventional petroleum gasoline of: 110% (van Vliet, 2009); 119%(EPA (g), 2007); 200% (Jaramillo, 2008; AAAS, 2009) and 2,000% (Patzek, 2007). When sequestration is added, LCA GHG intensities report: a decrease of 4% (Jaramillo, 2008); 0% change (NAS, 2009) and increases of 4% (EPA (g), 2007) and25% (van Vliet, 2009) compared to CPB. According to Jaramillo, only CO2 compression is needed to make facilities CCS capable and compression to achieve 90% CCS would require an additional 80 - 140 MWh per metric ton of CO2 compressed (Jaramillo, 2008).

---

[4] Some direct effects and emission impacts, such as refinery outputs and forest conversion of surface mined areas, are thus far poorly understood in current literature and require further study in order to accurately evaluate them (Unnasch, 2009)

Land Use: Strip mining and other coal mining techniques such as mountaintop removal can permanently reshape the landscape, destroy wildlife habitat and compromise local aquatic ecosystems. Mountaintop mining and valley fills (MTM-VF), in particular, is a form of surface coal mining in which explosives are used to access coal seams. The resulting waste that then fills valleys and streams can significantly compromise water quality. "MTM-VF lead directly to five principal alterations of stream ecosystems: (1) springs, intermittent streams, and small perennial streams are permanently lost with the removal of the mountain and from burial under fill, (2) concentrations of major chemical ions are persistently elevated downstream, (3) degraded water quality reaches levels that are acutely lethal to standard laboratory test organisms, (4) selenium concentrations are elevated, reaching concentrations that have caused toxic effects in fish and birds and (5) macroinvertebrate and fish communities are consistently and significantly degraded. It is estimated that almost 2,000 miles of Appalachian headwater streams have been buried by mountaintop coal mining" (EPA (t)).

Water Use: Estimates of energy balances of hypothetical CTL plants suggest that water use could vary from l-1.5 barrels of water per barrel of product for a zero-discharge air-cooled plant to 5-7 barrels of water per barrel of product for a plant with water cooling and less use of waste heat for process heat or cogeneration (Nowakowski, 2008). Coal to Liquid produces very large volumes of discharged contaminated water (Patzek, 2007). It is necessary to consider water availability in all CTL placement decisions (Höök et.al, 2009).

Acidification: Increased SOx and H_2S emissions, as compared to conventional petroleum, are released during the refining and combustion of coal (Patzek, 2007). SOx contributes to acid rain which causes acidification (Hess, 2008).

Eutrophication: Information addressing this impact category from studies employing life cycle based methodologies where not found.

Photochemical Oxidation: Information addressing this impact category from studies employing life cycle based methodologies where not found.

Health Effects: Information addressing this impact category from studies employing life cycle based methodologies where not found.

Natural Gas

Natural gas is a combustible mixture of methane gas and other hydrocarbons such as propane, butane and pentane. The main products of natural gas combustion are carbon dioxide and water vapor (NaturalGas.org, 2010). Natural gas is found in reservoirs, often near oil deposits and located within sandstone and carbonate rock. Technological improvements, such as horizontal drilling and multi-stage hydraulic fracturing, allow for shale gas to be economically viable to be extracted (Natural Gas Use in Transportation Roundtable, 2010). Additionally, natural gas can be derived from capturing the gas that is emitted from landfills called biomethane, and is considered a renewable resource. (Mintz, et al, 2010). The United States produces eighty-four percent of its energy demand for natural gas, and imports the remaining energy need from primarily Canada and to a lesser extent, Mexico (U.S. Department of Energy, 2011). Natural gas, whether from natural deposits or from landfills, is processed before it enters the pipeline that delivers the gas to the end-user. In transportation, natural gas is processed for use in two forms, liquid natural gas (LNG), and compressed natural gas (CNG). CNG is formed by compressing the gas to high pressures between 3,000 to 3,600 pounds per square inch. The volume of the gas is reduced by a factor of 300 compared to gas at standard temperature and pressure. In a natural gas vehicle, the CNG enters a pressure regulator and into a spark-ignited or compression ignition engine to propel the vehicle (Natural Gas Use in Transportation Roundtable, 2010). LNG is created by cooling the natural gas temperature to -162 °C, which reduces the gas volume by a factor of 600 compared to gas at standard temperature and pressure. In a natural gas vehicle, the LNG is vaporized before injection into the engine. The goal for natural gas vehicles is to increase the density of the fuel to increase the available energy onboard, which increases driving range.

Global Warming: Combustion of natural gas emits lower levels of CO2, NOx, and particulate emissions, with almost no SO2 emissions (NaturalGas.org, 2010). Natural gas produces between 20 (CNG) to 30 (LNG) percent less carbon equivalent emissions than diesel, which considers the emissions produced during resource recovery, refining, shipping and tail pipe emissions. Bio-methane is a renewable fuel and is considered carbon-neutral because it is derived from methane that would otherwise be flared and released to the atmosphere (Natural Gas Use in Transportation Roundtable, 2010).

Water Use: Hydraulic fracturing (HF) is one process used to recover natural gas from coal beds and shale gas formations. The process involves pumping fluid into a well at high pressure to induce fractures in the rock formation thus releasing the gas. HF requires large amounts of water as well as an array of chemicals that, along with the expansion of HF in the U.S., has led to increasing concerns about its potential environmental and human health impacts. In 2011, the EPA is undertaking a study that examines the overall impact of hydraulic fracturing on water. The study will examine the full life cycle of water in hydraulic fracturing, from acquisition of the water, through the mixing of chemicals and fracturing, to the post-fracturing stage of treatment and disposal (EPA (q), 2011).

Land Use: On-shore extraction of natural gas requires a significant amount of direct and indirect land-use. Land must be cleared for the drill pad, as well as for runoff and water treatment. If the drill is successful, a pipeline will be built to transport the gas to market. Indirect land-use is primarily related to using diesel-fuel for drilling (See Figure 2). A single production field typically has around 120 gas wells, drilled 1500 m deep. Offshore drilling requires less land-use, but encompasses about 140 m^2/GWh of water surface (Fthenakis and Kim, 2009).

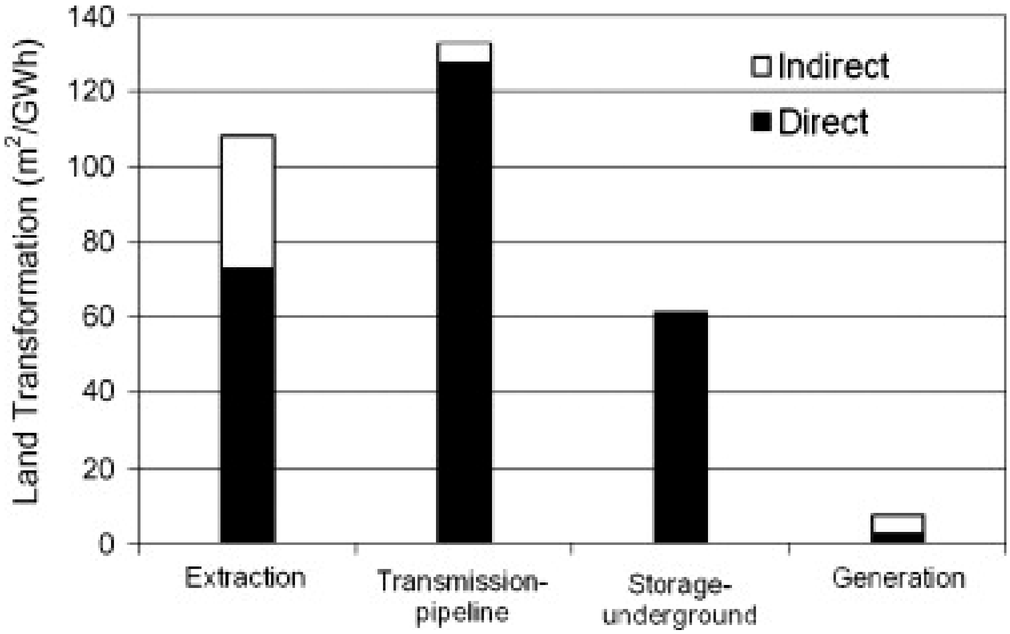


Figure 2: Source: Fthenakis and Kim, 2009.

Health Effects: Particulate matter emissions (PM 10) for CNG/LNG powered vehicles amount to approximately 15 kg over its lifetime which is only slightly less than diesel vehicles, which emit around 16 kg over its lifetime. However, when comparing PM emissions to gasoline-powered vehicles, CNG/LNG vehicles emit 10 kg less than gasoline vehicles (Hackney and Neufville, 2001)

Ozone Depletion: The impact on ozone depletion of vehicles fueled by natural gas is about a factor of 3 less than both diesel and gasoline-powered cars (Nigge, 2000).

Acidification: The impact on acidification of vehicles fueled by natural gas is about a factor of 3 less than gasoline-powered cars, and a factor of 4 less than diesel (Nigge, 2000).

Eutrophication: Information addressing this impact category from studies employing life cycle based methodologies where not found.

<u>Plug-In Electric Powered Vehicles</u>

Background: Plug-in Electric Vehicles (PEV), also known as Battery-Electric Vehicles (BEV), are powered and propelled solely by electric motors. The power source of electric vehicles stem from the chemical energy stored in battery packs that can be recharged on the electricity grid (Nemry, et. al, 2009). An efficient battery is the key technological element to the development of practical electric vehicles. There are six types of batteries for use within BEVs; nickle- metal hydride, nickel-cadmium, lithium ion, zinc-air, and flywheels. The most commonly used battery in BEVs is the lithium-ion battery because they are lighter and can store more energy. Li-ion batteries are virtually maintenance free, does not lose its capacity when repeatedly charged after a partial charge, and have a low self-discharge rate (Notter, et. al, 2010). The metals present within the batteries must first be mined, processed to remove impurities and isolate the metals, and then manufactured into the battery packs.

Global Warming: Although electric vehicles are characterized by having zero local emissions, much of the GHG emissions depend primarily on the source of electricity used for charging car batteries (Creutzig, et. al, 2009). The energy mix that the power plant has significantly impacts GHG emissions. If the electric vehicle plugs into a power provider that is dominated by coal, then GHG emissions in gCO2/km are similar for gasoline-powered cars- around 130-150 gCO2/km. However, if the power provider uses exclusively renewable and hydroelectric energy, GHG emissions are significantly reduced to less than 20 gCO2/km (Creutzig, et. al, 2009). Equally dependent on fuel mix is the amount of energy required to power the car a certain distance, known as the efficiency. Electric vehicles require less primary energy (MJ/km) than gasoline cars for both coal dependent and renewable energy plants, although it is significantly less so for renewable energy plants. A recent study by the Swiss Federal Laboratories for Material Science and Technology investigated the contribution of lithium-ion batteries to the total environmental impact of a BEV. They found that only fifteen percent of the total environmental burden is attributed to the battery which includes its manufacture, maintenance and disposal. (Notter, et. al, 2010).

Acidification: Powering a car with electricity would result in a 31 percent decrease in NO_x emissions, which includes coal-powered plant emissions, when compared to powering a car with gasoline (Kaplan and Sargent, 2010).

Health Effects: Particulate matter (PM 10) emissions from battery electric vehicles are derived entirely from the electricity generation. Power plants that use coal has higher PM emissions than would be generated from cleaner fuels and renewable energy sources. With the current energy mix, PM emissions for BEV amount to approximately 20 kg over its lifecycle, whereas PM emissions for gasoline vehicles amount to approximately 25 kg (Hackney and Neufville, 2001).

There is significant concern of mercury emissions to water. The impact mercury emissions have on human health and water quality is well researched although how data from this research is used by TRACI was not clear. The Minnesota Department of Health and Minnesota Pollution Control Agency both track and publish health advisories due to mercury emissions (Pollution Control Agency (a)). Fifty six percent of mercury emissions to the states waterways come from coal fired power generation plants (Pollution Control Agency (b)). Investigation was not able to determine how risk of exposure to mercury is included in non-cancer impacts due to electricity consumption used to produce these fuels.

Ozone Depletion: Battery electric vehicles can reduce ozone depletion emissions by about 40% compared to petroleum fuels due to the use of low-methane content fuels and improved vehicle efficiency which lower NO_x and other hydrocarbon emissions (Hackney and Neufville, 2001).

Eutrophication: Information addressing this impact category from studies employing life cycle based methodologies where not found.

Table 3: Summary of life-cycle literature impacts for select second generation and emerging transport fuels (directional comparisons to baseline petroleum fuels vary across individual studies).

Fuels	**Global Warming Potential**	**Acidification**	**Eutrophication**	**Photochemical Oxid. (smog)**	**Health Effects/Resp.**	**Land**	**Water Use**
Cellulosic Ethanol	70% -106% ↓ [1]	Feedstock dependent: NOx ↑ [4]	Feedstock dependent: Corn Stover ↑ Switchgrass ↓ [7]	Feedstock dependent: VOCs some forest biomass ↑ [8]	PM 2.5 ↓ compared to corn ethanol [9]	0.7 - 0.97 global HA/car/year [11]	Refining: 1.9 gal/gal Thermochemical; 6 gal Biochemical [14]
Oil Sands Gasoline	13-300%↑ [2]	NOx and Sox: 200% ↑ [5]			Napthenic acids ↑ [10]	2 tons of oil sand mined per BBL crude oil; land fragmentation [12]	Refining: 2 - 4.5 gal./gal. [15] Extraction: Unknown
Coal to Liquid	W/O CSS: 110%, -, 2,000% ↑ With CSS: 4%↓ -25% ↑ [3]	↑SOx [6]				Expanded coal mining [13]	Refining: 5 - 7 gal/gal [16] Extraction: Unknown
Plug-In Electric Vehicle (Battery Electric Vehicle)	27% ↓ [17]	NOx : 31% ↓ [19]		VOCs 93% ↓ [21]	PM 10 ↓ compared to gasoline [22]		
Natural Gas	20 (CNG)-30% (LNG) ↓ Biomethane: carbon neutral [18]	3x ↓ compared to gasoline [20]			PM 10: ↓ Compared to gasoline [23]	312 m^2/GWh [24]	

1. LCA results of GHG intensity measured in gm CO2 equiv./MJ: Farrell, 2006 (as compared to reference value of 94 gCO2eq/MJ for gasoline). Measured as % GHG's are reduced compared to reported value of CPB: Searchinger, 2008;Wang, 2007; Farrell, 2006; EPA (g), 2007; Range Fuels, NREL, 2008.
2. LCA results of GHG intensity in grams of CO2eq./MJ: Charpentier, 2009; Brandt/Farrell, 2007; Unnasch, 2009. Reported as an increase compared to baseline: Marano, 2009; McCann, 1999;Pembina Institute&Woynillowicz, 2007.A shift from crude oil to oil sands technology would greatly increase emissions unless accompanied by simultaneous abatement technology(Hill, 2009)
3. LCA results of GHG intensity for CTL w/o carbon sequestration in grams of CO2 equiv./MJ: Brandt/Farrell, 2007; van Vliet, 2009;EPA (g), 2007; Jaramillo, 2008; AAAS,2009; Patzek, 2007. Values w/ carbon sequestration: Jaramillo, 2008; NAS, 2009 (Tillman);EPA (g), 2007;van Vliet,2009.
4. Acidification potential is feedstock dependent: Corn stover pretreatment with sulfuric acid significantly adds to acidification potential(Kim/Dale (2005);Inputof 1000 kg straw to produce lignocellulosic ethanol showed 5 Eco-Indicator 99 points(low acidification potential)(Uihlein,2009); NOx is 12X higher for cellulosic than gasoline (1.854 g NO2/mile vs. 0.149 gNO2/mile) mostly due to soil emissions (NREL/Cleary, 2008).
5. Emissions of NOx and SO2 increased relative to petroleum diesel. Current acidification not increased- appears that P loading will persist until sediment and groundwater is overwhelmed, and then acidification will occur (Hazewinkel, 2008). NOx and SO2 emissions more than double fossil (Bergerson/Keith, 2006)
6. SOx and H2S emissions will be significant (Patzek, 2007).

7.Continuous corn w/ stover collection increases the eutrophication potential by almost a factor of 3 vs. corn-soybean w/ conventional till (Powers, 2005); Corn stover pretreatment by sulfuric acid significantly adds to eutrophication potential(Kim/Dale,2008). An increase in monocrops for cellulosic would reduce crop diversification and would cause the degradation of soil and water quality through eutrophication of downstream water bodies (Blanco-Canqui ,2009). Harvest of corn stover for cellulosic ethanol prod. would likely increase erosion and nutrient loads, which will adversely affect these already nutrient-stressed waters. An extensive root network of switchgrass can reduce runoff, erosion, and associated N and P loss(Simpson,2008).

8. Tree plantations of a number of species (e.g. Poplar) for cellulosic ethanol are significant isoprene emitters. Isoprene is the most abundant biogenic VOC. Also, tropospheric Ozone is associated with forest degradation (Chameides et. al. 1994 - from Hess 2008).

9. Growing perennial biomass crops for cellulosic ethanol results in lower PM2.5 levels than corn ethanol because less fossil fuel and fertilizer are required. (Hill,2008); Hess et.al (2008).

10. Naphthenic acids in tailings pond water can have acute aquatic toxicity to a variety of aquatic organisms including fish (Marano, 2009).

11. 0.7 hectares required to fuel one car (Farrell, 2006). 0.97 global cropland hectares Ecological Footprint(Vos,2007). Uncertainties exist rg. the availability of excess, abandoned ag. Land and marginal and degraded lands (Sagar,2007) Land Occupation - 25 Eco-Indicator points (Uihlein,2009).

12. 2 tons sand mined for 1brl.crude oil(Patel,2007); Mining of tar sands in northern Alberta leaves behind large open pits, tailings and overburden piles (Elshorbagy ,2005); Alberta issued their first-ever oil sands land reclamation certificate for a 104 ha. property (Gateway Hill) located near Edmonton in 2008. (Alberta Gov.,2008); Landscape fragmentation (wildlife) is of concern with strip mining as well as in-situ. (Jordaan, 2009), (Unnasch, 2009)

13. NRDC,2008

14. Refining:Biochemical- 6 gallons. Thermochemical- 1.9 gallons (Aden,NREL,2007)

15. Refining: 2 - 4.5 gallons of water/gallon- 82% of water coming from Athabasca River (Thomas-Muller,2008). Complete disruption of subsurface hydrology- extensive reclamation work to reestablish hydrologic cycle (Elshorbagy et. al. 2005). In-situ extraction poses severe groundwater contamination problems due to leakage of diluting materials (Patel, 2007).

16. Hypothetical CTL - water use could vary froml-1.5 barrel/ per barrel product (zero-discharge air-cooled plant) to 5-7 bbl water/ barrel product (water cooling and less use of waste heat for process heat)(Nowakowski, 2008). Large volumes of discharged contaminated water result from FT coal-to-liquid (Patzek,66).

17. A study conducted by the Northwest National Laboratory (PNNL) found that a car fueled by electricity from unused capacity in our current system emits 27 percent less global warming pollution than a car fueled by gasoline. This percentage varies from region to region, but emissions would be lower in every area of the country except for the Northern Plains states where emissions would stay the same. (Kinter-Meyer, et. al, 2007).

18. On a BTU-BTU displacement basis, switching from diesel to fossil-based CNG by 20-25% and LNG by 25-30%. Switching from fossil based CNG and LNG to biomethane based CNG can reduce emissions further (Natural Gas Use in Transportation Roundtable, 2010).

19. Kaplan and Sargent, 2010

20. The impact on acidification of vehicles fueled by natural gas is about a factor of 3 less than gasoline powered cars, and a factor of 4 less than diesel (Nigge, 2000)

21. Energy’s Pacific Northwest National Laboratory found that electricity powered vehicles powered by our current energy sources result in 93% less smog forming VOCs (Kaplan, and Sargent, 2010).

22. PM emissions from battery electric vehicles amount to 20 kg over its lifetime compared to 25 kg for gasoline. However diesel powered vehicles PM emissions amount to only slightly over 15 kg over its lifetime (Hackney and Neufville, 2001).

23. PM 10 emissions from CNG/LNG vehicles (15 kg) are only slightly lower than diesel (16 kg), but much lower than gasoline emissions (25 kg) (Hackney and Neufville, 2001).

24. Land use is determined by both direct and indirect use. Indirect use includes using diesel fuel for drilling (Fthenakis and Kim, 2009).

Environmental Life Cycle Impact Assessment

The modeling analytical framework sought to allow analysis of selected environmental impacts due to various transportation fuel policies and estimation of relative impacts to air quality, water use and quality, and wildlife/ecological quality for a variety of policies and fuel pathways. The framework allows for the analysis of variable inputs to estimate environmental impacts at a local (Minnesota) and global scale. A literature review was conducted to survey available LCA models and related documentation. The sources and methodology of each was studied to determine which may be appropriate to the state of Minnesota. The selection of an LCA-based model with the ability to explore a broad set of environmental impacts was made based on factors such as the compatibility of a model's methodology with the framework developed in this project, and the ability to consistently adapt a model's data inputs for Minnesota values.

Goal and Scope of LCA for Four Fuel Pathways
The goal of this portion of the study is to more thoroughly assess the multiple environmental and human health impacts potentially resulting from lower carbon fuels and to investigate potential impact trade-off between fuels. To this end, we performed a Life Cycle Impact Assessment (LCIA) according to the methods delineated in the ISO14040 series. In doing so, the potential environmental impacts and potential human health effects of fuel pathways under study can be identified in greater detail. Due to project limitations regarding the availability of comprehensive emission inventories of all pathways studied in the GHG portion of the analysis, only four U.S. fuel pathways, currently in production and where more complete inventory databases are available through commercial sources, were chosen for analysis. The four pathways chosen for analysis are: conventional gasoline (petroleum), corn ethanol, conventional diesel (petroleum) and soy biodiesel. The function of the four fuel pathways is to provide fuel energy for vehicle operation and the functional unit of the fuel pathways is defined as 1 MJ of fuel used for vehicle operation for the comparison of LCA results.

A 'well to wheel' system boundary was created for this analysis that includes mineral extraction (energy crop cultivation), mass transportation (truck/rail/pipeline), regional storage, fuel pumping station and fuel combustion in vehicle operation. A process flow diagram that depicts the petroleum and bio-based fuels under study, their system boundaries and the data sources employed is displayed in Figure 3. The fuel product system is subdivided into a set of unit process. These processes are linked to one another by flows of intermediate products and/or wastes for treatment, to other product systems by product flows, and to the environment by elementary flows. Examples of elementary flows entering the unit process are materials or energy such as crude oil, diesel and electricity entering, leaving or used in the system. Examples of elementary flows leaving the unit process are emissions to air, water and soil. The boundary of a unit process is determined by the level of detail in the study model to satisfy the goal defined in the study (ISO 14044. In creating a consistent system boundary for our analysis of the four fuel types examined, we determined that the GREET model used in the GHG portion of the study (particularly the emissions inventories included) was inadequate for exploring multiple non-carbon environmental impacts. Therefore, a new life cycle emissions inventory (LCI) was built to include additional emissions that could potentially affect the environmental outcomes. The Eco-invent commercial database was introduced for this purpose and displaced GREET inventories "from well to tank." The LCI was completed by combining the Eco-invent life cycle inventory "from well to tank" with MN GREET direct emissions inventory from "wheel". The importance of exploring multiple data sources for the LCIA analytical modeling framework became evident over the course of the project. Although it was known that Ecoinvent inventories more than 1,200 kinds of emissions, and GREET only includes 9 kinds of emissions, the specific effects associated with utilizing a more comprehensive quantification of fuel production compared to fuel combustion emissions would have on results was not known. Improving data availability of comparable fuels at tail-pipe combustion and across a wider range of emissions is sorely needed and will certainly alter this report's findings significantly. Findings regarding these results begin on page 41.

The following sections discuss data assumptions and selection provide additional detail regarding analysis scope.

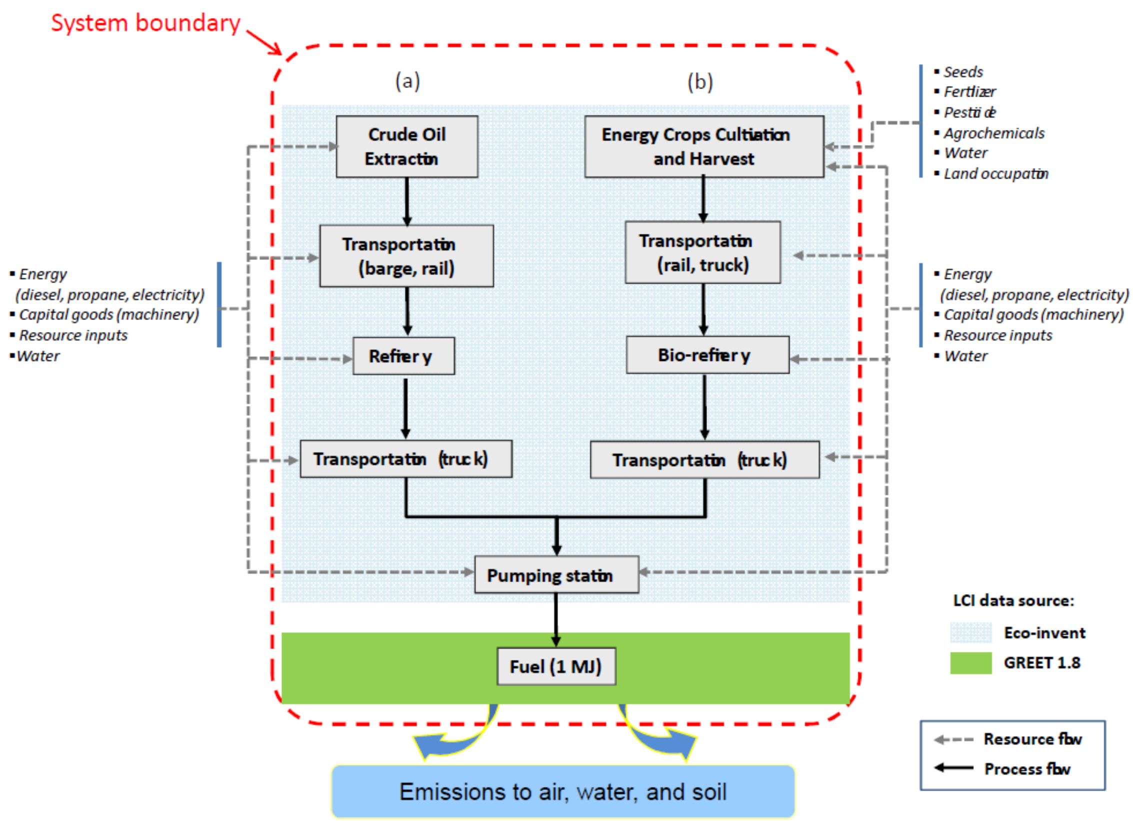


Figure 3: Process flow diagram of (a) conventional fuels and (b) renewable fuels.

Life Cycle Inventory Analysis

New Life Cycle Inventories were created using both the GREET model and ecoinvent commercial database. While the emission inventory created by GREET works very well when looking at fuels from strictly a GHG standpoint, when used to determine all possible impacts to the environment, it creates huge data gaps that can lead to incomplete or very misleading results. GREET's nine emission inventory mostly contributes to global warming potential and human respiratory effects; other impact categories simply cannot be addressed by these inventories alone. Therefore, while the GREET 1.8 model is employed to identify Minnesota-Specific GHGs emissions, in order to more comprehensively address environmental impacts other than global warming potential, the Ecoinvent commercial database (created by the Swiss Centre for

Life Cycle Inventories) is introduced to displace GREET's life cycle inventory "from well to tank" and for upstream transportation calculations. The benefit brought by use of the Ecoinvent database was a more complete emissions inventory of unit processes in a fuel life cycle. The Ecoinvent model creates an inventory list of more than 1,200 resources/emissions. Because of the level of detail and the limited inventory data available for 2nd generation fuels, complete LCIA was not possible for all fourteen pathways studied within the larger project GHG analysis.

Table 4 provides a summary the researchers' assessment of life cycle inventory data sources impacting selection choice. Discussions of each are provided in the following sections.

Table 4: Comparison of life cycle inventory database examined for inclusion in this study.

	GREET 1.8	US LCI	Ecoinvent
Description	• Process-based life cycle model	• Unit process-based inventory data	• Process-based inventory data
Scope	• Life cycle air emissions and energy use of U.S. transportation fuels (traditional and alternative fuels) • Current and future estimates possible	• U.S. data for industry sectors including most environmental impacts • Temporal representation of process depends on data source and model updates	• European and U.S. data for large variety of industry sectors including most environmental impacts • Temporal representation of process depends on data source and model updates
Advantages	• Publicly available • Transparent • Flexible to user assumptions and input manipulation • Relatively quick results	• Publicly available • Applicable to any process	• Applicable to any process • Large inventory of a variety of industrial unit processes • Relatively comprehensive environmental impacts
Disadvantages	• Limited to transportation and related sectors (e.g. vehicle manufacturing) • Limited to criteria air pollutants and greenhouse gases	• Labor intensive • Inventory modeling is not transparent • Lack of data quality information • Inconsistencies possible between different modules	• Expensive • Not publicly available • Labor intensive • Inconsistencies possible between different modules

Selection of the GREET Model for Tank to Wheel LCI

The GHG section of this project performed a detailed comparison of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET), Lifecycle Emissions Model (LEM) and Biofuel Energy system simulator (BESS) GHG emissions modeling. A summary of the evaluation is included in that section of the full report. Acquisition of tailpipe emissions inventory data was problematic. Estimated MN GREET emissions for vehicle operation (tailpipe emissions) provided in the carbon calculations of the GHG section of this report are used in an effort to include impacts from the use phase. It is important to note that emissions included in this phase are limited to nine GHG and criteria pollutants and thus may significantly underestimate impacts associated with this phase of all fuels assessed. No statistical data is provided for the GREET inputs, therefore only point estimates were used in characterization calculations.

While we explored the use of EPA's Office of Transportation and Air Quality (OTAQ) Motor Vehicle Emission Simulator (MOVES), at the time in which our modeling work was being developed, the MOVES simulator only contained gasoline and corrected for E10 tailpipe emissions (criteria, GHG, and toxic emissions). At the time of publication, MOVES did not separately model E85 vehicles.. This emission modeling system, once available across multiple fuels, estimates emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis. GREET, acknowledging its limitations, was selected for use in the "tank to wheel" emissions portion of the environmental impact analysis for this project.

GREET was developed and is maintained by the Systems Assessment Section Center for Transportation Research at Argonne National Laboratory. It was developed as a multidimensional spreadsheet model in Microsoft Excel and is available free of charge for anyone to use. The first version of GREET was released in 1996. Since then, Argonne has continued to update and expand the model. GREET 1.8b was the version available for use during this LCFS project. However, development of the model continues and version 1.8d was released July 30, 2010. The definition of "lifecycle" used in GREET is consistent with lifecycle as defined in the Energy Independence and Security Act of 2007 (EISA 2007), Title II, Subtitle A, Sec. 201 and encompasses resource extraction, resource transport, refining/distillation, distribution/storage, and consumption/use.

GREET separately calculates inventories for the following emissions for more than 100 fuel production pathways and more than 70 vehicle/fuel systems:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, fossil natural gas, and coal together), petroleum, coal and natural gas.
- Emissions of CO_2-equivalent greenhouse gases - primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).
- Emissions of six criteria pollutants:
  - volatile organic compounds (VOCs),
  - carbon monoxide (CO),
  - nitrogen oxide (NOx),
  - particulate matter with size smaller than 10 micrometer (PM10]),
  - particulate matter with size smaller than 2.5 micrometer (PM2.5),
  - and sulfur oxides (SOx)

Selection of Ecoinvent for Well to Tank LCI

Our study also investigated the U.S LCI database published by National Renewable Energy Laboratory (NREL) in an effort to gain greater insight into potential variation within LCI resource and emission data. The USLCI database contains inventory data of a variety of industrial processes with relatively complete emissions inventory. However, it only provides corn agriculture inventory data and is lacking information about data quality. The USLCI database only reports mean values with no statistical information. In contrast, Eco-invent database contains corn agriculture and corn ethanol conversion process in the U.S. Compared to the USLCI database, Ecoinvent provides more comprehensive process inputs and emission inventory with data quality information. However, Ecoinvent is a proprietary database and access to it is under the terms of a license agreement between the licensor (Swiss Center for Lifecycle Inventories) and the licensee who is prohibited from releasing the inventory data used in the model. Even though the process inventory database is not publicly available, reports are available through online sources for increased transparency in inventory modeling. Although recognized that this would cause a limitation to full review of all data inputs, the U of M had previously invested in a license for access to Ecoinvent and could leverage that investment and experience with it. Since the main goal of the project was to develop modeling analytical frameworks that could be used to compare implications of a wide range of LCFS options, not produce definitive numbers, but rather, emphasis was placed on the task of outlining opportunities and challenges related to results. Ecoinvent has a wider range of datasets available, and includes all the USLCI datasets. Both Ecoinvent and USLCI are updated on an on-going basis (although there is a time lag between USLCI updates and their incorporation into Ecoinvent). Results shown in this report would vary from the same analysis done today. For example, in July 2010 USLCI significantly modified data on LCA of U.S. soybean oil-based biodiesel production which shows substantially reduced environmental impacts relative to previous data (United Soybean Board 2010). However, due to lack of statistical information around LSLCI, data used in the modeling exercise within this report was that in use by Ecoinvent in 2009.

The Ecoinvent data sets generally provide statistical information, which are not currently available for the USLCI Database. The USLCI Database currently uses national averages; however, using Ecoinvent data provides the opportunity to assess variability. Timeline and budget did not allow further analysis to occur. We recommend that future analysis compare the mean values from Ecoinvent with the national averages from the USLCI database (which does better represent US processes and products) to determine variability.

The Ecoinvent project began during late 1990s. Project support came from the Swiss Federal Roads Authority (ASTRA), the Swiss Federal Office for Construction and Logistics (BBL), the Swiss Federal Office for Energy (BFE), the Swiss Federal Office for Agriculture (BLW), and the Swiss Agency for the Environment, Forests and Landscape (BUWAL). The database software development was funded by the Swiss Centre for Life Cycle Inventories, distributor of Eco-Invent. Ecoinvent version v2.2 is now the world's leading Life Cycle Inventory (LCI) database with more than 4,000 LCI datasets in the areas of agriculture, energy supply, transport, biofuels and biomaterials, bulk and speciality chemicals, construction materials, packaging materials, basic and precious metals, metals processing, ICT and electronics as well as waste treatment and offers one of the most comprehensive international LCI databases. Life Cycle Impact Assessment tools, USEtox and ReCiPe LCIA methods have been integrated into the Eco-Invent database.

Lifecycle assessment (LCA) studies using Ecoinvent database may address the environmental aspects of product systems, from raw material acquisition to final disposal (from "cradle to grave"). Emissions from the past (infrastructure construction), the present (e.g. heating) and the future (e.g. disposal options) virtually without temporal boundaries are all included in the Ecoinvent inventory. Sectors included, database contents and sources in Ecoinvent data v2.0 are listed below.

Table 5: Ecoinvent data v2.0 contents and data generators.

Sector	Database content	Data generator
Energy	Hard coal	Paul Scherrer Institute
	Oil	ESU-services Ltd.
	Natural gas	ESU-services Ltd., Paul Scherrer Institute
	Nuclear power	Paul Scherrer Institute
	Hydroelectric power	Paul Scherrer Institute
	Wood energy	Paul Scherrer Institute
	Wind power	Paul Scherrer Institute
	Photovoltaics	ESU-services Ltd.
	Solar heat	ESU-services Ltd.
	Electricity supply and mixes	ESU-services Ltd., Paul Scherrer Institute
	Small scale CHP systems	Basler & Hofmann
	Biofuels	ESU-services Ltd., Carbotech, ENERS, ETHZUNS1,Infras, LASEN/EPFL, Paul Scherrer Institute,Umwelt- und Kompostberatung
Materials	Building materials	Empa2, Bau- und Umweltchemie, ESU-services Ltd.
	Metals	Empa2, ESU-services Ltd.
	Plastics	Empa2
	Paper and Board	Empa2
Renewable materials	Wood	Empa2
	Tropical wood	Dr. Frank Werner Environment and Development
	Renewable fibres	Carbotech
Chemicals	Basic Chemicals	ETHZ-ICB3, Empa2, Chudacoff Ökoscience, ESUservicesLtd.
	Petrochemical solvents	ETHZ-ICB3
	Detergents	Empa2
Transport	Transport services	Paul Scherrer Institute, ESU-services Ltd.
Waste management	Waste treatment services	Doka Life Cycle Assessments
Agriculture	Agricultural products and processes	ART4, Carbotech, ETHZ-ICB3
Electronics	Electronics	Empa2
Mechanical engineering	Metals processing and compressed air	ESU-services Ltd

[1] Institute for Environmental Decisions, Natural and Social Science Interface, Swiss Federal Institute of Technology, Zurich (ETHZ)
[2] Swiss Federal Laboratories for Materials Testing and Research
[3] Institute for Chemical and Bioengineering, Safety and Environmental Technology Group, Swiss Federal Institute of Technology Zurich (ETHZ)
[4] Agroscope Reckenholz-Tänikon Research Station, Life Cycle Assessment group

Ecoinvent datasets often serve as background data in specific LCA studies. The LCI and LCIA results of Ecoinvent datasets should not directly be compared with the aim to identify environmentally preferable products or services. For comparative assessments, problem- and case-specific particularities need to be taken into account. Inventory data are in most cases collected on the level of national averages. Hence, no regional differentiation can be made. Data sources are assessed according to the six characteristics "reliability", "completeness", "temporal correlation", "geographic correlation", "further technological correlation" and "sample size." Each characteristic is divided into five quality levels with a score between 1 and 5. Accordingly, a set of six indicator scores is attributed to each individual input and output flow (except reference product) reported in a data source (this set of six indicator scores is reported in the general comment field of each input and output). An uncertainty factor (expressed as a contribution to the square of the geometric standard deviation) is attributed to each of the score of the six characteristics.

For well to fuel LCI, Ecoinvent's cumulative LCI with maximum, mean, and minimum values are used. Ecoinvent provides high and low estimates for its inventory resource and emission data. In an effort to provided greater transparency with regard to likely variation of inputs and thus impact estimates, we present findings for all available LCI levels for each fuel pathway. Data considerations for each pathway are as follows:

Conventional Gasoline

For LCI of conventional gasoline, Ecoinvent's unleaded gasoline produced by an average refining technology in Europe is employed. The inventory data is created based on in-site specific data of 100 refineries in Europe (Jungbluth N. et al., 2007). Given the limited time frame of the study, and an effort to create US or MN specific LCI data, this relationship is assumed to represent domestic refining technology, similar to refining available in the US and distributed to local pumping stations in MN. The assumption might not be reasonable to represent the US averaged or MN specific refining. Approximately 83% of the total percentage of crude oil consumed within Minnesota is refined from Canadian oil sands. (GHG section of this report). However, the goal of our LCIA study to focus on not compiling whole LCI for fuel pathways but to develop a modeling analytical framework to serve as a means for further evaluation of LCFS options. Data was not available to characterize all emissions with MN specified characterization factors and identifying the significance of the impacts of all emissions within the state of MN. The framework included are all processes on the refinery site, all resources/emissions in all upstream processes and waste treatments, process emissions and direct discharges from refinery site to rivers. Excluded are the emissions from combustion facilities as GREET models finished gasoline products that are delivered to regional bulk terminal and thereafter distributed to regional fuel pumping station. The framework used GREET's direct emissions from transportation and the distance from refinery to bulk terminal and from bulk terminal to regional fuel pumping station. Process flow and system boundary of gasoline production is shown in process flow diagram in Figure 1.

Corn Ethanol

For corn ethanol LCI analysis, 'ethanol, 99.7% in H2O, from biomass, at distillation' is selected for cumulated LCI until distillery. Processes within system boundary for corn cultivation and corn ethanol production are in the US context. Ecoinvent includes the transport of corn grains to the distillery, and the processing of corn grains to hydrated ethanol (95%) and DDGS (92% dry matter). System boundary is at the distillery. The process described corresponds to the dry-milling technology. Hydrated ethanol input is corn-based ethanol, produced in the US context. The ratio of hydrated to anhydrous (wet basis) is equal to 0.997/0.95, i.e. 1.05 kg hydrated ethanol per kg of anhydrous ethanol. On a dry matter basis, the input of hydrated ethanol 95% is 1 kg per kg of anhydrous ethanol 99.7%. The energy use for the dehydration process are electricity (8.8kWh) and steam (1002 MJ) per ton of anhydrous ethanol (Ecoinvent, 2007). The treatment of waste streams is also included.

Ecoinvent's corn ethanol life cycle inventory database includes all resources and emissions produced from upstream processes and foreground processes are incorporated with GREET direct emissions data for fuel combustion for vehicle operation. The life cycle stages within corn ethanol production system are 'corn cultivation and harvest at farm,' 'corn feedstock transportation,' 'corn fermentation, hydrated ethanol production, and dehydration of hydrated ethanol at bio-refinery,' and 'corn ethanol combustion in vehicle operation,' as shown in Figure 3. Even though the life cycle emissions inventory is not clearly separated along each process, the cumulated emissions inventory through entire life cycle stages are available for corn ethanol system under this study. It is assumed that regional fuel pumping stations are located within 30-mile distance from ethanol refinery.

The benefit of using corn ethanol as renewable fuels is seen primarily at the end use (tailpipe or fuel combustion in vehicle operation). During the corn cultivation at farm, corn absorbs CO_2 from atmosphere (1.35 kg CO_2 per kg corn fresh matter) to produce carbon required for corn growth. Tailpipe CO_2 emissions are generally calculated based on the assumption that the CO_2 uptake from farm field equals to the tailpipe CO_2 emissions so that the biogenic carbon emitted is offset by the CO_2 uptake resulting from corn growth. Thus, the amount of CO_2 uptake is subtracted from ethanol combustion stage. However, the combustion CO_2 emission in our GREET model result is 1.91 kg/ kg of corn ethanol while CO_2 uptake of corn is 1.35 kg/kg of corn ethanol based on carbon balance.

Conventional Diesel

Life cycle inventory of conventional diesel production complied from Eco-invent. Due to time restriction to investigate MN-specific diesel production, life cycle inventory of diesel production system had to rely on Ecoinvent's European average diesel production. Even though it is based on European context, for the purposes of developing an analytical modeling framework it was assumed that there is no significant variation in diesel production systems between U.S., Minnesota and Europe. This allowed the significant impacts of all emissions emitted due to production of conventional diesel to be identified. Ecoinvents system boundary of the production system includes: oil field extraction, crude oil production, long distance transportation, and diesel refining;l processes at the refinery site including wastewater treatment, process emissions and direct discharges to rivers, and an environmental inventory that includes all emissions associated with upstream processes of production of resources, input products and energy used in the processes. It is important to understand, however, that although considered appropriate for developing a modeling analytical framework that can provide the means for comparing environmental impacts, the data inputs used were not specific to Minnesota. Approximately 83% of the total percentage of crude oil consumed within Minnesota is refined from Canadian oil sands. (GHG section of this report).

As was outlined in the literature review, the choices available for developing a modeling analytical framework for use as LCFS LCIA are evolving rapidly. Over the course of the project modeling options available in 2011 are different than those available when choices were evaluated in 2009. A similar evolution is occurring regarding data.

Improved data availability of petroleum processes is needed to reduce geopgraphic assumption beyond typical energy source adjustments when applying Ecoinvent data in a US setting.

Soybean Diesel

Life cycle processes of soybean diesel can be divided into soybean cultivation and harvest, transportation to refinery plant and refining of soybean to diesel. For soybean cultivation, soybean seeds, mineral fertilizers, pesticides, farming machine, and land preparation (conversion) are required. Soybean production area estimated in 2006 was about 29 million hectares and, on average yield over five years, 2,641 kg of soybean per hectare was produced. Minnesota Department of Agriculture most recent Minnesota Agricultural Statistics Report shows five year (2005-2009) average was 2,836 kg of soybean per hectare. According to national estimates, to cultivate 1 kg of soybean required 25.7g of fertilizers, of which diammonium phosphate (DAP, P_2O_5) and potassium chloride (K_2O) are used the most. In contrast. The United Soybean Board (February 2010) report states it takes 15.9 g of fertilizers to cultivate 1 kg of soybean. Machine and energy use considered for soybean farming in Eco-invent are for plowing, harrowing, fertilizing, sowing, and combine harvesting. Total annual energy use required for the machine is 55.42 liters of conventional diesel per hectare (NREL 2006).

In the U.S., soybeans uptake 1.370 kg of CO_2 per kg of soybeans during its growth. The energy content embodied in the biomass is about 20.5 MJ for every kg of soybeans. Every one ton of soybean cultivation liberates 355g of dinitrogen monoxide (N_2O), 943g of ammonia (NH_3) and 74.5 g of nitrogen oxides (NO_x) to the air. It also induces phosphorous releases as 301 g is emitted to surface water and 26.5g to ground water per one ton of soybean cultivated.

To produce soybean diesel, soybean oil has to be extracted. The production of soybean oil at refinery includes the mechanical extraction of soybean oil with hydraulic presses. Extraction yield of soy oil from soybeans with 11% moisture content has a range between 179.8 – 201.8 kg soy oil per ton of soybeans (Sheehan et al., 1999; Delucchi et al., 2003; Pimentel and Patzek, 2005; Ecoinvent, 2007). This study assumed that 188.1 kg soy oil for soy oil extraction rate.

The soybean diesel conversion LCI used Eco-invent's 'Soybean methylester, at esterification plant, US' for the U.S. context and it included cumulated emissions inventory of all upstream process associated with the life cycle process. In the esterification process in the U.S. context, two products are produced from one ton of soybean oil: 972.7 kg soybean diesel and 106.1 kg glycerine. Economics allocation approach is applied with allocation factors of 92.0% to soybean diesel and 8.0% to glycerine because glycerine is co-product that is not used within our soybean diesel system boundary.

LCIA Characterization Tool Selection

Our LCIA study complies with a guideline documented in International Organization for Standardization ISO 14040 -14044 series, delineating principles and frameworks needed for Life Cycle Impact Assessment (LCIA) and Life Cycle Assessment (LCA). According to ISO 14042, LCIA consists of two steps: classification and characterization. In the classification step, the identified life cycle resources/emissions are assigned to the respective impact categories: i.e. global warming, ozone depletion, acidification, eutrophication, photochemical smog, ecological toxicity, and so on. . Next, the classified resources/emissions are characterized. Characterization factors (C.F.) are applied for each of resources/emissions by the impact category and media of release. The calculation involves the conversion of LCI results to common units and the aggregation of the converted results within the impact category (ISO 14042). For example, characterization of CO_2 emission is done by multiplying the quantity of chemical emission with characterization factor. Within each impact category, the characterized results will be summed up to form characterization score for each impact category. These two steps are called characterization.

While the MN GHG LCA models conducted previously in this report could be done entirely within the GREET model, a more comprehensive characterization tool is required to screen for the environmental impacts of fuels on air and water quality, and the quality of wildlife and aquatic habitat. To accomplish this, we employed an environmental assessment model developed by the US EPA called the *Tool for the Reduction and Assessment of Chemical and other environmental Impacts* or TRACI (Bare/Norris, 2002).The characterization factors provided by TRACI characterizes resources and emissions emitted in the U.S., and is recommended for estimating impacts to human health and the environment (Toffel & Marshall, 2008). Impact categories currently included in TRACI are provided in Table 6. Definitions and details of impacts categories included in TRACI model are described as below.

Table 6: Impact categories in TRACI model.

	Environmental impacts (category indicator)	Human health effects (category indicator)
Impact category	Global warming Ozone depletion Acidification Eutrophication Photochemical smog Ecological toxicity	Human health cancer (kg benzene-Eq) Human health non-cancer (kg toluene-Eq) Human health criteria (respiratory effect)

Global Warming: The global warming impact accounts for the potential change in the earth's climate as a result of the pileup of substances that are able to trap heat from the sunlight. The model for this category in TRACI follows the midpoint metric of global warming potentials proposed by the International Panel on Climate Change (IPCC). The potency of all greenhouse gases is measured in terms of CO_2 released per kilogram of emission.

Ozone Depletion: TRACI characterizes the potential contribution of substances to the destruction of the ozone layer, based on the metric of ozone depletion potentials proposed by the World Meteorological Organization. The chemicals in the metric are characterized relative to CFC-11.

Acidification: Acidification involves the natural mechanism that intensifies the acidity of water and soil systems by increasing [H+] or equivalents. In TRACI, the acidification model is based on an empirically calibrated atmospheric chemistry and transport model, enabling it to approximate total North American terrestrial deposition of expected H^+ equivalents as a function of the emission location (Bare et al., 2006a). Characterized acidification potential can be calculated by multiplying characterization factors of each acidification-causing emission, expressed in H+ mole equivalent deposition per kilogram of emission, with amount of the emission. The calculation results in the overall contribution in acidification as show in equation (2). The equation applies to all other impact categories' characterization calculation and thus omitted in the following description of impact categories for simplicity.

$$\text{Acidification index} = \sum_i e_i \times AP_i \qquad \textbf{(2)}$$

Where

e_i : emission (in kilogram) of environmental intervention *i*

APi : acidification potential of *i*.

Eutrophication: TRACI characterization factors for this impact category are derived from a nutrient factor and a transport factor. The former factor delivers the relative strength of influence on algae growth in aquatic ecosystems and the latter the probability that the release arrives in an aquatic environment. The final factors in this category are expressed in nitrogen equivalents released per kilogram of emission.

Photochemical Smog Formation: This category is responsible for examining the detrimental impacts in the troposphere, caused by ambient concentrations of nitrogen oxides (NO_x) and volatile organic compounds (VOCs), and a mixture of VOCs and others. The approach taken by TRACI integrates several components including; relative influence of individual VOCs on smog formation, relative influence of NO_x concentrations versus average VOC mixture on smog formation, impact of emissions upon concentration by stage, and methods for aggregation of effects among receiving states by area. The contribution of different substances in this category is converted to NOx equivalents.

Eco-toxicity: The eco-toxicity characterization model in TRACI employs Ecological Toxicity Potentials (ETPs) to quantify the ecological hazard of a unit quantity of chemical released into air and water. An overall of 161 chemicals, whose potential harms are measured in 2, 4-dichlorophenoxy acetic acid (2,4-D) equivalents per kilogram of emission, are documented in TRACI. An equation similar to Equation (1) can deliver the overall contribution in this impact category; it is thus omitted here for simplicity.

Human Health Cancer and Non-cancer: Both TRACI's human health cancer and non-cancer categories are grounded on Human Toxicity Potential (HTP), which was derived using a closed-system, steady-state version of CalTOX, a multimedia fate and multiple-exposure pathway model with fixed generic parameters for the United States (Bare . 2006b). Human health cancer characterization factors are expressed in benzene equivalents released per kilogram of emission and human health non-cancer in toluene equivalents.

Human Health Criteria (respiratory effect): This impact category identifies the association of changes in background rates of chronic and acute respiratory symptoms and mortality with ambient concentrations particular matter (PM). A three-stage method was developed in TRACI to examine the human impacts of chemicals, with the first stage dealing with atmospheric transport model, and the second stage relying on epidemiological studies, and the third stage arriving at a single score summary measure of disability-adjusted life-years (DALYs). PM 2.5 equivalents are used in TRACI to characterize the human health impacts of criteria emissions.

Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts TRACI

In 1995, U. S. EPA conducted a literature survey to ascertain the applicability, sophistication, and comprehensiveness of all existing methodologies to assist in impact assessment for Sustainability Metrics, Life Cycle Assessment, Industrial Ecology, Process Design, and Pollution Prevention programs of the Agency. As a result, the U.S. EPA decided to begin development of software to conduct impact assessment Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI). The current version of TRACI was developed in 2002. TRACI does not provide estimates of actual risk. TRACI is simply a screening tool to allow consideration and quantification of the potential for impacts (EPA (a)).

Because the U.S. EPA decided to make TRACI widely available, it was important that it be simple and small enough to run on a personal computer. This provided some constraints because advanced features such as geographical information system spatial linking and the inclusion of uncertainty modeling, such as Monte Carlo analysis for propagation of errors, could have exceeded the memory of many PCs and may have significantly complicated the use of TRACI. TRACI is designed for simplicity and therefore does not facilitate a quantification of propagated uncertainty.

The traditional pollution categories of ozone depletion, global warming, human toxicology, eco-toxicology, smog formation, acidification, and eutrophication were included within TRACI because various programs and regulations within the U.S. EPA recognize the value of minimizing effects from these categories. The category of human health was further subdivided into cancer, noncancer, and criteria pollutants (with an initial focus on particulates) to better reflect the focus of U.S. EPA regulations and to allow methodology development consistent with U.S. regulations, handbooks, and guidelines

Smog-formation effects were kept independent and not further aggregated with other human health impacts because environmental effects related to smog formation would have become masked and/or lost in the process of aggregation. Criteria pollutants were maintained as a separate human health impact category, allowing a modeling approach that can take advantage of the extensive epidemiological data associated with these well-studied impacts (Bare et.al. 2002).

Additional Consideration of USEtox for Ecotoxicity and Human Toxicity Characterization

Ecoinvent (for life cycle emissions) and TRACI (for toxicity values) were determined to be most appropriate for this modeling framework developed for this project. Due to the state of data availability and modeling science these limitations would likely be inherent in any databases chosen. Discovering and describing them is critical for the useful and constructive deliberations necessary in order for environmental LCIA considerations to be a part of LCFS policy development.

A number of different models have been developed for the development of characterization factors for the human and ecotoxicity categories over the last 15 years varying in their scope, applied modeling principles and not least in terms of the characterization factors they produce. These characterization models all cover a limited number of substances, and the current situation for the LCA practitioner who wishes to include the chemical-related impacts in the impact assessment is thus that: (a) there will probably be many substances in the life cycle inventory for which no characterization factor is available from any of the models, (b) for some substances several of the models may have published characterization factors, but these often vary substantially between the models. The chemical-related impacts are hence often excluded from the LCIA which de facto reduces it to an energy impact assessment (Hauschild et. al. 2008).

USEtox is a special purpose, multimedia, environmental systems modeling program intended for use in Life cycle impact assessment of human toxic and ecotoxic impacts focused on relative comparison of the hazard of chemicals. It is a research tool still in the development stage, currently available without charge in order to encourage scientific collaboration aimed at further development of the program. Any enhancements that are made shall be transferred and usable by others using the program (Hauschild et. al. 2008).

The USEtoxTM model was released in 2010 as an Excel model with recommended characterization factors for 1000 substances for human toxic impacts and for 1300 substances for freshwater ecotoxic impacts. The USEtox model is currently under review by the UNEP SETAC Life Cycle Initiative with the perspective of a global recommendation as the preferred model for characterization modeling of human and ecotoxic impacts in LCIA.

TRACI was selected for use in this project because of its long history of development by U.S. EPA and due to premature nature of USEtox at the time of selection. Restricted project resources and the scope of this project (explicit focus only on ecotoxicity), the research team was unable to integrate USEtox characterizations into the analysis for comparison with TRACI results. However, given the relatively large discrepancies across characterization factors developed within each model, further research into the use of USEtox is warranted.

Regarding pathways for exposure, toxicity values appear largely based upon the premises that all emissions for a specific chemical occur at the same time at the same location. Emissions due to fuel production are emitted over a wide variety of places from various processes over different times. Although toxicity models investigated in this project provide toxicity values for emissions so that screening to allow consideration of the potential impacts can occur, none investigated provided the means to estimate actual risk.

LCIA Results and Discussion

Life cycle impact assessment results presented below reflect the aforementioned life cycle inventories for conventional gasoline, corn ethanol, petro diesel and soy biodiesel based on the Ecoinvent commercial database and GREET model inputs. Emissions are characterized using U.S. EPA TRACI characterization factors and classified by impact category indicators. The characterized results with high, mean, and low variation values are presented in the following discussion.[5]

---

[5] Hi and Lo estimates only reflect variation in upstream resources and emissions provided in ecoinvent. Statistical data was not available for MN GREET tail pipe emissions employed in the use phase of fuels characterized, therefore mean point estimates were used in this phase across all scenarios (high, mean and low).

As documented in Appendix C., among all fuels, data to develop substance-level contribution analysis for global warming; human health effects; eutrophication; acidification; and ecological toxicity was only available for gasoline, diesel, corn ethanol (E100) and biodiesel (BD100) production and use. Consequently, the sensitivity analysis (Appendix D) was only performed for these fuels. The discovery that comparative data was not available for the production and use of all fuels commonly affect by LCFS policies represents a major impediment to performing comparative LCIA across all fuel types.

Although unable to do so for this project, we recommend that future modeling frameworks develop addition tail-pile combustion emission inventories, rather than the current approach which ignores many toxic emissions at combustion.

Results of using data in use when the modeling analytical framework for this project was developed (October 2009) follow. Both data inputs and modeling software has evolved since that time. Hence, the same analysis run today would show different results. Findings from this project provide indicators of directional importance as LCFS policies are considered, and describe specific limitations of data and modeling tools. The limitations described can be used to prioritize remaining research needed in order to perform effective, comparative LCIA modeling for each transportation fuel and production pathway influenced by LCFS policies.

Potential Environmental Impacts

Global Warming Potential (GWP)

The characterized result, shown in Figure 4, indicate that corn ethanol (denatured) has a mean value of global warming potential (GWP) as 743 g CO_2 equivalent compared to conventional gasoline as 902g CO_2 equivalent in terms of per MJ fuel functional unit basis. Most emissions inventory of corn ethanol includes carbon dioxide (CO_2), carbon monoxide (CO), dinitrogen monoxide (N_2O), methane (CH_4), and sulfur dioxide (SO_2). The inventory analysis indicates that they are released from cultivation and ethanol conversion process. Similarly, soybean diesel also produces these emissions at cultivation and harvest and diesel conversion refinery. However, soy diesel has the lowest GWP with lower GHGs (299 g CO_2-equivalent) than conventional diesel (873 g CO_2-equivalent) and two times lower the direct emissions than corn ethanol at fuel combustion in vehicle operation (tailpipe) stage. Global warming impacts of corn ethanol and soy-diesel are lower than conventional petroleum-based fuels. This is mainly due to the benefit of renewable fuels that the CO_2 emitted from biomass-based fuels combustion over the full life cycle of the fuels is generally assumed not to increase atmospheric CO_2 concentrations.

In Figure 4, variation between high and low values of the characterized global warming potential of conventional fuels is smaller than corn ethanol and soy-bio-diesel, likely due to less variation across petroleum industry practices. Corn ethanol has lower global impact potential than conventional gasoline, however, it is clear that not all corn ethanol is created equally with some ethanol estimated to be more carbon intense than conventional gasoline.

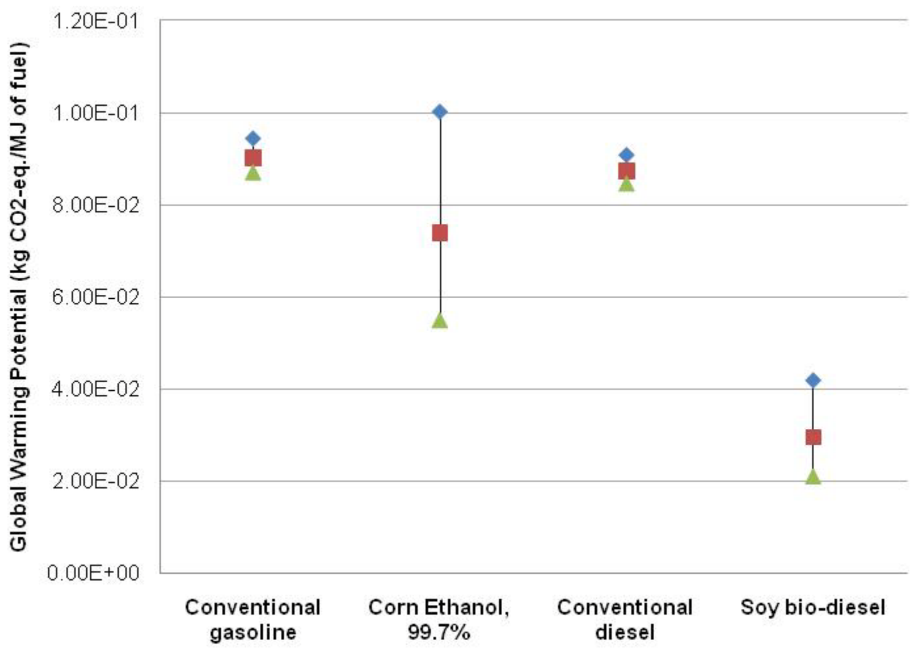


Figure 4: TRACI characterized result - global warming potential.

To further validate the models GHG result, the GHG value of corn ethanol derived from it are compared with other GHG findings from previous studies and models most commonly cited. In Figure 5, the mean value of four studies is 0.072 CO2-equivalents per MJ of corn ethanol supporting our result as in the reliable range of GHGs results.

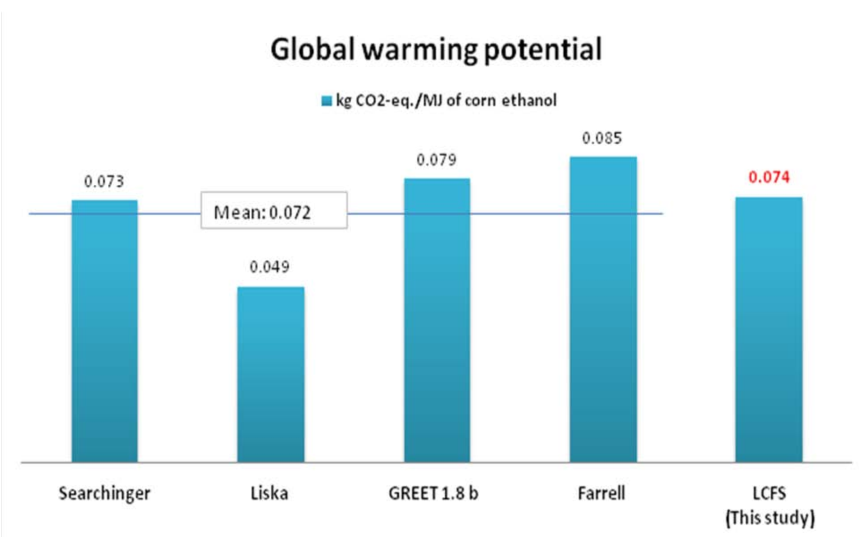


Figure 5: Summary comparison of global warming potential of corn ethanol with other studies.

The variation arises from the difference in the defined system boundaries of the studies including upstream processes. For instance, the BESS model based on Liska's research estimates lower life cycle GHG emissions for corn ethanol than does the widely-known GREET model. This divergence is specifically derived from the two facts that the BESS model uses efficient bio-refinery and fails to properly include upstream emissions (Plevin, 2009).

Ozone Depletion

Results of running the modeling analytical framework indicates that the reduction in ozone depletion is the benefit of the two renewable fuels. Soybean has the lowest environmental impacts on ozone depletion. Soybean can reduce 75% of the total ozone depleting air emissions of conventional diesel. Corn ethanol has nearly 64% less air emissions than conventional gasoline. Even though the two renewable fuels increase ozone depletion caused by methane compounds (bromochlorodifluoro-, Halon 1211) emissions, they reduce methane compounds (bromotrifluoro-, Halon 1301) emissions that has twice as significant as Halon 1211. While Halon has been used for fire and explosion protection throughout the 20th century, the Montreal Protocol required that all production of ne Halon cease by January 1, 1994. Recycled Halon and inventories produced before 1994 are now the only sources of supply. Because of the phase out of Halon and the difficulty in estimating emissions from rate events, future research would be useful in furthering understanding of these relationships.

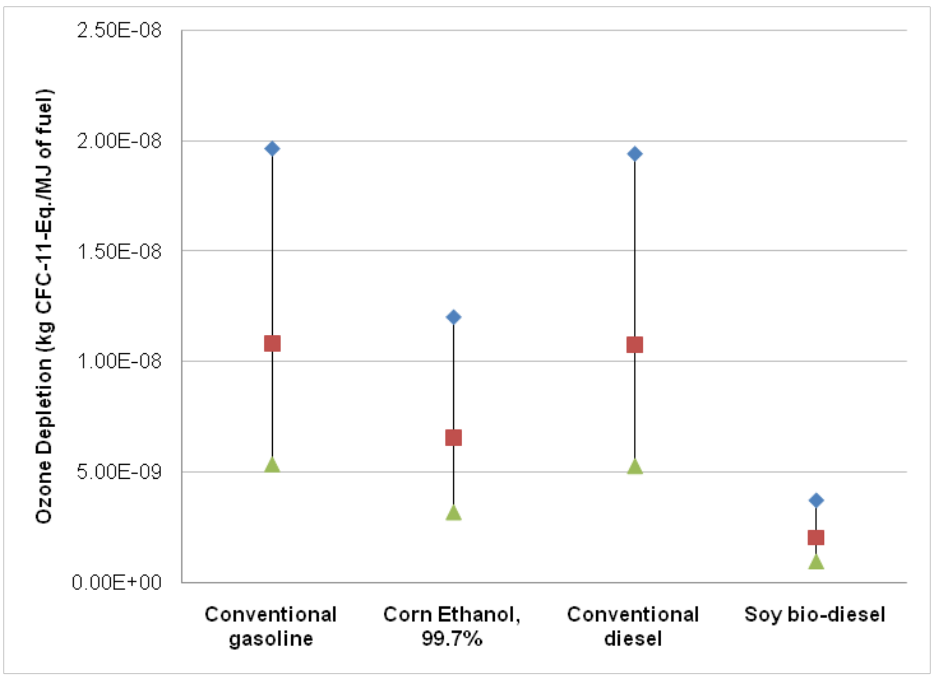


Figure 6: TRACI characterized result – ozone depletion.

Acidification

With regard to acidification potential, the two renewable fuels do not appear to fare well. The main contributors to the acidification impacts of all fuel pathways are ammonia (NH_3), nitrogen oxide (NO_x), and sulfur dioxide (SO_2). Corn ethanol has the highest acidification potential followed by soybean diesel because more NH_3, NO_x, and SO_2 emissions are liberated from corn ethanol and soybean diesel conversion plants. Despite higher SO_2 air emissions in conventional fuels, corn ethanol and soybean diesel produce NH_3 and NO_x air emissions that have more serious impacts on acidification than SO_2 does. It is partly because of fertilizer application and energy consumption for farming at crop cultivation and process energy consumption at bio-refinery.

As with results across all impact categories presented in this report, TRACI characterization factors for ozone depletion attempt to approximate total National deposition of expected H^+ equivalents. Therefore, the higher lifetime ammonia and NOx emissions from corn ethanol are the main contributors to its higher acidification potential. However, it is important to note that the TRACI formulation estimates the total acidifying deposition potential and not actual harm. The sensitivity of soils and waters to acid deposition varies by location. These spatially specific differences can lead to vastly different characterized results. Future research examining the specific sensitivities of MN soils and waters to acid deposition, nitrate mobility and uptake is important to understanding local impact.

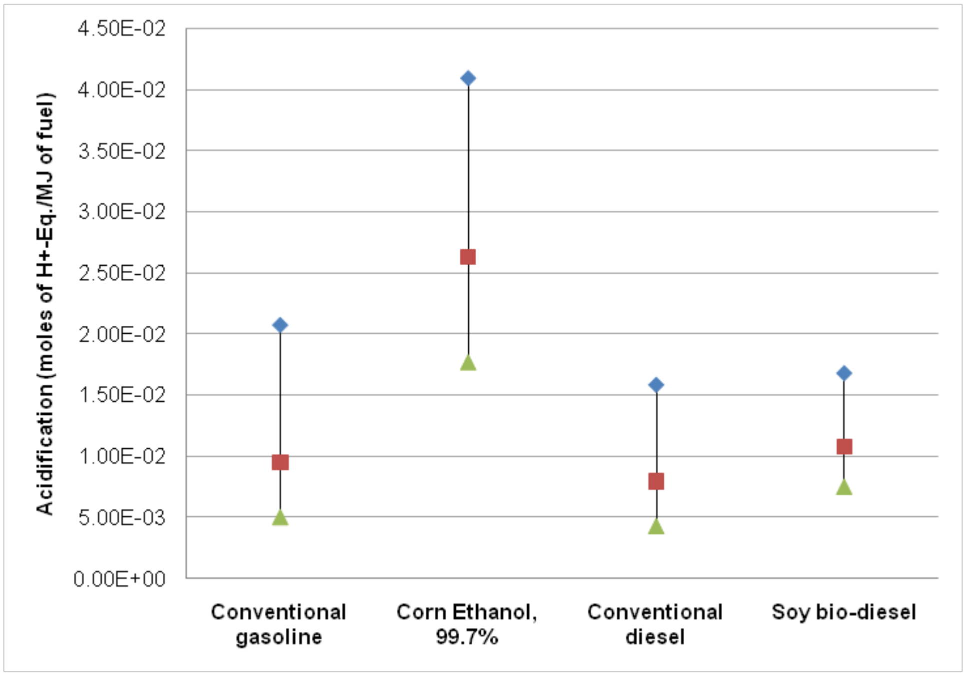


Figure 7: TRACI characterized result – acidification.

Acid rain is recognized as a significant concern. In general, high temperatures created by the combustion of petroleum because nitrogen gas in the surrounding air to oxidize, creating nitrous oxides. Nitrous oxides, along with sulfur dioxide from the sulfur in the oil, combine with water in the atmosphere to create acid rain. Acidification of oceans due to uptake of CO_2 emissions by water to form carbonic acid is also recognized as a significant concern. However, it is beyond the scope of this study to explore emission pathways incorporated in the TRACI tool which result in their characterization.

<u>Eutrophication and Photochemical Oxidation</u>

Based TRACI emissions characterization factors corn ethanol and soybean diesel tend to contribute more to eutrophication than conventional fuels. N-fertilizer use in energy crop cultivation induces infiltration nitrate substance to ground water and river leading eutrophication.

The difference between corn ethanol and soybean diesel is that corn ethanol requires much higher P-fertilizer than soybean cultivation.

Similar to other locally specific impacts, eutrophication is an issue for which the spatial distribution of emissions is important since it is a threshold phenomenon, in which the sensitivity of receiving waters is important. Nutrient transport in the form of leaching or runoff can vary dramatically by region. The transport factors in TRACI estimate the fraction of a nutrient release that eventually reaches an aquatic ecosystem for which it is limiting. Therefore, this analysis serves as a screening tool and additional LCI and characterization efforts are needed to better estimate local specificity. Future research should attempt to incorporate recent data of nutrient levels in streams and groundwater to assess the variability of eutrophication effects regionally and within the state.

Use of TRACI emissions characterization factors also indicates that Nitrogen Oxides (NOx) emissions result in high photochemical oxidation potential for corn ethanol and soybean diesel. Smog (photochemical oxidation) has a major respiratory human health impact effect.

U.S EPA uses Community Multi-Scale Air Quality (CMAQ) model as a means to account for local ozone formation chemistry (EPA (o); EPA (p)). In some locations (generally rural areas where crops are grown) ozone formation chemistry is NOx-limited. VOC emissions do not affect ozone formation. However, in urban areas ozone formation chemistry is VOC-limited, and NOx emissions reduction can increase ozone formation (National Resource Council, 1991). Ozone in the lower atmosphere is created through complex chemical reactions involving volatile organic compounds and nitrogen oxides. If the ratio of ambient levels of VOC to NOx is high, ozone formation is said to be "NOx-limited," that is, at the margin ozone depends just on NOx emissions. If the VOC/NOx ratio is low, ozone formation is "VOC-limited" so that reducing NOx has little marginal effect (and may even increase ozone in the immediate vicinity of the sources). Recent evidence has led scientists to conclude that VOC emissions from both natural and man-made sources are higher than previously believed; this has raised estimates of VOC/NOx ratios, so there is a renewed interest in control of NOx (National Research Council, 1991) (Small and Kazimi 1995). Hudman et al. (2007) modeled simulated summertime ozone concentrations associated with decreases in power plant and industry NOx emissions and report corresponding overall reductions in ozone formation. That said, even though the NOx emission reduction was largest in the Midwest during the years studied, the ozone decrease was greater in the southeast due to higher ozone production efficiency (OPE) per unit NOx. In addition, while urban areas are generally classified as being VOC-limited, recent research found that observed VOC/NOx ratios vary from urban area to urban area, within urban areas, and sometimes from hour to hour - suggesting that current emissions inventories may not be accurately capturing 03 production regimes (Baker and Carlton 2010). This same study predicts that urban areas will be more NOx-limited in the future. The result of this fundamental difference between VOC-limited and NOx-limited areas is that the spatial distribution of ozone reductions from VOC reductions is dramatically different from the spatial distribution of ozone reductions from NOx reductions (Huess, 2003; Sillman, 1999).

In contrast to EPA's CMAQ model, TRACI characterization factors give equal credit to both VOC and NOx reductions at all locations. The development of the TRACI methodology for characterizing photochemical smog or ozone formation is described in Bare et al., 2002 and described in somewhat greater detail in Norris, 2002. Bare et al. states, "We assume that VOC emission impacts on regional O_3 concentrations have the same spatial distribution as the ambient NOx concentration impacts." TRACI characterizations relied on the Cardelino and Chameides 1995 study of the Atlanta metropolitan area and two Northern Europe (greater population density than in rural U. S.) as inputs for VOC-limited rural areas.

Although beyond the scope of this study, we recommend that future research use inputs available through EPA's CMAQ model in place of TRACI default values so that a sensitivity analysis can be performed to show range of confidence for the values calculated.

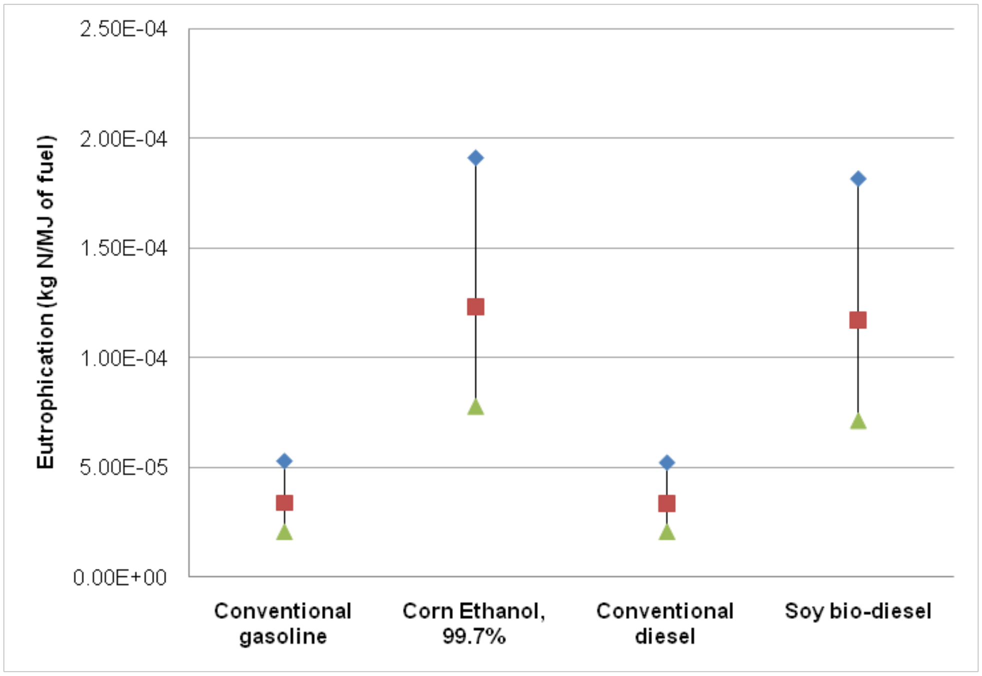


Figure 8: TRACI characterized result - eutrophication potential.

<u>Ecological Toxicity</u>

Reduced ecological toxicity is perhaps another environmental benefit of soy diesel over conventional diesel. Results from the modeling analytical framework show it to have a lower impact than corn ethanol but higher than conventional gasoline and diesel. Heavy metals uptake during soybean cultivation is a major contributor to ecological toxicity as well as human non-cancer effects. Most of the heavy metals are nutrient metals for plant growth (nickel, zinc and copper) except for cadmium. Ecoinvent database assumed that the heavy metals release to the environment is net negative because harvested soybeans uptake higher heavy metal content than the inputs of heavy metals in fertilizer use and soybean seeds. Soybean can be capable of absorbing the heavy metal, however, the actual amount of soybeans' uptake are still unknown because of regional variation of faming practice and natural environment such as topology, soil characteristics, etc. Thus, we made an assumption that net environmental emissions of the heavy metals are zero even though soybeans' capability to absorb the heavy metals may offset all heavy metal emissions at cultivation.

Ecological toxicity is also an impact category for which the location of emissions is important. Because of the lack of spatial consideration from the TRACI tool (derived using a closed-system, steady-state version of CalTOX), local variation of emissions cannot be assessed in this study. Aluminum emissions to air occurs from phosphorus mineral mining for fertilizer production. TRACI results specifically draw out aluminum emissions to air as the largest contributor toward the ecological toxicity of biodiesel and corn ethanol fuel life cycles.

Aluminum is ubiquitous, as the third most prevalent element and the most abundant metal in the earth's surface, human beings are naturally exposed to relatively large amounts of aluminum from food, water and air. Recently, however, aluminum toxicity has increased precipitously. Today, nearly 80% of those tested for metal toxicity reveal excessively high hair aluminum levels.

Aluminum toxicity is associated with soluble aluminum. U.S. EPA's ecological screening tool takes into account that toxic effects are observed with it, and how the solubility of aluminum is dependent upon the pH of the soil in which it is deposited. Bioavailability of aluminum for plant uptake and toxicity is associated with pH, since aluminum is soluble and biologically available in acidic (pH <5.5) soils and waters, Chemical and toxicological information suggests that aluminum must be in a soluble form in order to be toxic to biota (EPA (j); EPA (k)).

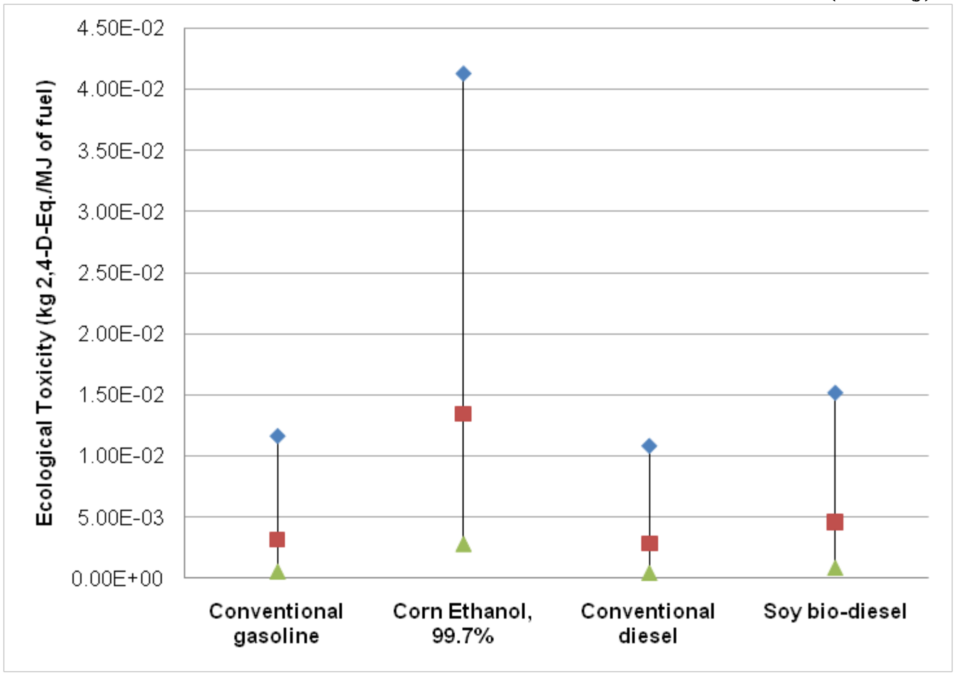


Figure 9: TRACI characterized result – ecological toxicity.

Sensitivity analysis is provided for select impact factors associated with corn ethanol and soy biodiesel in an effort to shed additional light on key substances' and emissions' influence over characterized results. These analyses can be found in Appendix IV. With regard to aluminum to air, the largest contributor to ecological toxicity identified through the sensitivity analysis (Appendix C), a 25 % reduction might reduce the ecological toxicity impacts of corn ethanol by 10% and soy biodiesel by 14%. A 100% reduction of aluminum impacts as characterized by

TRACI might reduce the overall ecological toxicity of corn ethanol by 42% and soy biodiesel by 58%.

TRACI employs Ecological Toxicity Potentials to model ecological hazard from 161 chemicals released to air and water. As an example of data limitations, it was discovered that TRACI assigns no values due to accidental release of transportation fuels to land and water (TRACI).

Although U.S. EPA maintains a large body of research and data on these releases the data is not in a form that can be readily integrated into the LCIA modeling programs. Similarly, the national Spills and Accidents database contains data on toxic chemical spills and other accidents reported to the National Response Center, however, it is also not in a form that allows for ready integrated into current LCIA modeling tools. Such limitations were found across all fuel types investigated for this project. Converting dissimilar emissions data into metrics and formats consistent with that used in LCIA modeling is critical for achieving improved comparative analysis (OPA; EPA (l)).

Potential Human Health Impacts
Potential cancer, non-cancer and respiratory affects are characterized for human health impacts.

Human Health – Cancer

Results from running the modeling analytical framework indicates that corn ethanol has the highest potential cancer effects of all other fuels characterized. The production and use of fertilizer cause arsenic emissions to air and the application of atrazine as herbicide on agricultural crop lands releases atrazine emissions to soil. These emissions are currently characterized by TRACI to contribute to human cancer effects, although significant debate continues to exist.[6] Although TRACI characterizes atrazine as a carcinogen, EPA determined in 2000 and again in 2003 that atrazine is "not likely to be carcinogenic to humans." Currently, given the new body of scientific information as well as the documented presence of atrazine in both drinking water sources and other bodies of water, in 2010 the EPA determined it appropriate to consider the new research and to ensure that regulatory decisions about atrazine protect public health. EPA is currently engaging the independent FIFRA Scientific Advisory Panel (SAP) to reevaluate the potential for atrazine cancer and non-cancer effects, including data generated since 2003 from laboratory animal and human epidemiology studies. Specifically, the watershed monitoring program examining flowing water bodies between 2004 and 2008 in watersheds identified as vulnerable to atrazine exposure found characteristics that make them more prone to have atrazine water concentrations that exceed the Agency's levels of concern, sparking additional monitoring across the Midwest starting in 2010 (http://www.epa.gov/oppsrrd1/reregistration/atrazine/).

Sensitivity analysis is provided for key substances' and emissions' influence over characterized results of human health – cancer impacts in Appendix IV. With regard to atrazine to soil, the largest contributor to human cancer impacts identified through our analysis, removing atrazine

[6] EPA initiated a reevaluation of the triazine pesticide atrazine in fall 2009. For updates and information on recent 2010 meetings, see, http://www.epa.gov/oppsrrd1/reregistration/atrazine/atrazine_update.htm.

from the analysis might reduce the human cancer impacts of the corn ethanol life cycle by 39% to 78%. Arsenic to air was found to be the largest contributor to human health – cancer impacts. A 25% reduction in arsenic releases might reduce the overall characterized human cancer impacts of soy biodiesel by 10-13%; a 50% reduction might lead to reductions in human cancer impacts of 20-25%.

With the introduction of USEtox as an LCIA tool, some of the human health and ecological toxicity characterizations have been recently challenged. In particular, TRACI relies on CalTOX to develop the estimated oral and inhalation doses. The limitations of CalTOX regarding spatial allocation of emissions could be expected to result in an overestimate of the exposures from all fuels. Chemical and physical processes that determine substance concentrations in various media are much more complex than considered in most models, and TRACI was specifically designed to provide simple and accessible compilation of the most sophisticated impact assessment methodologies that can be utilized on a desktop. USEtox uses characterization factors that are significantly lower than those of TRACI for arsenic and lead. Significant future study of human health impacts are needed to improve our understanding of life cycle impacts of fuels.

Finally, it is important that the reader recognize that this analysis is unable to examine the contributions from benzene and 1,3-butadiene to estimate cancer risk during the combustion (use) phase of all fuel pathways. While the U.S. EPA has extensively evaluated mobile sources of air toxics in recent years, at the time of publication, biofuel modules were not available through the EPA MOVES model. Therefore, while our analysis provides an apples-to-apples comparison of fuel pathways, emissions profiles of fuels at this life-cycle stage could significantly alter our findings.

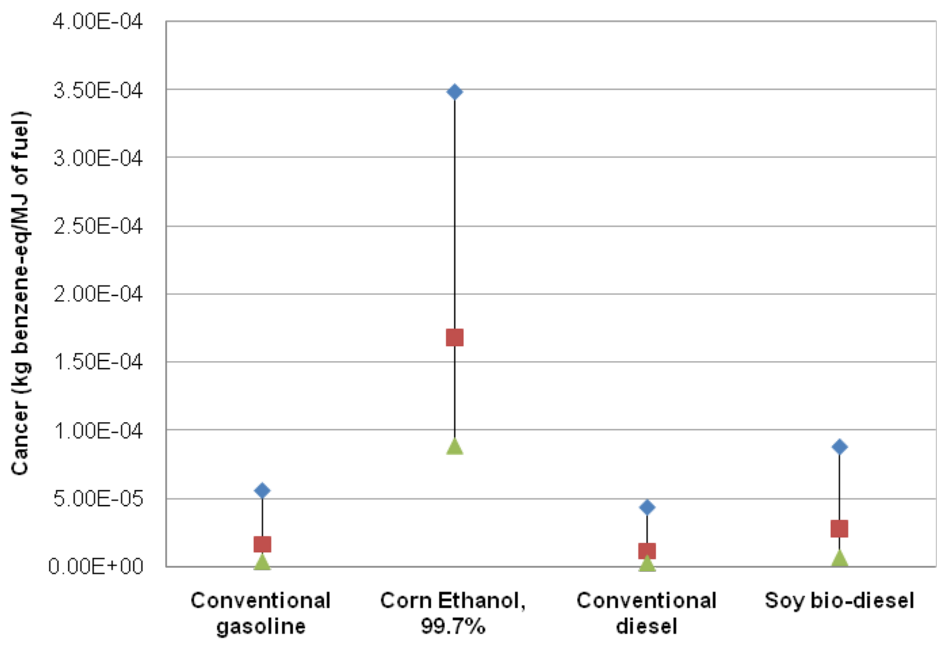


Figure 10: TRACI characterized result – human health, cancer.

Human Health – Non-Cancer

Potentially significant additional non-cancer human health impacts associated with corn ethanol and soy diesel are also evident in our findings. Lead to soil and ground water and cadmium ion release to groundwater are the major contributors for corn ethanol's higher contribution to non-cancer health impacts. TRACI characterization shows the non-cancer effects of soy biodiesel are mainly associated with heavy metals releases from agricultural farming machines.

Results of modeling human non-cancer health impact with TRCI showed lead released to soil and ground water are the major factors for potential impact. U.S. EPA guidance documents on soil screening of lead point out that that lead in soil is relatively immobile and persisted whether added to the soils as halides, hydroxides, oxides, carbonates, or sulfates (EPA (m)). EPA guidance further points out that the efficient fixation of lead in soils limits the transfer of lead to aquatic systems. In general and in specific to TRACI, how pathways of human exposure to Pb emissions were difficult to discern.

In addition, soybean bio-diesel also increases acidification potential with ammonia and NO_x emitted from soybean cultivation and refining at plant. TRACI assumptions used for ammonia and NOx emissions provided results showing these chemicals as the main contributors to the higher acidification potential.

TRACI assumes that all N emissions are equally acidifying, although it is recognized that different ecosystems vary in the effect N emissions have on acidification. This is a symptom of all toxic modeling investigated. General assumptions are used due to limitations of data available.

As previously discussed, TRACI's human health non-cancer factors were derived using a closed-system, steady-state version of CalTOX, a multimedia fate and multiple-exposure pathway model with fixed generic parameters for the United States. Therefore, characterization factors for non-cancer impacts, as assigned by TRACI tend to be much higher than more recently identified C.F.s employed in the USETox model. This holds true for TRACI characterizations of lead to water, the largest contributor to non-cancer human health impacts of corn ethanol and soy biodiesel.

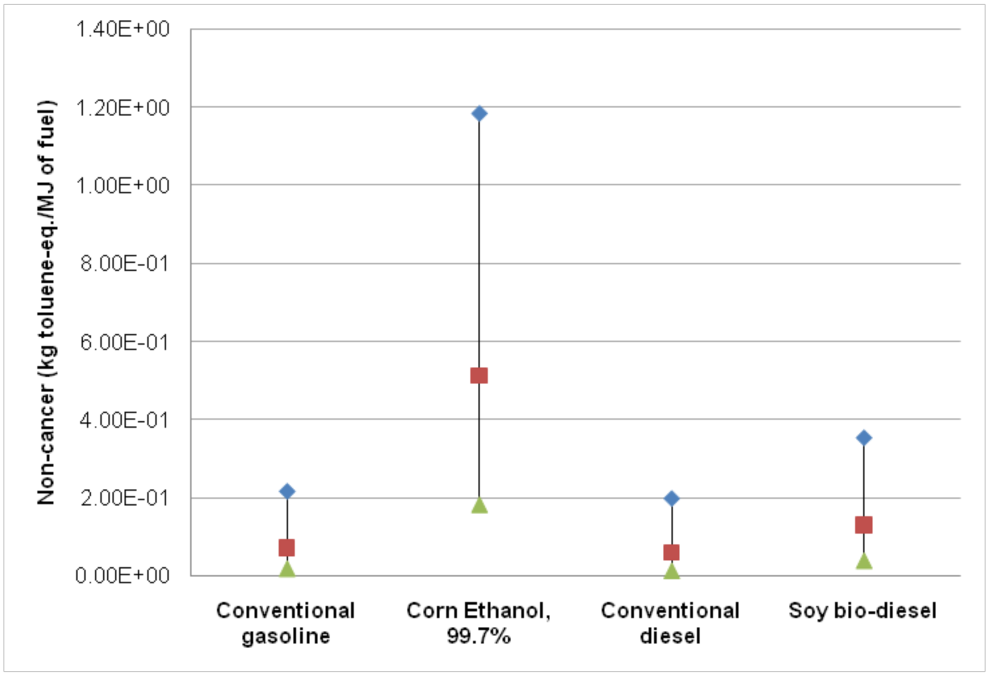


Figure 11: TRACI characterized result – human health, non-cancer.

Sensitivity analysis is provided for lead depositions to water, with regard to its influence over characterized results of human health – non-cancer impacts in Appendix IV. A 25 % reduction in lead to water might reduce the human health – non-cancer impacts of corn ethanol by 11-14% and soy biodiesel by 13-16%. A 100% reduction of lead to water impacts might reduce the overall non-cancer human health impacts of corn ethanol by 45-58% and soy biodiesel by 52-64%.

Human Health Criteria (Respiratory Effect-particulate emissions)

With regard to potential respiratory effects, our findings reinforce prior research examining health impacts of particulates (Hill 2009), and point to increased particulate concentrations associated with biofuel life cycles. That said, our findings are based on commercial and less than fully transparent data and require additional validation from subsequent and more geographically targeted research. Specifically, spatial and temporal research examining where and when these emissions occur is important to our greater understanding of population-weighted exposure to particulates and their potential impact to human health. This work is ongoing and may significantly impact the results of this assessment.

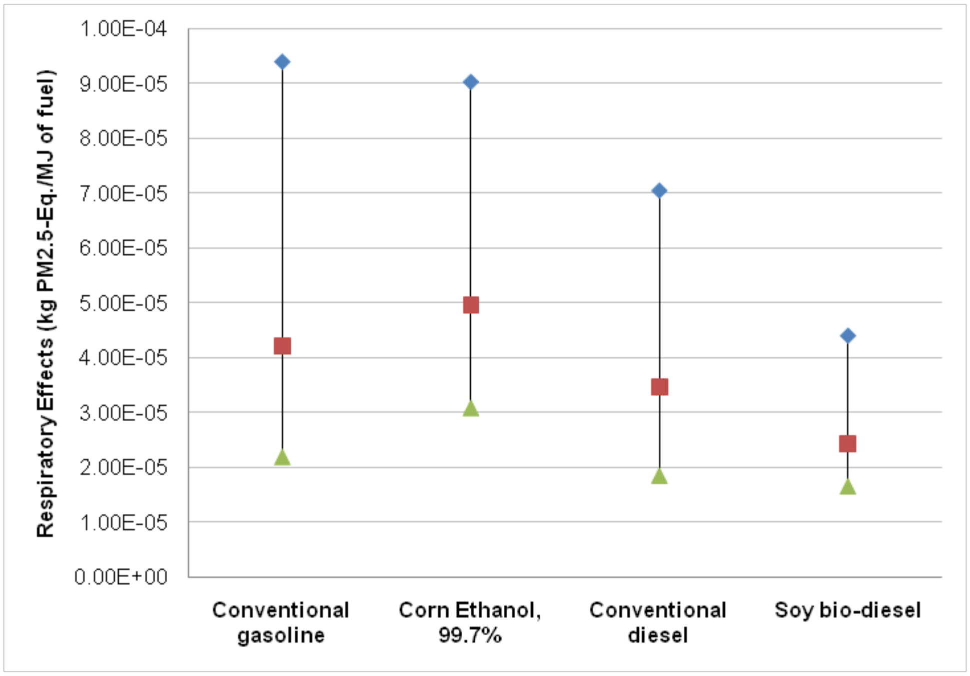


Figure 12: TRACI characterized result – human health criteria (respiratory effects).

Although a significant amount of research has taken place regarding health impacts of particulates the manner in which it is incorporated into TRACI was not determined over the course of this project. U.S. EPA identifies the eight largest pollution source categories of particulate emissions are: traffic, coal combustion, secondary sulfates, soil, salt, residual oil combustion, metals, and steel production. Research is needed to determine how particulate concentrations associated with biofuel life cycles compare with these sources and allow for it integration into the LCIA models investigated for this project (EPA (n)).

Summary of LCIA Results

In summary, while the popular conception of biofuels predominantly focuses on reduced climate change impacts, corn ethanol and soy biodiesel may produce additional environmental and human health impacts worthy of consideration by practitioners, policy makers and future research. Given the lack of previous research addressing environmental and human health impacts of first-generation biofuels, particularly with regard to toxics, our findings should be interpreted as directional in nature. It is the opinion of the authors that this work represents reasonable methodological approaches for an initial screening and assessment of broad environmental impacts of currently inventoried low-carbon transport fuels available in Minnesota. However, these methodologies are nascent and many data elements employed in this approach continue to be developed (particularly, issues of temporal and spatial specificity with regard to impact characterization). Therefore, caution should be taken when interpreting these results.

Results of running the modeling analytical framework indicate increased potential life cycle impacts of corn-based ethanol over conventional gasoline in the categories of eutrophication, photochemical oxidation, human cancer and human non-cancer, *though the significance and magnitude of these impacts are difficult to conclude with certainty.*

With regard to soy biodiesel, results from the modeling analytical framework indicates increased eutrophication impacts across this fuel's life cycle and decreased ozone depletion impacts. Again, these results should only be interpreted as directional indicators for further consideration and analysis. While it is important to recognize the potential environmental and health impacts of first generation biofuels (particularly those of corn ethanol) over conventional petro fuels, it is equally important to recognize that conventional petro fuels are increasingly "less conventional" as tar sand fuels play an exceedingly large role in the current Minnesota fuel mix and coal-to-liquid technologies are often projected as likely fuel substitutes in a petro-constrained world. In both cases, the current literature cites massive environmental impacts associated with these technologies vis-à-vis conventional light crude fuels – with little suggestion that human health impacts would improve and may in fact worsen as fuels take on the emission profiles of coal fired utilities. In addition to greater global warming impacts, gasoline and diesel from heavy oil sands are thought to significantly increase acidification and respiratory impacts, in addition to leaving large open pits, tailings, overburden piles and contributing to land fragmentation. Similarly, along with the higher GHG profile of coal-to-liquid fuels is also expected increased acidification impacts. It is uncertain to what effect, but coal-to-liquid fuels would also be accountable for the impacts associated with increased coal mining and the toxicity profiles of coal fired facilities. As the baseline gasoline and diesel LCIs increasingly include these higher impact inputs and processes, the relative performance of first generation biofuels with by default improve. These analyses were not possible at this time.

Consideration of Normalized and Weighted Results

Characterized results cannot provide comparisons across impact categories. Global warming potential is calculated based on a kg CO_2-equivalent characterization factor, which is not comparable to a human respiratory health effects potential in kg PM 2.5-equivalents. Each fuel pathway can only be compared within each category (i.e. GWP to GWP) but not across impact categories (i.e. GWP to eutrophication). In order to make these comparisons, the optional LCIA steps of Normalization and Weighting are necessary.

Normalization and weighting steps are optional elements in LCA, but are often useful to policy makers. Normalization transforms each characterized indicator results by dividing it by a reference value. The reference values have spatial and temporal scales of the environmental mechanism by impact category. Dividing each characterized value by a respective normalization reference creates a dimensionless value representing the significance of each impact category in time and/or space. Normalized results show duration and magnitude of the characterized impact within a given temporal and geographical system boundary under consideration. However, the normalized results still do not show which impact category is relatively more dominant than others. In order to accomplish this type of comparison weighting is required.

In the weighting step, a relative importance value is assigned to each impact category's normalized result. Since weighting is based on value choices, the results can be subjective. There are two types of methods commonly employed to develop weighting factors: distance-to-target method and panel methods (Lee et al. 2004). 'Distance-to-target' method is to relate relative significance of the impact category to a policy target, e.g. future reduction in targeted emissions as a proxy of urgency. This method varies by differences in the structure of equation that relates the targets to weighting factors. Thus, the choice is subjective to the equation used to develop the weighting factors. In contrast, the panel method quantifies relative significance of impact categories by a group of people asked to rate for the relative significance based on their expert opinion. The selected group may consist of various stakeholders: producers, consumers, governors, general public and LCA experts. Weighting remains a controversial element of LCA, as in other assessments—mainly because weighting involves social, political and ethical value choices. Not only are there values involved when choosing weighting factors, but also the type of method to use, and whether to use a weighting method at all. However, weighting methods include aspects from the natural, social and behavioral sciences – particularly, techniques, knowledge and theories developed within decision analysis and environmental economics.

Ultimately, in order to create institutionalized indexes or rating systems able to account for multiple environmental and/or social dimensions of transport fuels, some form of normalization and weighting is required. Early versions of this report included normalized and weighted assessment of corn ethanol and soy biodiesel, along with their conventional fuel counterparts. Normalization and weighting were developed based on pilot normalization factors under development within the EPA for inclusion in the TRACI model and weighting factors developed by National Institute of Standards and Technology (Gloria et al., 2007). However due to errors detected in TRACI normalization factors and the controversial and subjective nature of weighting, weighted findings are not reported. In short, the state of the art for the normalization and valuation (weighting) processes did not yet support inclusion, at the risk of possible misinterpretation and misuse.

Conclusion

This report provides an assessment of seven alternative fuel pathways likely to play important roles in the determination of Minnesota's transport fuel carbon intensity. While data availability constraints only allowed for a comprehensive life-cycle impact assessment for corn ethanol, soy biodiesel and their respective conventional substitutes (gasoline and petrol diesel), tar sands gasoline, coal-to-liquid fuels cellulosic ethanol, electric plug-in vehicles and natural gas vehicles are also examined for likely environmental and human health impacts. Results of running the modeling analytical framework suggest that first generation biofuels provide carbon reductions similar to previous studies employing similar systems boundary conditions (e.g. well-to-wheel, U.S. National assessment, excluding indirect land-use effects, etc.). Similar to previous studies, our assessment of these fuels find increased eutrophication impacts relative to conventional petro fuels, and, we highlight biodiesel's potential to reduce photochemical smog. Results also suggest potentially greater impacts associated with photochemical smog and human health (cancer and non-cancer) throughout the life cycle of producing and using first generation corn ethanol, *though significant additional research incorporating more robust and geographically specific methods is required to verify these early findings*.

Similar to other sections of this report, our investigations into non-carbon environmental impacts of a low carbon fuel policy revealed a wide range in data quality and availability. Certain data elements were found to be so uncertain—whether because there is no existing technology or because the methods of assessment are under active research—that they were not usefully examined in this section of the study.

While significant life cycle based research has been conducted to assess energy content and GHG emissions, little work has been done to explore non-carbon impacts of transport fuels that encompass many other environmental impacts of fuels across production, refining and use. Without equivalent data a statically compelling comparison of non-carbon impacts among all transportation fuels cannot be obtained. Work undertaken for this project discovered three primary areas in need of improved emissions data; 1) the extraction, processing, transporting, refining and use of petroleum and coal; 2) consensus-based characterization tools toward the specific pathways by impacts are estimated ; and 3) comparable tailpipe emissions data. A major overriding need is to integrate consistent metrics into existing data sets developed for dissimilar emissions sources so that aggregation is possible for use in LCIA modeling.

Both data and modeling will be improved over time through the efforts of current and subsequent researchers. Many of the data elements that are presently unknown or known only within extremely wide bounds will eventually be estimated with more certainty, at which time they might be usefully enfolded into modeling undertaken for this project. Findings reported here provide specific examples of uncertainties and reveal focused areas of research needed to reduce them. We urge readers not to make policy decisions based upon the specific numbers reported but rather use findings as early indicators of directional importance and to help prioritize research needed for comprehensive, comparative assessments of environmental implications for low carbon fuels standards.

References

AAAS (2009). “AAAS Policy Brief: Coal-to-Liquid Technology Issue Summary.” American Association for the Advancement of Science, Technology and Congress.

Aden, A. (2007). NREL. “Water Usage for Current and Future Ethanol Production.” Southwest Hydrology, Vol. 22 Sept/Oct. 2007.

Alberta Government (2008). ”Certification for land reclamation.” Accessed Aug. 25, 2009: http://environment.alberta.ca/695.html

Argonne National Laboratory. 2008. Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean Derived Biodiesel and Renewable Diesel.

Argonne National Laboratory. Wang, Michael; Han, Jeongwoo. November 2, 2010. Updated Greenhouse Gas Emissions

Arons S.M. et al. (2007). A Low-Carbon Fuel Standard for California, Part 1: Technical Analysis, www.energy.ca.gov/low_carbon_fuel_standard/.

Baker, K., Carlton, A. "Assessment of NOX & VOC in Urban Areas: Potential Implications for O3 Planning" U.S. Environmental Protection Agency, Office of Research and Development and Office of Air Quality Planning and Standards. 2010.

Bare, J., G. Norris, et al. (2002). "The tool for the reduction and assessment of chemical and other environmental impacts." Journal of Industrial Ecology 6(3-4): 49-78.

Bare, J.C., G.A. Norris, D.W. Pennington, and T. McKone. (2003). “TRACI – The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts.” *Journal of Industrial Ecology*, 6, 3.

Bare, J.C., T.P. Gloria, and G. Norris. (2006a). “Development of the Method and U.S. Normalization Database for Life Cycle Impact Assessment and Sustainability Metrics.” *Environmental Science and Technology*, 40, 16.

Bare, J.C. (2006b). “Risk Assessment and Life Cycle Impact Assessment (LCIA) for Human Health Cancerous and Noncancerous Emissions: Integrated and Complementary With Consistency Within the U.S. EPA.” *Human and Ecological Risk Assessment*, 12, 3.

Bergerson,J.,D. Keith. (2006). “*Life Cycle Assessment of Oil Sands Technologies.*” The Institute for Sustainable Energy,University of Calgary. www.iseee.ca.

Blanco-Canqui, H., R. Lal (2009).”Crop Residue Removal Impacts on Soil Productivity and Environmental Quality.” Critical Reviews in Plant Science. Vol.28: pgs. 39–163.

Brady, D., G. Pratt. (2007).”Volatile Organic Compound Emissions from Dry Mill Fuel Ethanol Production;” Journal of Air and Waste Mgmt. Vol. 57: pgs. 1091-1102. Sept. 2007.

Brandt, A.; A. Farrell. (2007). “Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources.” Climatic Change (2007) 84: 241-263.

C.A.R.B.` (2009). “Proposed Regulation to Implement the Low Carbon Fuel Standard. Volume II. Appendices”. California Air Resources Board. March 5, 2009.

Cardelino, C., Chameides, W.L., 1995. An observation-based model for analyzing ozone-precursor relationships in the urban atmosphere. Journal of Air and Waste Management Association 45, 161—180.

Carpenter, S. (2005). “Eutrophication of aquatic ecosystems: Bistability and soil phosphorus.” Proceedings of the National Academy of Sciences of the United States of America (PNAS). Vol 102 no. 29. July 19, 2005. Pgs. 10002-10005.

Charpentier, A., J. Bergerson, H. MacLean. (2009). “Understanding the Canadian oil sands industry's greenhouse gas emissions. “Environ. Res. Lett. 4 (January-March 2009) 014005.

Chameides,W.L.,P.S. Kasibhatla, J. Yienger, H. Levy II. (1994). “Growth of continental-scale metro-agroplexes, regional ozone pollution and world food production. Science 264 (5155): 74-77.

Chiu, Y., B. Walseth, S. Suh. (2009). “Water Embodied in Bioethanol in the United States.” Environmental Science Technology. Vol. 43. pgs. 2688 - 2692.

Cleary, J. (2008) NREL Powerpoint presentation. 1/25/2008.

Clement, C., S. Bricker, D. Pirhalla. (2001).”Eutrophic Conditions in Estuarine Waters. In: NOAA's State of the Coast Report.” Silver Spring, MD: National Oceanic and Atmospheric Administration.URL: http://state-of-coast.noaa.gov/bulletins/html/eut_18/eut.html

Clemente, Joyce S.; Fedorak, Phillip M. (2005). “A review of the occurrence, analyses, toxicity, and biodegradation of naphthenic acids.”*Chemosphere*. Vol. 60 Issue 5, p585-600 16p

Creutzig, F., Papson, A., Schipper, L., Kammen, D. (2009).”*Economic and environmental evaluation of compressed-air cars.*” Available: http://iopscience.iop.org/17489326/4/4/044011/fulltext#erl323265s4.3. Last accessed 3/3/11.

Curran, M.A. (2008). “Gap Analysis of Tools Used to Assess the Environmental and Socioeconomic Impacts of Biofuels in the United States.” Draft Copy.

Czarnecki J, B. Radoev, L.L.Schramm, R. Slavchev (2005). “On the nature of Athabasca Oil Sands.” *Adv. Colloid Interface Science.* 2005 Jun 30;114-115

Dincer, K. (2008). “Lower Emissions from Biodiesel Combustion.” Energy Sources, Part A, 30: 963-968.

Delucchi M.A. and Lipman T. (2003). A life cycle emissions model (LEM): Life cycle emissions from transportation fuels, motor vehicles, transportation modes, electricity use, heating and cooking fuels, materials, Report UCD-ITS-RR-03-17A, Institute of Transportation Studies, University of California, Davis, CA, US, 2005

Delucchi, M. (2006). Draft Manuscript: "Lifecycle Analysis of Biofuels." Rep. UCD-ITS-RR-06-08. University of California-Davis. Institute of Transportation Studies. Many 2006. pg. 1-80.

DNR (2005). Wisconsin Dept. of Natural Resources. "Ozone Air Quality Effects of a 10% Ethanol Blended Gasoline in Wisconsin." DNR Bureau of Mgmt, Madison,WI.

Dorn, P.B., J. P. Salanitro, S. H. Evans, L. Kravetz (1993). "Assessing the aquatic hazard of some branched and linear nonionic surfactants by biodegradation and toxicity." *Environmental Toxicology and Chemistry.* Vol. 12. Issue 10. Pages. 1751-1762.

Ecoinvent (2007) Swiss Centre for Life Cycle Inventories. Overview and MethodologyData v2.0 Rolf Frischknecht, Niels Jungbluth (Editors). Online: http://www.ecoinvent.org/fileadmin/documents/en/01_OverviewAndMethodology.pdf

EIA (2007). Energy Information Administration. Official Energy Statistics from the U.S. Government. Biofuels in the U.S. Transport Sector. Release date: February 2007.

Elshorbagy, A.,A. Jutla, L. Barbour, J. Kells (2005). "Systems dynamics approach to assess the sustainability of reclamation of disturbed watersheds." Canadian Journal of Civil Engineering; Vol. 32. Issue 1; Feb. 2005; pg. 144-158.

Energy Independence and Security Act of 2007 (EISA) (2007). A Summary of Major Provisions. Online: http://energy.senate.gov/public/_files/RL342941.pdf

EPA (a). "Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User's Guide and System Documentation," U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory. EPA/600/R-02/052 www.epa.gov/nrmrl/pubs/600r02052/600R02052.pdf

EPA (b) (2002). "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions." Draft Technical Report. EPA420-P-02-001. Washington DC.

EPA (c) (2004). "Photochemical smog-what it means for us." EPA 90/04. Online: http://www.epa.sa.gov.au/pdfs/info_photosmog.pdf

EPA (d) (2010). Regulation of fuels and fuel additives: Changes to Renewable Fuel Standard Program: Final rule. Available at http://www.regulations.gov/search/Regs/contentStreamer?objectId=0900006480ac93f2&988disposition=attachment&contentType=pdf

EPA (e). 2010. Renewable fuel standard program (RFS2) regulatory impact analysis. EPA-420-R-10-006. Available at: http://www.epa.gov/otaq/renewablefuels/420r10006.pdf .

EPA (f) (2006). Alternative Fuels: Biodiesel. EPA420-F-06-044. October 2006.

EPA (g) (2007). "Greenhouse Gas Impacts of Expanded Renewable and Alternative Fuels Use." EPA420-F-07-035, April 2007.

EPA (h) (2008). "National Ambient Air Quality Standards (NAAQS)- PM 2.5". Last updated on Monday, July 14th, 2008. Online: http://www.epa.gov/ttnnaaqs/pm/pm25_index.html

EPA (i) (2009). Civil Enforcement Document. Corn Plus CAA Ethanol Settlement. Last updated Jan. 2, 2009. Online: www.epa.gov.compliance/resources/cases/civil/caa/cornplus.html

EPA (j). Ecological Soil Screening Level for Aluminum Interim Final OSWER Directive 9285.7-60) http://www.epa.gov/ecotox/ecossl document http://www.epa.gov/ecotox/ecossl/pdf/eco-ssl_aluminum.pdf

EPA (k). Integrated Science Assessment (ISA) for Oxides of Nitrogen and Sulfur Ecological Criteria (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-08/082F, 2008. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=201485

EPA (l). The Accidental Release Information Program (ARIP) database (July, 1999) (ZIP) (4 files, 1.1MB) is contained in a zip file that contains the ARIP database file (DBF format) and supporting documentation.

EPA (m). Ecological Soil Screening Levels for Lead, Internal Final, OSWER Directive 9285.7-70, p2.

EPA (n). Particulate Exposure Assessment Research: Supplement to *Accomplishments of the Particulate Matter (PM) Centers (1999-2005) Outdoor Exposure PM2.5 Components 40.* http://www.epa.gov/ncer/science/pm/2008sab/supp_reports_accomplishmentspm_centers_1999-2005[1].pdf

EPA (o). 1999. "Science Algorithms of EPA Models-3 Community Multiscale Air Quality." (CMAQ Modeling System D.W. Byun and J.K.S. Ching,Eds. EPA/600/R-99/030, Office of Research and Development), and U.S EPA Photochemical Assessment Monitoring Program http://www.epa.gov/oar/oaqps/pams/analysis/ozone/ozone.html

EPA (p). National Ambient Air Quality Standards (NAAQS): Characterizing Ozone and Modeling Tools Used in This Analysis http://www.epa.gov/ttn/ecas/regdata/RIAs/2-ozoneriachapter2.pdf

EPA (q). (2011)."*Hydraulic Fracturing.*" Available: http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/index.cfm Last accessed 3/3/11.

EPA (r). (2009). Health Effects of Ozone in the General Population. Available 5/24/2011: http://www.epa.gov/apti/ozonehealth/population.html

EPA (s). (2002). "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions." Draft Technical Report. EPA420-P-02-001. Washington DC.

EPA (t). 2009. The Effects of Mountaintop Mines and Valley Fills on Aquatic Ecosystems of the Central Appalachian Coalfields. Office of Research and Development, National Center for Environmental Assessment, Washington, DC. EPA/600/R-09/138A.

Fargione, J., J. Hill, D. Tilman, S. Polasky, P. Hawthorne (2008). "Land clearing and the biofuel debt" *Science* **319**, 1235.

Farrell A., R. Plevin, B.Turner, A. Jones, M. O'Hare, D. Kammen (2006). "Ethanolcan contribute to energy and environmental goals. " *Science 311:506–8.*

Fthenakis, V. and Kim, H. C. (2009). "Land use and electricity generation: A life-cycle analysis." *Renewable and Sustainable Energy Reviews*. 13 (6-7), p1465-1474.

Fang, T., Y.C. Lin, T.M. Foong, C.F. Lee (2008). "Reducing NOx Emissions from a Biodiesel-Fueled Engine by Use of Low-Temperature combustion." Environmental Science Technology. Vol. 42, 8865-8870.

Furey, Robert L. SAE International, paper number 852116, "Volatility Characteristics of Gasoline-Alcohol and Gasoline-Ether Fuel Blends." http://papers.sae.org/852116

Gloria, T., B. Lippiatt, et al. (2007). "Life cycle impact assessment weights to support environmentally preferable purchasing in the United States." Environ. Sci. Technol 41(21): 7551-7557.

Hackney, J and Neufville, R. (2001). "Life cycle model of alternative fuel vehicles: emissions, energy, and cost trade-offs." *Transportation Research Part A: Policy and Practice*. 35 (3), p243-266.

Harto, C., R. Meyers, E. Williams (2007). "Life Cycle Water Consumption of Alternative, Low-Carbon Transportation Energy Sources". Arizona Water Institute. Online: www.azwaterinstitute.org/media/Harto%20Final%20Report

Hauschild, M.Z., M. Huijbregts, O. Jolliet, M. Macleod, M. Margni, D. van de Meent, R.K. Rosenbaum, T.E. McKone (2008). "Building a Model Based on Scientific Consensus for Life Cycle Impact Assessment of Chemicals: The Search for Harmony and Parsimony" Environmental Science & Technology. Vol 42(19), 7032-7037

Hazewinkel, R., A. Wolfe, S. Pla, C. Curtis, K. Dadley. (2008). "Have atmospheric emissions from the Athabasca Oil Sands impacted lakes in northeastern Alberta, Canada?" Candadian Journal of Fishery Aquatic Science. Vol 65 1554-1567.

Hess, P., M. Johnson,B. Brown-Steiner, T. Holloway, J. de Andrade,P. Artaxo. (2008) "Air Quality Issues Associated with Biofuel Production and Use; Biofuels: Environmental Consequences & Implications of Changing Land Use." Proceedings of the Scientific Committee on Problems of the Environment (SCOPE). pgs. 169 -194.

Heuss, J., Kahlbaum, D., and Wolff, G., 2003. Journal of Air and Waste Management Association 53, 772-787. And related papers in the July 2003 AWMA Journal.

Hill J., E. Nelson, D.Tilman,S. Polasky, D. Tiffany.(2006). "Environmental, economic, andenergetic costs and benefits of biodiesel and ethanol biofuels." *Proc. Natl. Acad. Sci. USA*103:11206–10

Hill, J.,S. Polasky, E. Nelson, D. Tilman, J. Huo, L. Ludwig, J. Neumann, H. Xheng, D. Bonta. (2009). "Climate Change and Health Costs of Air Emissions from Biofuels and Gasoline." PNAS. Vol. 106. No. 6 February 10, 2009. 2077-2082.

Höök,M., K. Aleklett (2009). A review on coal to liquid fuels and its coal consumption . International Journal of Energy Research. www.tsl.uu.se/uhdsg/Publications/CTL_Article.pdf

Howarth R., H. Pearl (2008). "Coastal marine eutrophication: Control of both nitrogenand phosphorus is necessary." *Proc Natl Acad Sci USA* 105:E103.

Hudman, R C. "North American influence on tropospheric ozone and the effects of recent emission reductions: Constraints from ICARTT observations." Journal of geophysical research. (2009).

Huston, M.A. (1994) *Biological Diversity*, Cambridge University Press: 546–548.

IPCC (Intergovernmental Panel on Climate Change). 2006. Volume 4 Agriculture, Forestry and Other Land Use. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

IPCC (1996). Technical Paper I - Technologies, Policies and Measures for Mitigating Climate Change. RT Watson, MC Zinyowera, RH Moss (Eds). IPCC, Geneva, Switzerland. pp 84. November 1996.

ISO (2006). Environmental Management - Life-Cycle Assessment-Principles and Framework, International Standard 14040. Geneva, Switzerland, International Organization for Standardization (ISO).

ISO (2006). Environmental Management - Life-Cycle Assessment-Principles and Framework, International Standard 14042. Geneva, Switzerland, International Organization for Standardization (ISO).

ISO (2006). Environmental Management - Life-Cycle Assessment-Principles and Framework, International Standard 14044. Geneva, Switzerland, International Organization for Standardization (ISO).

Jacobson, M. Z. (2007). "Effects of Ethanol (E85) versus Gasoline Vehicles on Cancer and Mortality in the United States." Environmental Science & Technology 41(11): 4150-4157.

Jaramillo, P., M. Griffin, S. Matthews. (2008). " Comparative Analysis of the Production Costs and Life-Cycle GHG Emissions of FT Liquid Fuels from Coal and Natural Gas." Environmental Science & Technology. Vol. 42. 7559-7565.

Jordaan, S., D. Keith, B. Stelfox. (2009). "Quantifying land use of oil sands production: a life cycle perspective." Environmental Research Letters. 4 (April-June 2009) 024004.

Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist Emmenegger, M., Gnansounou, E., Kljun, N., Schleiss, K., Spielman, M., Stetter, C., Sutter, J. 2007: "Life Cycle Inventories of Bioenergy. Ecoinvent report No. 17," Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

Kaplan, S. and Sargent, R. (2010)."*Plug-In Cars Powering America Toward a Cleaner Future.*"Available: http://www.environmenttexas.org/uploads/bd/93/bd931b95c6a88f1cb595f86705248535/TXE-Plug-ins-text.pdf. Last accessed 3/3/11.

Keeney, D., M. Muller. (2006). "Water Use by Ethanol Plants: Potential Challenges." Institute for Agriculture and Trade Policy; Oct. 2006.

Kim, S., B. Dale. (2005). "Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. " Biomass and Bioenergy. Vol. 29 (2005) pg. 436-439.

Kim, S., B. Dale. (2008). "Life Cycle assessment of fuel ethanol derived from corn grain via dry milling. Bioresource Technology." Vol. 99. (2008) pgs. 5250-5260.

Kintner-Meyer, M., Schneider, K., Pratt, R. *Impacts Assessment of Plug-In in Hybrid Vehicles on Electronic Utilities and Regional U.S. Power Grids Part 1: Technical Analysis*. Pacific Northwest National Laboratory. http://www.ferc.gov/about/com-mem/wellinghoff/5-24-07-technical-analy-wellinghoff.pdf

Lane, B. (2006). "Life Cycle Assessment of Vehicle Fuels and Technologies." Final report . London Borough of Camden. March 2006.

Landis, D., M. Gardiner, W. van der Werf, S. Swinton. (2008). " Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes." Proceedings of the National Academy of Sciences of the United States of America (PNAS). Vol. 105 no. 51. December 23, 2008.

Lee, K., and A. Inaba (2004)., *Life Cycle Assessment: Best Practices of ISO 14040 Series,* Suwon, Korea: Center for Ecodesign and LCA (CEL), Ajou University, 2004

Lippiatt, B. (2007). "BEES 4.0: Building for Environmental and Economic Sustainability Technical Manual and User Guide." Office of Applied Economics, National Institute of Standards and Technology, Gaithersburg, MD.

Liska, A., H. Yang, V. Bremer, T. Klopfenstein, D. Walters, G. Erickson, K. Cassman. (2008). "Improvements in Life Cycle Energy Efficiency and GHG Emissions of Corn-Ethanol." Journal of Industrial Ecology; 2008.

Madill, R., M.T. Orzechowski, G. Chen, B. Brownlee, N. Bunce (2001) "Preliminary risk assessment of the wet landscape option for reclamation of oil sands mine tailings: Bioassays with mature fine tailings pore water. " *Environmental Toxicology.* Vol. 16. Issue 3. pp. 197-208.

Marano, J. (2009). GHG Profiles for Distillate Fuels Produced from Conventional Petroleum, Oil Sands, Shale Oil and Xtl. Energy Procedia 1 (2009) 3795-3799.

McCann, T.**,** P. Magee (1999). "Crude oil greenhouse gas life cycle analysis helps assign values for CO2 emissions trading." Oil & Gas Journal. Feb. 1999. Vol. 97. Iss. 8. pp.38-43.

Mintz, M., Han, J., Wang, M., Saricks, C. (2010)."*WELL-TO-WHEELS ANALYSIS OF LANDFILL GAS-BASED PATHWAYS AND THEIR ADDITION TO THE GREET MODEL.*" Available: http://www.transportation.anl.gov/pdfs/TA/632.PDF. Last accessed 3/3/11.

Mintz-Testa, B. (2008). "Tar on Tap." *Mechanical Engineering.* Dec. 2008. I30, 12.

NAS (2009). "Liquid Transportation Fuels from Coal and Biomass." National Academy of Sciences. Online: http://dels.nas.edu/dels/rpt_briefs/alt_fuels_brief_final.pdfNETL/

National Energy Technology Laboratory (2008). "Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels." November 26, 2008 DOE/NETL-2009/1346. Online: http://www.netl.doe.gov/energy-analyses/pubs/NETL%20LCA%20Petroleum-based%20Fuels%20Nov%202008.pdf

National Research Energy Laboratory (2006). Research Review. Online: http://www.nrel.gov/research_review/pdfs/2006/40764.pdf

National Resource Council (1991): Rethinking the Ozone Problem in Urban and Regional Air Pollution. Washington: National Academy Press.

National Resource Defense Council (NRDC) (2008). "There is no such thing as "Clean Coal"" Online: http://www.nrdc.org/globalwarming/files/coalmining.pdf.

National Response Center Spills and Accidents database. http://www.rtknet.org/db/erns

National Agricultural Statistics Service, 2008 FRIS – GENERAL DATA Table 28. Estimated Quantity of Water Applied and Primary Method of Distribution by Selected Crops Harvested: 2008 and 2003 http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/fris08_1_28.pdf

NaturalGas.org. (2010). *Natural Gas and the Environment.* Available: http://www.naturalgas.org/environment/naturalgas.asp. Last accessed 3/3/11.

Natural Gas Use in Transportation Roundtable (2010). *Natural Gas Use in the Canadian Transportation Sector Deployment Roadmap*. Ottawa. p1-54.

Nemry, F., Leduc, G., Munoz, A (2009).”Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency.” Luxembourg: European Communities. p1-37.

Nigge, K. (2000). “Life Cycle Assessment of Natural Gas Vehicles.” *6th Annual European NGV Conference*. p 369.

National Renewable Energy Laboratory (Internet), *Life-Cycle Inventory Database*, August 2008 (Accessed June 2009), http://www.nrel.gov/lci/database/.

Norris, G. 2002. Impact characterization in the tool for the reduction and assessment of chemical and other environmental impacts: Methods for acidification, eutrophication, and ozone formation. Journal of Industrial Ecology 6(3/4): 83 – 105.

Notter, D., Gauch, M., Widmer, R., Waeger, P., Stamp, A., Althaus, H. (2010). “Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles.” *Environmental Science & Technology*. 1 (1), p1-2

Nowakowski, S. (2008). Coal to Liquids Water Usage. Prepared for November 8 ETIC meeting http://leg.mt.gov/content/committees/interim/2007_2008/energy_telecom/assigned_studies/coal2liquidpage/Coal2liquidone.pdf

Patel, S. (2007). “Canadian oil sands: Opportunities, Technologies and Challenges.” Special Report. Hydrocarbon Processing. February 2007. pgs. 65 – 73.

Patzek, T. (2007). “Problems with Coal-to-liquids in Montana.” Department of Civil and Environmental Engineering, University of California, Berkeley. May 23, 2007.

Pimentel D. and Patzak T. (2005). “Ethanol production using corn, switchgrass, and wood; Biodiesel production using soybean and sunflower,” *Natural Resources Research*, vol. 14, No. 1, Jan. 2005, pp. 65-76

Plevin, R. (2009). Modeling corn ethanol and climate: A critical comparison of the BESS and GREET models. Journal of Industrial Ecology 13(4):495-507.

Pollution Control Agency (a). http://www.pca.state.mn.us/index.php/topics/mercury/mercury-in-minnesota-research-and-reduction-initiative.html?menuid=&missing=0&redirect=1 Department of Health fish consumption advisory http://www.health.state.mn.us/divs/eh/fish

Pollution Control Agency (b). http://www.pca.state.mn.us/index.php/water/water-types-and-programs/minnesotas-impaired-waters-and-tmdls/tmdl-projects/special-projects/statewide-mercury-tmdl-pollutant-reduction-plan.html and Sources of Mercury Pollution and the Methylmercury Contamination of Fish in Minnesota (p-p2s4-06)Powers (2005). NREL. "Water Use for Production." Power point presentation.

Powers, S.E. (2005) *Quantifying Cradle-to-Farm Gate Life Cycle Impacts Associated with*

Fertilizer Used for Corn, Soybean, and Stover Production, NREL/TP-510-37500, technical report prepared for National Renewable Energy Laboratory, Golden Colo., May. Online: http://www.transportation.anl.gov/pdfs/TA/377.pdf

Range Fuels (2009). Biomass Energy. Online: http://www.rangefuels.com/

Rochette P, H. Janzen (2005). "Towards a revised coefficient for estimating N2O emissions from legumes." *Nutrient Cycling in Agroecosystems* **73,** 171–179.

Saaty, T. (1980). "The Analytic Hierarchy Process: Planning Setting Priorities, Resource Allocation." Mcgraw- Co.. New York. ISBN-10: O07O543712.

Sagar, A., S. Kartha. (2007). "Bioenergy and Sustainable Development?" Annual Review Environmental Resources. Vol. 32. pgs. 131-157.

Schramm, L.L., E. N. Stasiuk, M. MacKinnon (2000). "Surfactants in Athabaska Oil Sands: Slurry Conditioning, Floatation, Recovery and Tailings Processes." Petroleum Recovery Instititute and Chemistry Dept. University of Calgary.

Scott, A. C., W. Zubot, M.D. MacKinnon, D. W. Smith, P.M. Fedorak (2007) "Ozonation of oil sands process water removes naphthenic acids and toxicity." *Chemosphere*, Vol. 71. Issue 1, pp. 156-160.

Shumway, S. E. (1990). "A Review of the Effects of Algal Blooms on Shellfish and Aquaculture." *Journal of the World Aquaculture Society* 21(2):65-104.

Searchinger, T., R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes,T. Yu. (2008). "Use of US Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change." Science; Vol 319, pgs. 1238-1240; Feb. 29, 2008.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, H. Shapouri. (1998). " Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus." NREL/SR-580-24089.

Sillman, S. 1999. The relation between ozone, NOx and hydrocarbons in urban and polluted rural environments. Atmospheric Environment 33: 1821 — 1845.

Simpson, T., A. Sharpley, R. Howarth, H. Paerl, K. Mankin. (2008). "The New Gold Rush: Fueling Ethanol Production while Protecting Water Quality." Journal of Environmental Quality 37:318–324.

Small, K A., and Kazimi, C. "On the costs of air pollution from motor vehicles." *Journal of transport economics and policy* 29.1 (1995):7.

Tegtmeier E, M. Duffy (2004)."The external costs of agricultural production in the United States." *Int. J. Agric. Sust.* 2(1), 155-175

"Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User's Guide and System Documentation," 1.4 Limitations of TRACI, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory. EPA/600/R-02/052 www.epa.gov/nrmrl/pubs/600r02052/600R02052.pdf

Toffel, M.W., J. D. Marshall (2008). "Improving Environmental Performance Assessment: A Comparative Analysis of Weighting Methods Used to Evaluate Chemical Release Inventories." Journal of Industrial Ecology, Vol 8, No. 1-2. pp. 143-172.

Tenenbaum, D. (2009). "Oil Sands Development." Environmental *Health Perspectives*, *117*(4), A150-A156.

Thomas-Muller, C. (2008). "Tar Sands." Canadian Dimension. Mar/Apr. 2008, Vol. 42 Issue 2, p11-14.

Tilman, D., J. Hill, C. Lehman. (2006). "Carbon-Negative Biofuels from Low-Input High Diversity Grassland Biomass." Science; Vol 314; Dec. 8, 2006.

Uihlein, A., L. Schebek. (2009). "Environmental impacts of a lignocellulose feedstock biorefinery system: An assessment." Biomass and Bioenergy. Vol 33. Pgs. 793-802.

United Soybean Board. February 2010. Life Cycle Impact of Soybean Products and Soy Industrial Products. Available at: http://www.soybiobased.org/wp-content/uploads/2010/02/Soy-Life-Cycle-Profile_-WhitePaper-.pdf

United Soybean Board. 2010. Cycle Impact of Soybean Products and Soy Industrial Products. Available at: http://www.soybiobased.org/wp-content/uploads/2010/02/Soy-Life-Cycle-Profile_-WhitePaper-.pdf.

United States Department of Agriculture (USDA) (2003) "Farm and Ranch Irrigation Survey(2003)," Volume 3, Special Studies, Part 1.

United States Department of Energy (USDOE) (2006). "Energy Demands on Water Resources." REPORT TO CONGRESS ON THE INTERDEPENDENCY OF ENERGY AND WATER. Online: http://www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf

United States Department of Energy (US DOE) (2009). EERE. Internet: www.afdc.energy.gov/afdc/sabre/methodology.html Accessed July 2009

United States Department of Energy (US DOE) (2011). "*Natural Gas Import & Export Regulation - Frequently Asked Questions.*" Available: http://fossil.energy.gov/programs/gasregulation/analyses/Frequently_Asked_Questions.html. Last accessed 3/1/11.

U.S. Oil Pollution Act (OPA) §4301(a) and (c) required increased reporting and fine for failing to notify the appropriate Federal agency of a discharge. http://www.epa.gov/oem/content/lawsregs/opaover.htm

United States Geological Survey (USGS)(2008).. Mueller, D., D. Helsel. "Nutrients in the Nation's Waters--Too Much of a Good Thing?" USGS Circular 1136. September 8, 2008. Online: http://toxics.usgs.gov/definitions/eutrophication.html

Unnasch. S., et al. (2009). "Assessment of Life Cycle GHG Emissions Associated with Petroleum Fuels, Life Cycle Associates Report LCA-6004-3P. 2009. Prepared for New Fuels Alliance.

Van Belle, J.F. (2006). "A model to estimate fossil CO2 emissions during the harvesting of forest residues for energy-with an application on the case of chipping." Biomass and Bioenergy. Vol. 30. pgs. 1067-1075.

Van Vliet, O., A. Faaij, W. Turkenburg.(2009). "Fischer–Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis." Energy Conversion and Management Vol.50 (February, 2009) pgs. 855–876.

Von Blottnitz, H., M.A. Curran (2007). "A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective," Journal of Cleaner Production, Volume 15, Issue 7, 607-619.

Vos, J. (2007). "The Ecological Footprint of Biofuels." Sustainability Planning Partners. Mill Valley, California.

Wang, M., M. Wu, H. Huo. (2007)."Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types." Environmental Research Letters 2 (April–June 2007) 024001.

Wiedinmyer, C., X. Tie, A. Guenther, R. Neilson, C. Granier.(2006). "Future Changes in Biogenic Isoprene Emissions: How Might They Affect Regional and Global Atmospheric Chemistry?" *Earth Interactions*, Vol. 10 Issue 1, p1-19.

Wilcove D. S., C. H. Mclellan, A. P. Dobson (1986). "Habitat fragmentation in the temperate zone," *International Journal of Shape Modeling*,WI.

Woods, J., A. Bauen. (2003). "Technology Status Review and Carbon Abatement Potential of Renewable Transport Fuels (RTF) in the UK." DTI; AEAT. B/U2/00785/REP URN 03/982:1–150. Available online at http://www.dti.gov.uk/renewables/publications/pdfs/

Worldwatch Institute (2006). "Biofuels for transport: global potential and implications for energy and agriculture." Prepared by Worldwatch Institute for the German Ministry of Food, Agriculture and Consumer Protection in coordination with the German Agency for Technical Cooperation and the German Agency of renewable resources. Earthscan: London

Woynillowicz, D. (2007). "Tar Sands Fever." World Watch, Vol. 20, Issue 5, Sept/Oct. 2007

WSTB (2008). "Water Implications of Biofuels Production in the United States. " Water Science and Technology Board. The National Academies Press. Paperback book. 2008.

Zah, R., H. Boni, M. Gauch, R. Hischier, M. Lehmann, P. Wager. (2007). "Environmental Imapct Assessment of Biofuels." Empa, Swiss Federal Institute for Materials Science and Technology. www.empa.ch/tsl .

Appendix A. TRACI Characterization Factors for Nine Impacts Categories

Chemical/substance	Unit	Destination category	Destination subcategory	Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
				kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
1,4-Butanediol	kg	air	high population density									
2-Propanol	kg	air	high population density					0.16121				0.012
Acenaphthene	kg	air	high population density						0.102			0.176
Acenaphthene	kg	air	low population density						0.102			
Acenaphthene	kg	air	unspecified						0.102			
Acetaldehyde	kg	air	high population density					1.4444	0.00344	0.00437		4.25
Acetaldehyde	kg	air	low population density					1.4444	0.00344			
Acetaldehyde	kg	air	unspecified					1.4444	0.00344			
Acetic acid	kg	air	high population density					0.13347				
Acetic acid	kg	air	low population density					0.13347				
Acetic acid	kg	air	unspecified					0.13347				
Acetone	kg	air	high population density					0.095806	0.0132			0.086
Acetone	kg	air	low population density					0.095806	0.0132			
Acetonitrile	kg	air	low population density									50.5
Acrolein	kg	air	high population density					1.6073	7.12			2370
Acrolein	kg	air	low population density					1.6073	7.12			
Acrolein	kg	air	unspecified					1.6073	7.12			
Acrylic acid	kg	air	high population density									31.4
Actinides, radioactive, unspecified	kBq	air	low population density									
Aerosols, radioactive, unspecified	kBq	air	low population density									
Aldehydes, unspecified	kg	air	high population density									
Aldehydes, unspecified	kg	air	low population density									
Aldehydes, unspecified	kg	air	unspecified									
Aluminium	kg	air	high population density						7030			11200
Aluminium	kg	air	low population density						7030			
Aluminium	kg	air	low population density, long-term						7030			
Aluminium	kg	air	unspecified						7030			
Ammonia	kg	air	high population density		95.5		0.1054		0.0738			3.21
Ammonia	kg	air	low population density						0.0738			
Ammonia	kg	air	unspecified						0.0738			
Ammonium carbonate	kg	air	high population density									
Antimony	kg	air	high population density									2800000
Antimony	kg	air	low population density									
Antimony	kg	air	low population density, long-term									
Antimony	kg	air	unspecified									
Antimony-124	kBq	air	low population density									
Antimony-125	kBq	air	low population density									
Argon-41	kBq	air	low population density									
Arsenic	kg	air	high population density						209	8500		469000
Arsenic	kg	air	low population density						209			
Arsenic	kg	air	low population density, long-term						209			
Arsenic	kg	air	unspecified						209			
Arsine	kg	air	high population density									
Barium	kg	air	high population density									18000
Barium	kg	air	low population density									
Barium	kg	air	low population density, long-term									
Barium	kg	air	unspecified									
Barium-140	kBq	air	low population density									
Benzal chloride	kg	air	unspecified									
Benzaldehyde	kg	air	high population density					-0.099677				
Benzene	kg	air	high population density					0.19863	0.00634	1		14.6
Benzene	kg	air	low population density					0.19863	0.00634			
Benzene	kg	air	lower stratosphere + upper troposphere						0.00634			
Benzene	kg	air	unspecified					0.19863	0.00634			
Benzene, ethyl-	kg	air	high population density					0.59032	0.00338			
Benzene, ethyl-	kg	air	low population density					0.59032	0.00338			
Benzene, hexachloro-	kg	air	high population density						273	82.7		1040
Benzene, hexachloro-	kg	air	unspecified						273			
Benzene, pentachloro-	kg	air	high population density						78.5			1350
Benzo(a)pyrene	kg	air	high population density						0.0688	914		
Benzo(a)pyrene	kg	air	low population density						0.0688			
Benzo(a)pyrene	kg	air	unspecified						0.0688			
Beryllium	kg	air	high population density							11.6		168000
Beryllium	kg	air	low population density									
Beryllium	kg	air	low population density, long-term									
Beryllium	kg	air	unspecified									
Boron	kg	air	high population density									
Boron	kg	air	low population density									
Boron	kg	air	low population density, long-term									
Boron	kg	air	unspecified									
Boron trifluoride	kg	air	high population density									
Bromine	kg	air	high population density									
Bromine	kg	air	low population density									
Bromine	kg	air	unspecified									
Butadiene	kg	air	low population density					2.6008		0.414		1.33
Butadiene	kg	air	lower stratosphere + upper troposphere									
Butadiene	kg	air	unspecified					2.6008				
Butane	kg	air	high population density					0.28573				
Butane	kg	air	low population density					0.28573				
Butane	kg	air	unspecified					0.28573				
Butanol	kg	air	high population density					0.70056				0.911
Butene	kg	air	high population density					1.7524				
Butyrolactone	kg	air	high population density									
Cadmium	kg	air	high population density						6.26	25		387000
Cadmium	kg	air	low population density						6.26			
Cadmium	kg	air	low population density, long-term						6.26			
Cadmium	kg	air	lower stratosphere + upper troposphere						6.26			
Cadmium	kg	air	unspecified						6.26			

Chemical/substance	Unit	Destination category	Destination subcategory	Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
				kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Calcium	kg	air	high population density									
Calcium	kg	air	low population density									
Calcium	kg	air	low population density, long-term									
Carbon dioxide, biogenic	kg	air	high population density									
Carbon dioxide, biogenic	kg	air	low population density									
Carbon dioxide, biogenic	kg	air	unspecified									
Carbon dioxide, fossil	kg	air	high population density	1								
Carbon dioxide, fossil	kg	air	low population density									
Carbon dioxide, fossil	kg	air	lower stratosphere + upper troposphere									
Carbon dioxide, fossil	kg	air	unspecified									
Carbon dioxide, land transformation	kg	air	low population density									
Carbon disulfide	kg	air	high population density									188
Carbon disulfide	kg	air	low population density									
Carbon disulfide	kg	air	unspecified									
Carbon monoxide, biogenic	kg	air	high population density					0.013387				
Carbon monoxide, biogenic	kg	air	low population density					0.013387				
Carbon monoxide, fossil	kg	air	high population density	1.57				0.013387				
Carbon monoxide, fossil	kg	air	low population density					0.013387				
Carbon monoxide, fossil	kg	air	lower stratosphere + upper troposphere									
Carbon monoxide, fossil	kg	air	unspecified					0.013387				
Carbon-14	kBq	air	low population density									
Cerium-141	kBq	air	low population density									
Cesium-134	kBq	air	low population density									
Cesium-137	kBq	air	low population density									
Chlorine	kg	air	high population density									
Chlorine	kg	air	low population density									
Chlorine	kg	air	low population density, long-term									
Chlorine	kg	air	unspecified									
Chloroform	kg	air	high population density	30					0.0398	0.813		12.5
Chloroform	kg	air	low population density						0.0398			
Chloroform	kg	air	unspecified						0.0398			
Chlorosilane, trimethyl-	kg	air	high population density									
Chromium	kg	air	high population density						1050	69.9		57700
Chromium	kg	air	low population density						1050			
Chromium	kg	air	lower stratosphere + upper troposphere						1050			
Chromium	kg	air	unspecified						1050			
Chromium VI	kg	air	high population density						1050	69.9		57700
Chromium VI	kg	air	low population density						1050			
Chromium VI	kg	air	low population density, long-term						1050			
Chromium VI	kg	air	unspecified						1050			
Chromium-51	kBq	air	low population density									
Cobalt	kg	air	high population density									29000
Cobalt	kg	air	low population density									
Cobalt	kg	air	low population density, long-term									
Cobalt	kg	air	unspecified									
Cobalt-58	kBq	air	low population density									
Cobalt-60	kBq	air	low population density									
Copper	kg	air	high population density						21700			13200
Copper	kg	air	low population density						21700			
Copper	kg	air	low population density, long-term						21700			
Copper	kg	air	lower stratosphere + upper troposphere						21700			
Copper	kg	air	unspecified						21700			
Cumene	kg	air	high population density					0.49331				0.33
Cumene	kg	air	low population density					0.49331				
Cumene	kg	air	unspecified					0.49331				
Cyanide	kg	air	high population density									1370
Cyanide	kg	air	low population density									
Cyanide	kg	air	unspecified									
Dinitrogen monoxide	kg	air	high population density	300								
Dinitrogen monoxide	kg	air	low population density									
Dinitrogen monoxide	kg	air	lower stratosphere + upper troposphere									
Dinitrogen monoxide	kg	air	unspecified									
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	air	high population density						8050	313000000		3.46E+11
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	air	low population density						8050			
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	air	unspecified						8050			
Ethane	kg	air	high population density					0.0705				
Ethane	kg	air	low population density					0.0705				
Ethane	kg	air	unspecified					0.0705				
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	air	high population density	1.41E+03								
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	air	low population density									
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	air	unspecified									
Ethane, 1,1,1-trichloro-, HCFC-140	kg	air	low population density	144		0.12		0.017839	0.00638			0.407
Ethane, 1,1,1-trichloro-, HCFC-140	kg	air	unspecified					0.017839	0.00638			
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	kg	air	high population density						0.151	1.83		204
Ethane, 1,1-difluoro-, HFC-152a	kg	air	high population density	122								
Ethane, 1,2-dichloro-	kg	air	high population density						0.046	2.29		7.17
Ethane, 1,2-dichloro-	kg	air	low population density						0.046			
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	air	low population density									
Ethane, hexafluoro-, HFC-116	kg	air	high population density	1.20E+04								
Ethane, hexafluoro-, HFC-116	kg	air	unspecified									

Chemical/substance	Unit	Destination category	Destination subcategory	Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
				kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Ethanol	kg	air	high population density					0.38121				
Ethanol	kg	air	low population density					0.38121				
Ethene	kg	air	high population density					1.9815				
Ethene	kg	air	low population density					1.9815				
Ethene, chloro-	kg	air	high population density						0.00107	1.63		105
Ethene, chloro-	kg	air	unspecified						0.00107			
Ethene, tetrachloro-	kg	air	high population density					0.023056	0.0194	0.718		74.9
Ethene, tetrachloro-	kg	air	low population density					0.023056	0.0194			
Ethene, tetrachloro-	kg	air	unspecified					0.023056	0.0194			
Ethyl acetate	kg	air	high population density					0.15895	0.00257			0.122
Ethyl cellulose	kg	air	high population density									
Ethylene diamine	kg	air	high population density									
Ethylene oxide	kg	air	high population density					0.017274		11		619
Ethylene oxide	kg	air	low population density					0.017274				
Ethylene oxide	kg	air	lower stratosphere + upper troposphere									
Ethylene oxide	kg	air	unspecified					0.017274				
Ethyne	kg	air	high population density					0.24492				
Ethyne	kg	air	low population density					0.24492				
Ethyne	kg	air	unspecified					0.24492				
Fluorine	kg	air	high population density									
Fluorine	kg	air	low population density									
Fluorine	kg	air	low population density, long-term									
Fluorine	kg	air	unspecified									
Fluosilicic acid	kg	air	high population density									
Formaldehyde	kg	air	high population density					1.8121	0.0505	0.00365		5.07
Formaldehyde	kg	air	low population density					1.8121	0.0505			
Formaldehyde	kg	air	lower stratosphere + upper troposphere						0.0505			
Formaldehyde	kg	air	unspecified					1.8121	0.0505			
Formic acid	kg	air	high population density					0.035927				0.0668
Formic acid	kg	air	low population density					0.035927				
Furan	kg	air	low population density					2.8516				36.3
Furan	kg	air	unspecified					2.8516				
Heat, waste	MJ	air	high population density									
Heat, waste	MJ	air	low population density									
Heat, waste	MJ	air	lower stratosphere + upper troposphere									
Heat, waste	MJ	air	unspecified									
Helium	kg	air	low population density									
Helium	kg	air	unspecified									
Heptane	kg	air	high population density					0.28492				
Hexane	kg	air	high population density					0.3354	0.00000131			0.636
Hexane	kg	air	low population density					0.3354	0.00000131			
Hexane	kg	air	unspecified					0.3354	0.00000131			
Hydrocarbons, aliphatic, alkanes, cyclic	kg	air	high population density									
Hydrocarbons, aliphatic, alkanes, cyclic	kg	air	low population density									
Hydrocarbons, aliphatic, alkanes, unspecified	kg	air	high population density									
Hydrocarbons, aliphatic, alkanes, unspecified	kg	air	low population density									
Hydrocarbons, aliphatic, alkanes, unspecified	kg	air	unspecified									
Hydrocarbons, aliphatic, unsaturated	kg	air	high population density									
Hydrocarbons, aliphatic, unsaturated	kg	air	low population density									
Hydrocarbons, aliphatic, unsaturated	kg	air	unspecified									
Hydrocarbons, aromatic	kg	air	high population density									
Hydrocarbons, aromatic	kg	air	low population density									
Hydrocarbons, aromatic	kg	air	unspecified									
Hydrocarbons, chlorinated	kg	air	high population density									
Hydrocarbons, chlorinated	kg	air	low population density									
Hydrocarbons, chlorinated	kg	air	unspecified									
Hydrogen	kg	air	high population density									
Hydrogen	kg	air	unspecified									
Hydrogen chloride	kg	air	high population density		44.7				3.19			0.21
Hydrogen chloride	kg	air	low population density						3.19			
Hydrogen chloride	kg	air	lower stratosphere + upper troposphere						3.19			
Hydrogen chloride	kg	air	unspecified						3.19			
Hydrogen fluoride	kg	air	high population density		81.3							
Hydrogen fluoride	kg	air	low population density									
Hydrogen fluoride	kg	air	unspecified									
Hydrogen peroxide	kg	air	high population density									
Hydrogen sulfide	kg	air	high population density									0.0483
Hydrogen sulfide	kg	air	low population density									
Hydrogen sulfide	kg	air	unspecified									
Hydrogen-3, Tritium	kBq	air	low population density									
Iodine	kg	air	high population density									
Iodine	kg	air	low population density									
Iodine	kg	air	unspecified									
Iodine-129	kBq	air	low population density									
Iodine-131	kBq	air	low population density									
Iodine-133	kBq	air	low population density									
Iodine-135	kBq	air	low population density									
Iron	kg	air	high population density									
Iron	kg	air	low population density									
Iron	kg	air	low population density, long-term									
Iron	kg	air	unspecified									
Isocyanic acid	kg	air	high population density									
Isoprene	kg	air	low population density					2.2806				
Isoprene	kg	air	unspecified					2.2806				
Krypton-85	kBq	air	low population density									
Krypton-85m	kBq	air	low population density									

				Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
Chemical/substance	Unit	Destination category	Destination subcategory	kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Krypton-87	kBq	air	low population density									
Krypton-88	kBq	air	low population density									
Krypton-89	kBq	air	low population density									
Lanthanum-140	kBq	air	low population density									
Lead	kg	air	high population density						1.44	58.2		2170000
Lead	kg	air	low population density						1.44			
Lead	kg	air	low population density, long-term						1.44			
Lead	kg	air	lower stratosphere + upper troposphere						1.44			
Lead	kg	air	unspecified						1.44			
Lead-210	kBq	air	high population density									
Lead-210	kBq	air	low population density									
Lead-210	kBq	air	unspecified									
Magnesium	kg	air	high population density									
Magnesium	kg	air	low population density									
Magnesium	kg	air	low population density, long-term									
Magnesium	kg	air	unspecified									
Manganese	kg	air	high population density									6090
Manganese	kg	air	low population density									
Manganese	kg	air	low population density, long-term									
Manganese	kg	air	unspecified									
Manganese-54	kBq	air	low population density									
Mercury	kg	air	high population density						16.3			99900
Mercury	kg	air	low population density						16.3			
Mercury	kg	air	low population density, long-term						16.3			
Mercury	kg	air	lower stratosphere + upper troposphere						16.3			
Mercury	kg	air	unspecified						16.3			
Methane, biogenic	kg	air	high population density	23				0.0029637				
Methane, biogenic	kg	air	low population density					0.0029637				
Methane, biogenic	kg	air	unspecified					0.0029637				
Methane, bromo-, Halon 1001	kg	air	unspecified	5		0.38		0.004804	0.835			1170
Methane, bromochlorodifluoro-, Halon 1211	kg	air	low population density	1.86E+03		6						
Methane, bromotrifluoro-, Halon 1301	kg	air	high population density	7.03E+03		12						
Methane, bromotrifluoro-, Halon 1301	kg	air	low population density									
Methane, chlorodifluoro-, HCFC-22	kg	air	high population density	1.78E+03		0.05			3.18E-05			2.24E-01
Methane, chlorodifluoro-, HCFC-22	kg	air	low population density						3.18E-05			
Methane, dichloro-, HCC-30	kg	air	high population density	10				0.019169	0.0139	0.142		1.13
Methane, dichloro-, HCC-30	kg	air	low population density					0.019169	0.0139			
Methane, dichlorodifluoro-, CFC-12	kg	air	high population density	1.07E+04		1			1.51E-03			3.80E+00
Methane, dichlorodifluoro-, CFC-12	kg	air	low population density						1.51E-03			
Methane, dichlorodifluoro-, CFC-12	kg	air	unspecified						1.51E-03			
Methane, dichlorofluoro-, HCFC-21	kg	air	high population density	148		0.04						
Methane, fossil	kg	air	high population density	23				0.0029637				
Methane, fossil	kg	air	low population density					0.0029637				
Methane, fossil	kg	air	lower stratosphere + upper troposphere									
Methane, fossil	kg	air	unspecified					0.0029637				
Methane, monochloro-, R-40	kg	air	high population density	16					0.00513	0.293		39.4
Methane, monochloro-, R-40	kg	air	low population density						0.00513			
Methane, tetrachloro-, R-10	kg	air	high population density	1.38E+03		0.73			1.18E-02	7.43E+00		1.77E+03
Methane, tetrachloro-, R-10	kg	air	unspecified									
Methane, tetrafluoro-, R-14	kg	air	high population density	5.82E+03								
Methane, tetrafluoro-, R-14	kg	air	unspecified									
Methane, trichlorofluoro-, CFC-11	kg	air	high population density	4.68E+03		1			6.55E-03			2.18E-01
Methane, trifluoro-, HFC-23	kg	air	high population density	1.43E+04								
Methanol	kg	air	high population density					0.19726	0.0192			0.0736
Methanol	kg	air	low population density					0.19726				
Methanol	kg	air	unspecified					0.19726				
Methyl acrylate	kg	air	high population density									0.357
Methyl amine	kg	air	high population density									
Methyl borate	kg	air	high population density									
Methyl ethyl ketone	kg	air	high population density						0.00957			0.94
Methyl formate	kg	air	high population density					0.027524				
Molybdenum	kg	air	high population density									36600
Molybdenum	kg	air	low population density									
Molybdenum	kg	air	low population density, long-term									
Molybdenum	kg	air	unspecified									
Monoethanolamine	kg	air	high population density									
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	air	high population density									
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	air	low population density									
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	air	lower stratosphere + upper troposphere									
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	air	unspecified									
Nickel	kg	air	high population density						7840	1.51		71900
Nickel	kg	air	low population density						7840			
Nickel	kg	air	low population density, long-term						7840			
Nickel	kg	air	lower stratosphere + upper troposphere						7840			
Nickel	kg	air	unspecified						7840			

Chemical/substance	Unit	Destination category	Destination subcategory	Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
				kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Niobium-95	kBq	air	low population density									
Nitrate	kg	air	high population density									
Nitrate	kg	air	low population density									
Nitrate	kg	air	low population density, long-term									
Nitrogen oxides	kg	air	high population density		40.22		0.03938	1			0.001453	
Nitrogen oxides	kg	air	low population density					1				
Nitrogen oxides	kg	air	lower stratosphere + upper troposphere									
Nitrogen oxides	kg	air	unspecified					1				
Noble gases, radioactive, unspecified	kBq	air	low population density									
Ozone	kg	air	high population density									
Ozone	kg	air	low population density									
Ozone	kg	air	unspecified									
PAH, polycyclic aromatic hydrocarbons	kg	air	high population density									
PAH, polycyclic aromatic hydrocarbons	kg	air	low population density									
PAH, polycyclic aromatic hydrocarbons	kg	air	unspecified									
Particulates, < 2.5 um	kg	air	high population density								0.11927	
Particulates, < 2.5 um	kg	air	low population density									
Particulates, < 2.5 um	kg	air	low population density, long-term									
Particulates, < 2.5 um	kg	air	lower stratosphere + upper troposphere									
Particulates, < 2.5 um	kg	air	unspecified									
Particulates, > 10 um	kg	air	high population density									
Particulates, > 10 um	kg	air	low population density									
Particulates, > 10 um	kg	air	low population density, long-term									
Particulates, > 10 um	kg	air	unspecified									
Particulates, > 2.5 um, and < 10um	kg	air	high population density								0.071561861	
Particulates, > 2.5 um, and < 10um	kg	air	low population density									
Particulates, > 2.5 um, and < 10um	kg	air	low population density, long-term									
Particulates, > 2.5 um, and < 10um	kg	air	unspecified									
Pentane	kg	air	high population density					0.34661				
Pentane	kg	air	low population density					0.34661				
Pentane	kg	air	unspecified					0.34661				
Phenol	kg	air	high population density					0.73782	0.0544			0.0499
Phenol	kg	air	low population density					0.73782	0.0544			
Phenol	kg	air	unspecified					0.73782	0.0544			
Phenol, pentachloro-	kg	air	high population density						2.52	4.74		218
Phenol, pentachloro-	kg	air	low population density						2.52			
Phosphine	kg	air	high population density									
Phosphorus	kg	air	high population density				0.9427					
Phosphorus	kg	air	low population density									
Phosphorus	kg	air	low population density, long-term									
Phosphorus	kg	air	unspecified									
Platinum	kg	air	high population density									
Platinum	kg	air	low population density									
Plutonium-238	kBq	air	low population density									
Plutonium-alpha	kBq	air	low population density									
Polonium-210	kBq	air	high population density									
Polonium-210	kBq	air	low population density									
Polonium-210	kBq	air	unspecified									
Polychlorinated biphenyls	kg	air	high population density									
Polychlorinated biphenyls	kg	air	unspecified									
Potassium	kg	air	high population density									
Potassium	kg	air	low population density									
Potassium	kg	air	low population density, long-term									
Potassium-40	kBq	air	high population density									
Potassium-40	kBq	air	low population density									
Potassium-40	kBq	air	unspecified									
Propanal	kg	air	high population density									
Propanal	kg	air	unspecified									
Propane	kg	air	high population density					0.12806				0.00773
Propane	kg	air	low population density					0.12806				
Propane	kg	air	unspecified					0.12806				
Propanol	kg	air	high population density					0.59089				
Propene	kg	air	high population density					2.4734	0.00000293			
Propene	kg	air	low population density					2.4734	0.00000293			
Propene	kg	air	unspecified					2.4734	0.00000293			
Propionic acid	kg	air	high population density					0.27282				
Propionic acid	kg	air	unspecified					0.27282				
Propylene oxide	kg	air	high population density					0.083871		0.316		
Protactinium-234	kBq	air	low population density									
Radioactive species, other beta emitters	kBq	air	high population density									
Radioactive species, other beta emitters	kBq	air	low population density									
Radium-226	kBq	air	high population density									
Radium-226	kBq	air	low population density									
Radium-226	kBq	air	unspecified									
Radium-228	kBq	air	high population density									
Radium-228	kBq	air	low population density									
Radium-228	kBq	air	unspecified									
Radon-220	kBq	air	high population density									
Radon-220	kBq	air	low population density									
Radon-220	kBq	air	unspecified									
Radon-222	kBq	air	high population density									
Radon-222	kBq	air	low population density									
Radon-222	kBq	air	low population density, long-term									

				Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
Chemical/substance	Unit	Destination category	Destination subcategory	kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Radon-222	kBq	air	unspecified									
Ruthenium-103	kBq	air	low population density									
Scandium	kg	air	high population density									
Scandium	kg	air	low population density									
Scandium	kg	air	low population density, long-term									
Selenium	kg	air	high population density						1530			71300
Selenium	kg	air	low population density						1530			
Selenium	kg	air	low population density, long-term						1530			
Selenium	kg	air	lower stratosphere + upper troposphere						1530			
Selenium	kg	air	unspecified						1530			
Silicon	kg	air	high population density									
Silicon	kg	air	low population density									
Silicon	kg	air	low population density, long-term									
Silicon	kg	air	unspecified									
Silicon tetrafluoride	kg	air	low population density									
Silver	kg	air	high population density						8490			39300
Silver	kg	air	low population density						8490			
Silver	kg	air	low population density, long-term						8490			
Silver-110	kBq	air	low population density									
Sodium	kg	air	high population density									
Sodium	kg	air	low population density									
Sodium	kg	air	low population density, long-term									
Sodium	kg	air	unspecified									
Sodium chlorate	kg	air	high population density									
Sodium dichromate	kg	air	high population density									
Sodium formate	kg	air	high population density									
Sodium hydroxide	kg	air	high population density									
Strontium	kg	air	high population density									
Strontium	kg	air	low population density									
Strontium	kg	air	low population density, long-term									
Strontium	kg	air	unspecified									
Styrene	kg	air	high population density					0.49984	0.00158			0.0313
Styrene	kg	air	low population density					0.49984	0.00158			
Styrene	kg	air	unspecified					0.49984	0.00158			
Sulfate	kg	air	high population density									
Sulfate	kg	air	low population density									
Sulfate	kg	air	low population density, long-term									
Sulfate	kg	air	unspecified									
Sulfur dioxide	kg	air	high population density		54.23						0.007661	
Sulfur dioxide	kg	air	low population density									
Sulfur dioxide	kg	air	lower stratosphere + upper troposphere									
Sulfur dioxide	kg	air	unspecified									
Sulfur hexafluoride	kg	air	low population density	2.25E+04								
Sulfur hexafluoride	kg	air	unspecified									
Sulfuric acid	kg	air	high population density									
Sulfuric acid	kg	air	low population density									
Terpenes	kg	air	low population density									
Thallium	kg	air	high population density						500			1920000
Thallium	kg	air	low population density						500			
Thallium	kg	air	unspecified						500			
Thorium	kg	air	high population density									
Thorium	kg	air	low population density									
Thorium-228	kBq	air	high population density									
Thorium-228	kBq	air	low population density									
Thorium-228	kBq	air	unspecified									
Thorium-230	kBq	air	low population density									
Thorium-232	kBq	air	high population density									
Thorium-232	kBq	air	low population density									
Thorium-232	kBq	air	unspecified									
Thorium-234	kBq	air	low population density									
Tin	kg	air	high population density									208
Tin	kg	air	low population density									
Tin	kg	air	low population density, long-term									
Tin	kg	air	unspecified									
Titanium	kg	air	high population density									
Titanium	kg	air	low population density									
Titanium	kg	air	low population density, long-term									
Titanium	kg	air	unspecified									
Toluene	kg	air	high population density					0.83226	0.0025			1
Toluene	kg	air	low population density					0.83226	0.0025			
Toluene	kg	air	unspecified					0.83226	0.0025			
Tungsten	kg	air	low population density									
Tungsten	kg	air	low population density, long-term									
Uranium	kg	air	high population density									
Uranium	kg	air	low population density									
Uranium alpha	kBq	air	low population density									
Uranium-234	kBq	air	low population density									
Uranium-235	kBq	air	low population density									
Uranium-238	kBq	air	high population density									
Uranium-238	kBq	air	low population density									
Uranium-238	kBq	air	unspecified									
Vanadium	kg	air	high population density									137000
Vanadium	kg	air	low population density									
Vanadium	kg	air	low population density, long-term									
Vanadium	kg	air	unspecified									
Water	kg	air	high population density									
Water	kg	air	low population density									

Chemical/substance	Unit	Destination category	Destination subcategory	Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
				kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Water	kg	air	lower stratosphere + upper troposphere									
Water	kg	air	unspecified									
Xenon-131m	kBq	air	low population density									
Xenon-133	kBq	air	low population density									
Xenon-133m	kBq	air	low population density									
Xenon-135	kBq	air	low population density									
Xenon-135m	kBq	air	low population density									
Xenon-137	kBq	air	low population density									
Xenon-138	kBq	air	low population density									
Xylene	kg	air	high population density						0.00161			0.0246
Xylene	kg	air	low population density						0.00161			
Xylene	kg	air	unspecified						0.00161			
Zinc	kg	air	high population density						5880			10200
Zinc	kg	air	low population density						5880			
Zinc	kg	air	low population density, long-term						5880			
Zinc	kg	air	lower stratosphere + upper troposphere						5880			
Zinc	kg	air	unspecified						5880			
Zinc-65	kBq	air	low population density									
Zirconium	kg	air	low population density									
Zirconium-95	kBq	air	low population density									
m-Xylene	kg	air	high population density					2.333	0.000999			
t-Butyl methyl ether	kg	air	high population density					0.266	0.00294			
2,4-D	kg	soil	agricultural						1	0.469		126
Aclonifen	kg	soil	agricultural									
Aldrin	kg	soil	agricultural						168	277		287000
Aluminium	kg	soil	agricultural						15500			20000
Aluminium	kg	soil	industrial						2160			8570
Antimony	kg	soil	agricultural									6600000
Arsenic	kg	soil	agricultural						348	8870		1000000
Arsenic	kg	soil	industrial						39.1			497000
Atrazine	kg	soil	agricultural						6.56	8.31		54.5
Barium	kg	soil	agricultural									40600
Barium	kg	soil	industrial									19700
Benomyl	kg	soil	agricultural						6.21	0.00657		1.6
Bentazone	kg	soil	agricultural						21.7			30.5
Boron	kg	soil	agricultural									
Boron	kg	soil	industrial									
Boron	kg	soil	unspecified									
Cadmium	kg	soil	agricultural						7.03	0.0921		622000
Cadmium	kg	soil	unspecified						0.788			309000
Calcium	kg	soil	agricultural									
Calcium	kg	soil	industrial									
Carbetamide	kg	soil	agricultural									
Carbofuran	kg	soil	agricultural						35.7			26.8
Carbon	kg	soil	agricultural									
Carbon	kg	soil	industrial									
Chloride	kg	soil	agricultural									
Chloride	kg	soil	industrial									
Chloride	kg	soil	unspecified									
Chlorimuron-ethyl	kg	soil	agricultural									
Chlorothalonil	kg	soil	agricultural						14.3	0.000185		0.167
Chlorpyrifos	kg	soil	agricultural						136			
Chromium	kg	soil	agricultural						2270	0.188		125000
Chromium	kg	soil	industrial						256	0.192		61800
Chromium	kg	soil	unspecified						256	0.192		
Chromium VI	kg	soil	unspecified						256	0.192		61800
Clethodim	kg	soil	agricultural									
Cloransulam-methyl	kg	soil	agricultural									
Cobalt	kg	soil	agricultural									56.9
Copper	kg	soil	agricultural						52000			28300
Copper	kg	soil	industrial						5880			14000
Copper	kg	soil	unspecified						5880			
Cypermethrin	kg	soil	agricultural						33700	0.238		367
Fenoxaprop	kg	soil	agricultural									
Fenpiclonil	kg	soil	agricultural									
Fluazifop-P-butyl	kg	soil	agricultural									
Flumioxazin	kg	soil	agricultural									
Fluoride	kg	soil	industrial									
Fluoride	kg	soil	unspecified									
Fomesafen	kg	soil	agricultural									
Glyphosate	kg	soil	agricultural						0.27	1.06E-06		0.0088
Glyphosate	kg	soil	industrial						0.245	7.90E-06		0.033
Heat, waste	MJ	soil	industrial									
Heat, waste	MJ	soil	unspecified									
Imazamox	kg	soil	agricultural									
Imazethapyr	kg	soil	agricultural									
Iron	kg	soil	agricultural									
Iron	kg	soil	industrial									
Iron	kg	soil	unspecified									
Lambda-cyhalothrin	kg	soil	agricultural									
Lead	kg	soil	agricultural						1.61	45.7		3490000
Lead	kg	soil	unspecified						0.181	45.9		1730000
Linuron	kg	soil	agricultural						423	0.544		75.9
Magnesium	kg	soil	agricultural									
Magnesium	kg	soil	industrial									
Mancozeb	kg	soil	agricultural									
Manganese	kg	soil	agricultural									15100
Manganese	kg	soil	industrial									6670
Mercury	kg	soil	agricultural						50.2			662000
Metaldehyde	kg	soil	agricultural									
Metolachlor	kg	soil	agricultural						0.343			27.1
Metribuzin	kg	soil	agricultural						0.0659			27.1
Molybdenum	kg	soil	agricultural									78600
Napropamide	kg	soil	agricultural									

Chemical/substance	Unit	Destination category	Destination subcategory	Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
				kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Nickel	kg	soil	agricultural						19900	0.000969		162000
Nickel	kg	soil	unspecified						2320	0.00103		78400
Oils, biogenic	kg	soil	forestry									
Oils, biogenic	kg	soil	unspecified									
Oils, unspecified	kg	soil	forestry									
Oils, unspecified	kg	soil	industrial									
Oils, unspecified	kg	soil	unspecified									
Orbencarb	kg	soil	agricultural									
Pendimethalin	kg	soil	agricultural									
Phosphorus	kg	soil	agricultural									
Phosphorus	kg	soil	industrial									
Pirimicarb	kg	soil	agricultural									36
Potassium	kg	soil	agricultural									
Potassium	kg	soil	industrial									
Silicon	kg	soil	agricultural									
Silicon	kg	soil	industrial									
Sodium	kg	soil	industrial									
Sodium	kg	soil	unspecified									
Strontium	kg	soil	agricultural									
Strontium	kg	soil	industrial									
Sulfentrazone	kg	soil	agricultural									
Sulfosate	kg	soil	agricultural									
Sulfur	kg	soil	agricultural									
Sulfur	kg	soil	industrial									
Sulfuric acid	kg	soil	agricultural									
Tebutam	kg	soil	agricultural									
Teflubenzuron	kg	soil	agricultural									
Thiram	kg	soil	agricultural						14.2			0.372
Tin	kg	soil	agricultural									440
Titanium	kg	soil	agricultural									
Trifluralin	kg	soil	agricultural									
Vanadium	kg	soil	agricultural									304000
Zinc	kg	soil	agricultural						14900			22900
Zinc	kg	soil	industrial						1740			11100
Zinc	kg	soil	unspecified						1740			
1,4-Butanediol	kg	water	river									
4-Methyl-2-pentanone	kg	water	unspecified									
AOX, Adsorbable Organic Halogen as Cl	kg	water	ocean									
AOX, Adsorbable Organic Halogen as Cl	kg	water	river									
AOX, Adsorbable Organic Halogen as Cl	kg	water	unspecified									
Acenaphthene	kg	water	ocean						48.7			1.76
Acenaphthene	kg	water	river						48.7			
Acenaphthylene	kg	water	ocean									
Acenaphthylene	kg	water	river									
Acetaldehyde	kg	water	river						0.307	0.00846		7.11
Acetic acid	kg	water	river									
Acetone	kg	water	unspecified						0.00962			0.171
Acidity, unspecified	kg	water	river									
Acidity, unspecified	kg	water	unspecified									
Acrylate, ion	kg	water	river									
Actinides, radioactive, unspecified	kBq	water	ocean									
Aluminium	kg	water	ground-						1840			20.5
Aluminium	kg	water	ground-, long-term						1840			
Aluminium	kg	water	ocean						1840			
Aluminium	kg	water	river						1840			
Aluminium	kg	water	unspecified						1840			
Ammonium, ion	kg	water	ground-				0.79					
Ammonium, ion	kg	water	ground-, long-term				0.79					
Ammonium, ion	kg	water	ocean				0.79					
Ammonium, ion	kg	water	river				0.79					
Ammonium, ion	kg	water	unspecified				0.79					
Antimony	kg	water	ground-									4210
Antimony	kg	water	ground-, long-term									
Antimony	kg	water	river									
Antimony	kg	water	unspecified									
Antimony-122	kBq	water	river									
Antimony-124	kBq	water	river									
Antimony-125	kBq	water	river									
Arsenic, ion	kg	water	ground-						246	282		13500
Arsenic, ion	kg	water	ground-, long-term						246			
Arsenic, ion	kg	water	lake						246			
Arsenic, ion	kg	water	ocean						246			
Arsenic, ion	kg	water	river						246			
Arsenic, ion	kg	water	unspecified						246			
BOD5, Biological Oxygen Demand	kg	water	ground-				0.05					
BOD5, Biological Oxygen Demand	kg	water	ground-, long-term				0.05					
BOD5, Biological Oxygen Demand	kg	water	ocean				0.05					
BOD5, Biological Oxygen Demand	kg	water	river				0.05					
BOD5, Biological Oxygen Demand	kg	water	unspecified				0.05					
Barite	kg	water	ocean									
Barium	kg	water	ground-									57.3
Barium	kg	water	ground-, long-term									
Barium	kg	water	ocean									
Barium	kg	water	river									
Barium	kg	water	unspecified									
Barium-140	kBq	water	river									
Benzene	kg	water	ocean						1.63	1		9.61
Benzene	kg	water	river						1.63			
Benzene	kg	water	unspecified						1.63			

				Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
Chemical/substance	Unit	Destination category	Destination subcategory	kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Benzene, chloro-	kg	water	river						8.86			4.09
Benzene, ethyl-	kg	water	ocean						3.27			
Benzene, ethyl-	kg	water	river						3.27			
Benzene, ethyl-	kg	water	unspecified						3.27			
Beryllium	kg	water	ground-									1050
Beryllium	kg	water	ground-, long-term									
Beryllium	kg	water	river									
Beryllium	kg	water	unspecified									
Boron	kg	water	ground-									
Boron	kg	water	ground-, long-term									
Boron	kg	water	ocean									
Boron	kg	water	river									
Boron	kg	water	unspecified									
Bromate	kg	water	river									
Bromine	kg	water	ground-									
Bromine	kg	water	ground-, long-term									
Bromine	kg	water	ocean									
Bromine	kg	water	river									
Bromine	kg	water	unspecified									
Butanol	kg	water	river									0.179
Butene	kg	water	river									
Butyl acetate	kg	water	river									
Butyrolactone	kg	water	river									
COD, Chemical Oxygen Demand	kg	water	ground-				0.05					
COD, Chemical Oxygen Demand	kg	water	ground-, long-term				0.05					
COD, Chemical Oxygen Demand	kg	water	ocean				0.05					
COD, Chemical Oxygen Demand	kg	water	river				0.05					
COD, Chemical Oxygen Demand	kg	water	unspecified				0.05					
Cadmium, ion	kg	water	ground-						10.4			2010000
Cadmium, ion	kg	water	ground-, long-term						10.4			
Cadmium, ion	kg	water	lake						10.4			
Cadmium, ion	kg	water	ocean						10.4			
Cadmium, ion	kg	water	river						10.4			
Cadmium, ion	kg	water	unspecified						10.4			
Calcium, ion	kg	water	ground-									
Calcium, ion	kg	water	ground-, long-term									
Calcium, ion	kg	water	lake									
Calcium, ion	kg	water	ocean									
Calcium, ion	kg	water	river									
Calcium, ion	kg	water	unspecified									
Carbonate	kg	water	river									
Carboxylic acids, unspecified	kg	water	ocean									
Carboxylic acids, unspecified	kg	water	river									
Cerium-141	kBq	water	river									
Cerium-144	kBq	water	river									
Cesium	kg	water	ocean									
Cesium	kg	water	river									
Cesium-134	kBq	water	river									
Cesium-136	kBq	water	river									
Cesium-137	kBq	water	ocean									
Cesium-137	kBq	water	river									
Chlorate	kg	water	river									
Chloride	kg	water	ground-									
Chloride	kg	water	ground-, long-term									
Chloride	kg	water	ocean									
Chloride	kg	water	river									
Chloride	kg	water	river, long-term									
Chloride	kg	water	unspecified									
Chlorinated solvents, unspecified	kg	water	ocean									
Chlorinated solvents, unspecified	kg	water	river									
Chlorine	kg	water	river									
Chloroform	kg	water	river						1.81	0.955		11.3
Chromium VI	kg	water	ground-						781			583
Chromium VI	kg	water	ground-, long-term						781			
Chromium VI	kg	water	river						781			
Chromium VI	kg	water	unspecified						781			
Chromium, ion	kg	water	ground-									583
Chromium, ion	kg	water	ocean									
Chromium, ion	kg	water	river									
Chromium, ion	kg	water	unspecified									
Chromium-51	kBq	water	river									
Cobalt	kg	water	ground-									2.58E-43
Cobalt	kg	water	ground-, long-term									
Cobalt	kg	water	ocean									
Cobalt	kg	water	river									
Cobalt	kg	water	unspecified									
Cobalt-57	kBq	water	river									
Cobalt-58	kBq	water	river									
Cobalt-60	kBq	water	river									
Copper, ion	kg	water	ground-						11500			5900
Copper, ion	kg	water	ground-, long-term						11500			
Copper, ion	kg	water	lake						11500			
Copper, ion	kg	water	ocean						11500			
Copper, ion	kg	water	river						11500			
Copper, ion	kg	water	unspecified						11500			
Cumene	kg	water	river									0.373
Cyanide	kg	water	ocean									1250
Cyanide	kg	water	river									
Cyanide	kg	water	unspecified									
DOC, Dissolved Organic Carbon	kg	water	ground-, long-term									

				Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
Chemical/substance	Unit	Destination category	Destination subcategory	kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
DOC, Dissolved Organic Carbon	kg	water	lake									
DOC, Dissolved Organic Carbon	kg	water	ocean									
DOC, Dissolved Organic Carbon	kg	water	river									
DOC, Dissolved Organic Carbon	kg	water	unspecified									
Dichromate	kg	water	river									
Dissolved solids	kg	water	ground-									
Dissolved solids	kg	water	river									
Dissolved solids	kg	water	unspecified									
Ethane, 1,2-dichloro-	kg	water	river						0.759	3.02		7.5
Ethanol	kg	water	river									
Ethene	kg	water	river									
Ethene, chloro-	kg	water	river						2.04	5.91		4820
Ethyl acetate	kg	water	river						0.0393			0.0343
Ethylene diamine	kg	water	river									
Ethylene oxide	kg	water	river							6.38		287
Fluoride	kg	water	ground-									
Fluoride	kg	water	ground-, long-term									
Fluoride	kg	water	ocean									
Fluoride	kg	water	river									
Fluoride	kg	water	unspecified									
Fluosilicic acid	kg	water	river									
Formaldehyde	kg	water	river						0.486	0.000401		0.481
Formaldehyde	kg	water	unspecified						0.486			
Glutaraldehyde	kg	water	ocean									
Heat, waste	MJ	water	ground-, long-term									
Heat, waste	MJ	water	ocean									
Heat, waste	MJ	water	river									
Heat, waste	MJ	water	unspecified									
Hydrocarbons, aliphatic, alkanes, unspecified	kg	water	ocean									
Hydrocarbons, aliphatic, alkanes, unspecified	kg	water	river									
Hydrocarbons, aliphatic, unsaturated	kg	water	ocean									
Hydrocarbons, aliphatic, unsaturated	kg	water	river									
Hydrocarbons, aromatic	kg	water	ocean									
Hydrocarbons, aromatic	kg	water	river									
Hydrocarbons, unspecified	kg	water	ocean									
Hydrocarbons, unspecified	kg	water	river									
Hydrocarbons, unspecified	kg	water	unspecified									
Hydrogen peroxide	kg	water	river									
Hydrogen sulfide	kg	water	ground-, long-term									22.3
Hydrogen sulfide	kg	water	river									
Hydrogen-3, Tritium	kBq	water	ocean									
Hydrogen-3, Tritium	kBq	water	river									
Hydroxide	kg	water	river									
Hypochlorite	kg	water	ocean									
Hypochlorite	kg	water	river									
Iodide	kg	water	ground-									
Iodide	kg	water	ground-, long-term									
Iodide	kg	water	ocean									
Iodide	kg	water	river									
Iodine-131	kBq	water	river									
Iodine-133	kBq	water	river									
Iron, ion	kg	water	ground-									
Iron, ion	kg	water	ground-, long-term									
Iron, ion	kg	water	ocean									
Iron, ion	kg	water	river									
Iron, ion	kg	water	unspecified									
Iron-59	kBq	water	river									
Lanthanum-140	kBq	water	river									
Lead	kg	water	ground-						2.37	350		11300000
Lead	kg	water	ground-, long-term						2.37			
Lead	kg	water	lake						2.37			
Lead	kg	water	ocean						2.37			
Lead	kg	water	river						2.37			
Lead	kg	water	unspecified						2.37			
Lead-210	kBq	water	ground-									
Lead-210	kBq	water	ocean									
Lead-210	kBq	water	river									
Lead-210	kBq	water	unspecified									
Lithium, ion	kg	water	unspecified									
Magnesium	kg	water	ground-									
Magnesium	kg	water	ground-, long-term									
Magnesium	kg	water	ocean									
Magnesium	kg	water	river									
Magnesium	kg	water	unspecified									
Manganese	kg	water	ground-									11.8
Manganese	kg	water	ground-, long-term									
Manganese	kg	water	ocean									
Manganese	kg	water	river									
Manganese	kg	water	unspecified									
Manganese-54	kBq	water	river									
Mercury	kg	water	ground-						3110			943000
Mercury	kg	water	ground-, long-term						3110			
Mercury	kg	water	lake						3110			
Mercury	kg	water	ocean						3110			
Mercury	kg	water	river						3110			
Mercury	kg	water	unspecified						3110			
Methane, dichloro-, HCC-30	kg	water	river						0.439	0.123		0.662
Methanol	kg	water	ocean						0.0106			0.0225
Methanol	kg	water	river						0.0106			
Methanol	kg	water	unspecified						0.0106			
Methyl acrylate	kg	water	river									

				Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
Chemical/substance	Unit	Destination category	Destination subcategory	kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Methyl amine	kg	water	river									
Methyl formate	kg	water	river									
Molybdenum	kg	water	ground-									828
Molybdenum	kg	water	ground-, long-term									
Molybdenum	kg	water	ocean									
Molybdenum	kg	water	river									
Molybdenum	kg	water	unspecified									
Molybdenum-99	kBq	water	river									
Nickel, ion	kg	water	ground-						2670			92.7
Nickel, ion	kg	water	ground-, long-term						2670			
Nickel, ion	kg	water	lake						2670			
Nickel, ion	kg	water	ocean						2670			
Nickel, ion	kg	water	river						2670			
Nickel, ion	kg	water	unspecified						2670			
Niobium-95	kBq	water	river									
Nitrate	kg	water	ground-				0.24					
Nitrate	kg	water	ground-, long-term									
Nitrate	kg	water	ocean									
Nitrate	kg	water	river									
Nitrite	kg	water	ground-, long-term									
Nitrite	kg	water	ocean									
Nitrite	kg	water	river									
Nitrogen	kg	water	ocean				1					
Nitrogen	kg	water	river									
Nitrogen, organic bound	kg	water	ground-, long-term									
Nitrogen, organic bound	kg	water	ocean									
Nitrogen, organic bound	kg	water	river									
Oils, unspecified	kg	water	ocean									
Oils, unspecified	kg	water	river									
Oils, unspecified	kg	water	unspecified									
PAH, polycyclic aromatic hydrocarbons	kg	water	ocean									
PAH, polycyclic aromatic hydrocarbons	kg	water	river									
Phenol	kg	water	ocean						0.353			0.00379
Phenol	kg	water	river						0.353			
Phenol	kg	water	unspecified						0.353			
Phosphate	kg	water	ground-				2.38					
Phosphate	kg	water	ground-, long-term									
Phosphate	kg	water	ocean									
Phosphate	kg	water	river									
Phosphorus	kg	water	ground-				7.29					
Phosphorus	kg	water	ocean									
Phosphorus	kg	water	river									
Phosphorus	kg	water	unspecified									
Polonium-210	kBq	water	ground-									
Polonium-210	kBq	water	ocean									
Polonium-210	kBq	water	river									
Potassium, ion	kg	water	ground-									
Potassium, ion	kg	water	ground-, long-term									
Potassium, ion	kg	water	ocean									
Potassium, ion	kg	water	river									
Potassium-40	kBq	water	ground-									
Potassium-40	kBq	water	ocean									
Potassium-40	kBq	water	river									
Propene	kg	water	river						0.981			0.0743
Propylene oxide	kg	water	river							0.601		0.339
Protactinium-234	kBq	water	river									
Radioactive species, Nuclides, unspecified	kBq	water	ocean									
Radioactive species, Nuclides, unspecified	kBq	water	river									
Radioactive species, alpha emitters	kBq	water	river									
Radium-224	kBq	water	ocean									
Radium-224	kBq	water	river									
Radium-226	kBq	water	ground-									
Radium-226	kBq	water	ocean									
Radium-226	kBq	water	river									
Radium-226	kBq	water	unspecified									
Radium-228	kBq	water	ocean									
Radium-228	kBq	water	river									
Radium-228	kBq	water	unspecified									
Rubidium	kg	water	ocean									
Rubidium	kg	water	river									
Ruthenium-103	kBq	water	river									
Scandium	kg	water	ground-									
Scandium	kg	water	ground-, long-term									
Scandium	kg	water	river									
Selenium	kg	water	ground-						1080			1420
Selenium	kg	water	ground-, long-term						1080			
Selenium	kg	water	ocean						1080			
Selenium	kg	water	river						1080			
Selenium	kg	water	unspecified						1080			
Silicon	kg	water	ground-									
Silicon	kg	water	ground-, long-term									
Silicon	kg	water	ocean									
Silicon	kg	water	river									
Silver, ion	kg	water	ground-						7530			539
Silver, ion	kg	water	ground-, long-term						7530			
Silver, ion	kg	water	ocean						7530			
Silver, ion	kg	water	river						7530			
Silver, ion	kg	water	unspecified						7530			
Silver-110	kBq	water	river									
Sodium formate	kg	water	river									
Sodium, ion	kg	water	ground-									
Sodium, ion	kg	water	ground-, long-term									
Sodium, ion	kg	water	ocean									

				Env. impact global warming	Env. impact acidification	Env. impact ozone depletion	Env. impact eutrophication	Env. impact photochemical oxidation	Env. impact ecotoxicity	Human health Carcinogenics	Human health respiratory effects	Human health non-carcinogenics
Chemical/substance	Unit	Destination category	Destination subcategory	kg CO2-Eq	moles of H+-Eq	kg CFC-11-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq	kg benzene-Eq	kg PM2.5-Eq	kg toluene-Eq
Sodium, ion	kg	water	river									
Sodium, ion	kg	water	unspecified									
Sodium-24	kBq	water	river									
Solids, inorganic	kg	water	ground-									
Solids, inorganic	kg	water	river									
Strontium	kg	water	ground-									
Strontium	kg	water	ground-, long-term									
Strontium	kg	water	ocean									
Strontium	kg	water	river									
Strontium	kg	water	unspecified									
Strontium-89	kBq	water	river									
Strontium-90	kBq	water	ocean									
Strontium-90	kBq	water	river									
Sulfate	kg	water	ground-									
Sulfate	kg	water	ground-, long-term									
Sulfate	kg	water	ocean									
Sulfate	kg	water	river									
Sulfate	kg	water	unspecified									
Sulfide	kg	water	ocean									
Sulfide	kg	water	river									
Sulfite	kg	water	river									
Sulfur	kg	water	ocean									
Sulfur	kg	water	river									
Sulfur	kg	water	unspecified									
Suspended solids, unspecified	kg	water	ocean									
Suspended solids, unspecified	kg	water	river									
Suspended solids, unspecified	kg	water	unspecified									
TOC, Total Organic Carbon	kg	water	ground-, long-term									
TOC, Total Organic Carbon	kg	water	ocean									
TOC, Total Organic Carbon	kg	water	river									
TOC, Total Organic Carbon	kg	water	unspecified									
Technetium-99m	kBq	water	river									
Tellurium-123m	kBq	water	river									
Tellurium-132	kBq	water	river									
Thallium	kg	water	ground-						611			64000
Thallium	kg	water	ground-, long-term						611			
Thallium	kg	water	river						611			
Thallium	kg	water	unspecified						611			
Thorium-228	kBq	water	ground-									
Thorium-228	kBq	water	ocean									
Thorium-228	kBq	water	river									
Thorium-230	kBq	water	river									
Thorium-232	kBq	water	river									
Thorium-234	kBq	water	river									
Tin, ion	kg	water	ground-									15.5
Tin, ion	kg	water	ground-, long-term									
Tin, ion	kg	water	river									
Tin, ion	kg	water	unspecified									
Titanium, ion	kg	water	ground-									
Titanium, ion	kg	water	ground-, long-term									
Titanium, ion	kg	water	ocean									
Titanium, ion	kg	water	river									
Titanium, ion	kg	water	unspecified									
Toluene	kg	water	ocean						1.63			1
Toluene	kg	water	river						1.63			
Toluene	kg	water	unspecified						1.63			
Tributyltin compounds	kg	water	ocean									
Triethylene glycol	kg	water	ocean									
Tungsten	kg	water	ground-									
Tungsten	kg	water	ground-, long-term									
Tungsten	kg	water	river									
Uranium alpha	kBq	water	river									
Uranium-234	kBq	water	river									
Uranium-235	kBq	water	river									
Uranium-238	kBq	water	ground-									
Uranium-238	kBq	water	ocean									
Uranium-238	kBq	water	river									
VOC, volatile organic compounds, unspecified origin	kg	water	ocean									
VOC, volatile organic compounds, unspecified origin	kg	water	river									
Vanadium, ion	kg	water	ground-									547
Vanadium, ion	kg	water	ground-, long-term									
Vanadium, ion	kg	water	ocean									
Vanadium, ion	kg	water	river									
Vanadium, ion	kg	water	unspecified									
Xylene	kg	water	ocean						2.53			0.0471
Xylene	kg	water	river						2.53			
Xylene	kg	water	unspecified						2.53			
Zinc, ion	kg	water	ground-						2050			17.9
Zinc, ion	kg	water	ground-, long-term						2050			
Zinc, ion	kg	water	lake						2050			
Zinc, ion	kg	water	ocean						2050			
Zinc, ion	kg	water	river						2050			
Zinc, ion	kg	water	unspecified						2050			
Zinc-65	kBq	water	river									
Zirconium-95	kBq	water	river									
m-Xylene	kg	water	unspecified						7.68			0.864
o-Dichlorobenzene	kg	water	river						4.77			11.5
o-Xylene	kg	water	unspecified						5.76			1.03
t-Butyl methyl ether	kg	water	ocean		0.295			0.185				
t-Butyl methyl ether	kg	water	river		0.295							

Appendix B. TRACI Characterized Results and Normalized Results (with Mean Value)

Characterized results

	Human health Carcinogenics	Environmental impact Global warming	Environmental impact Acidification	Human health Respiratory effects	Human health Non-carcinogenics
Fuel pathways	Cancer (kg benzene-Eq)	GWP (kg CO2-Eq)	AD (moles of H+-Eq)	Res. Effects (kg PM2.5-Eq)	Non-cancer (kg toluene-Eq)
Conventional gasoline	2.23E-05	9.02E-02	9.96E-03	2.49E-06	2.19E-01
Corn Ethanol, 99.7%	2.05E-04	7.43E-02	2.68E-02	3.65E-06	9.74E-01
Conventional diesel	1.68E-05	8.73E-02	8.25E-03	2.31E-06	1.83E-01
Soy bio-diesel	4.02E-05	2.99E-02	1.10E-02	2.18E-06	2.85E-01

Normalized results

Fuel pathways	Human health Carcinogenics	Environmental impact Global warming	Environmental impact Acidification	Human health Respiratory effects	Human health Non-carcinogenics
Conventional gasoline	3.10E-13	1.32E-14	4.79E-15	1.17E-16	5.34E-13
Corn Ethanol, 99.7%	2.85E-12	1.08E-14	1.29E-14	1.71E-16	2.37E-12
Conventional diesel	2.34E-13	1.27E-14	3.97E-15	1.09E-16	4.46E-13
Soy bio-diesel	5.58E-13	4.37E-15	5.30E-15	1.02E-16	6.93E-13

Appendix C. Contribution Analysis (Substance-Level): Yellow highlights show key contributing emissions/inputs

1) Global Warming Potential (GWP)

Corn Ethanol (E100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total GWP (%)
Carbon dioxide, biogenic	kg	as a credit, uptaken during corn growth		-7.30E-02	-98.67%
Carbon dioxide, fossil	kg	air	high population density	3.23E-02	43.63%
Dinitrogen monoxide	kg	air	low population density	2.11E-02	28.48%
Carbon dioxide, fossil	kg	air	low population density	1.02E-02	13.73%
Dinitrogen monoxide	kg	air	high population density	4.05E-03	5.48%
Carbon dioxide, fossil	kg	air	unspecified	3.75E-03	5.08%
Methane, fossil	kg	air	low population density	1.72E-03	2.32%
The rest	kg			9.39E-04	1.27%

Conventional Gasoline

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total GWP (%)
Carbon dioxide, fossil	kg	air	unspecified	7.32E-02	81.13%
Carbon dioxide, fossil	kg	air	high population density	9.14E-03	10.13%
Carbon dioxide, fossil	kg	air	low population density	4.82E-03	5.34%
Carbon monoxide, fossil	kg	air	unspecified	1.13E-03	1.26%
Methane, fossil	kg	air	low population density	9.92E-04	1.10%
The rest	kg			9.47E-04	1.05%

Soybean Diesel (BD100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total GWP (%)
Carbon dioxide, biogenic	kg	as a credit, uptaken during soyebean growth		-6.70E-02	-226%
Dinitrogen monoxide	kg	air	low population density	1.35E-02	45.61%
Carbon dioxide, fossil	kg	air	high population density	7.11E-03	24.03%
Carbon dioxide, fossil	kg	air	low population density	4.70E-03	15.89%
Carbon dioxide, fossil	kg	air	unspecified	2.07E-03	6.98%
Dinitrogen monoxide	kg	air	unspecified	8.65E-04	2.92%
Methane, fossil	kg	air	low population density	7.46E-04	2.52%
The rest	kg			6.06E-04	2.05%

Conventional Diesel

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total GWP (%)
Carbon dioxide, fossil	kg	air	unspecified	7.53E-02	86.34%
Carbon dioxide, fossil	kg	air	high population density	5.30E-03	6.08%
Carbon dioxide, fossil	kg	air	low population density	4.50E-03	5.16%
Methane, fossil	kg	air	low population density	9.52E-04	1.09%
The rest	kg			1.17E-03	1.34%

2) Eutrophication (EP)

Corn Ethanol (E100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total EP (%)
Phosphorus	kg	water	river	8.76E-05	71.00%
Ammonia	kg	air	low population density	1.60E-05	12.98%
Nitrogen oxides	kg	air	low population density	4.39E-06	3.56%
COD, Chemical Oxygen Demand	kg	water	river	3.26E-06	2.64%
BOD5, Biological Oxygen Demar	kg	water	river	3.18E-06	2.58%
Phosphate	kg	water	river	2.20E-06	1.78%
Nitrogen oxides	kg	air	unspecified	1.59E-06	1.29%
Nitrogen oxides	kg	air	high population density	1.47E-06	1.19%
Ammonium, ion	kg	water	river	1.37E-06	1.11%
The rest	kg			2.30E-06	1.87%

Conventional Gasoline

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total EP (%)
COD, Chemical Oxygen Demand	kg	water	river	1.52E-05	45.07%
BOD5, Biological Oxygen Demanc	kg	water	river	1.51E-05	44.81%
Nitrogen oxides	kg	air	unspecified	1.32E-06	3.93%
Nitrogen oxides	kg	air	low population density	1.32E-06	3.91%
Nitrogen oxides	kg	air	high population density	5.40E-07	1.60%
The rest	kg			2.30E-07	0.68%

Soybean Diesel (BD100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total EP (%)
Phosphorus	kg	water	river	1.03E-04	87.85%
Ammonia	kg	air	low population density	5.40E-06	4.61%
Nitrogen oxides	kg	air	unspecified	2.15E-06	1.84%
Phosphate	kg	water	river	2.12E-06	1.81%
Nitrogen oxides	kg	air	low population density	1.76E-06	1.50%
The rest				2.82E-06	2.40%

Conventional Diesel

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total EP (%)
COD, Chemical Oxygen Demand	kg	water	river	1.51E-05	45.15%
BOD5, Biological Oxygen Demanc	kg	water	river	1.51E-05	44.89%
Nitrogen oxides	kg	air	unspecified	1.55E-06	4.62%
Nitrogen oxides	kg	air	low population density	1.29E-06	3.83%
The rest	kg			5.06E-07	1.51%

3) Acidification (AD)

Corn Ethanol (E100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total AD (%)
Ammonia	kg	air	low population density	1.29E-02	49.07%
Nitrogen oxides	kg	air	low population density	3.97E-03	15.09%
Sulfur dioxide	kg	air	high population density	3.03E-03	11.53%
Sulfur dioxide	kg	air	low population density	2.46E-03	9.36%
Nitrogen oxides	kg	air	unspecified	1.43E-03	5.46%
Nitrogen oxides	kg	air	high population density	1.33E-03	5.05%
Ammonia	kg	air	high population density	6.92E-04	2.63%
Sulfur dioxide	kg	air	unspecified	3.43E-04	1.31%
The rest	kg			1.35E-04	0.51%

Conventional Gasoline

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total AD (%)
Sulfur dioxide	kg	air	low population density	4.39E-03	46.23%
Sulfur dioxide	kg	air	high population density	2.13E-03	22.43%
Nitrogen oxides	kg	air	unspecified	1.20E-03	12.58%
Nitrogen oxides	kg	air	low population density	1.19E-03	12.52%
Nitrogen oxides	kg	air	high population density	4.88E-04	5.14%
The rest	kg			1.04E-04	1.10%

Soybean Diesel (BD100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total AD (%)
Ammonia	kg	air	low population density	4.35E-03	40.41%
Nitrogen oxides	kg	air	unspecified	1.95E-03	18.09%
Nitrogen oxides	kg	air	low population density	1.59E-03	14.81%
Sulfur dioxide	kg	air	high population density	1.33E-03	12.34%
Sulfur dioxide	kg	air	low population density	9.31E-04	8.65%
Nitrogen oxides	kg	air	high population density	3.16E-04	2.94%
Sulfur dioxide	kg	air	unspecified	1.84E-04	1.71%
The rest	kg			1.13E-04	1.05%

Conventional Diesel

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total AD (%)
Sulfur dioxide	kg	air	low population density	3.74E-03	47.31%
Nitrogen oxides	kg	air	unspecified	1.40E-03	17.74%
Sulfur dioxide	kg	air	high population density	1.25E-03	15.88%
Nitrogen oxides	kg	air	low population density	1.16E-03	14.72%
Nitrogen oxides	kg	air	high population density	2.79E-04	3.54%
The rest	kg			6.44E-05	0.82%

4) Ecological Toxicity (ET)

Corn Ethanol (E100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total ET (%)
Aluminium	kg	air	unspecified	5.59E-03	41.55%
Copper	kg	air	high population density	2.42E-03	17.98%
Aluminium	kg	air	low population density, long-terr	7.80E-04	5.80%
Zinc	kg	air	high population density	6.53E-04	4.86%
Aluminium	kg	soil	agricultural	5.37E-04	3.99%
Aluminium	kg	air	high population density	5.06E-04	3.76%
Aluminium	kg	water	river	4.96E-04	3.69%
Aluminium	kg	soil	industrial	4.57E-04	3.39%
Copper	kg	air	low population density	3.42E-04	2.55%
Copper, ion	kg	water	river	2.48E-04	1.84%
Nickel	kg	air	high population density	1.98E-04	1.47%
Copper	kg	air	unspecified	1.64E-04	1.22%
Cypermethrin	kg	soil	agricultural	1.51E-04	1.12%
Zinc	kg	air	low population density	1.47E-04	1.09%
The rest	kg			7.63E-04	5.67%

Conventional Gasoline

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total ET (%)
Aluminium	kg	soil	industrial	1.65E-03	52.18%
Aluminium	kg	air	unspecified	6.51E-04	20.52%
Aluminium	kg	air	low population density, long-term	1.85E-04	5.82%
Zinc, ion	kg	water	river	1.74E-04	5.49%
Nickel	kg	air	high population density	1.34E-04	4.22%
Aluminium	kg	water	river	7.48E-05	2.36%
Copper	kg	air	high population density	5.76E-05	1.82%
Nickel	kg	air	low population density	3.82E-05	1.21%
Copper	kg	air	low population density	3.26E-05	1.03%
The rest	kg			1.70E-04	5.36%

Soybean Diesel (BD100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total ET (%)
Aluminium	kg	air	unspecified	2.67E-03	57.73%
Aluminium	kg	air	high population density	6.65E-04	14.37%
Aluminium	kg	air	low population density, long-terr	2.46E-04	5.30%
Aluminium	kg	soil	industrial	1.30E-04	2.81%
Copper	kg	air	low population density	1.13E-04	2.43%
Copper	kg	air	unspecified	1.04E-04	2.24%
Copper, ion	kg	water	river	9.34E-05	2.02%
Aluminium	kg	soil	agricultural	8.89E-05	1.92%
Aluminium	kg	water	river	8.38E-05	1.81%
Copper	kg	air	high population density	7.22E-05	1.56%
Zinc	kg	air	low population density	5.55E-05	1.20%
The rest	kg			3.07E-04	6.63%

Conventional Diesel

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total ET (%)
Aluminium	kg	soil	industrial	1.65E-03	57.75%
Aluminium	kg	air	unspecified	5.28E-04	18.51%
Zinc, ion	kg	water	river	1.62E-04	5.69%
Aluminium	kg	air	low population density, long-term	1.47E-04	5.15%
Nickel	kg	air	high population density	8.64E-05	3.03%
Aluminium	kg	water	river	5.63E-05	1.97%
Copper	kg	air	high population density	3.54E-05	1.24%
Nickel	kg	air	low population density	3.54E-05	1.24%
The rest	kg			1.55E-04	5.43%

5) Human Respiratory Effect (HRE)

Corn Ethanol (E100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total HRE (%)
Sulfur dioxide	kg	air	high population density	1.44E-05	29.02%
Sulfur dioxide	kg	air	low population density	1.17E-05	23.55%
Particulates, < 2.5 um	kg	air	low population density	7.65E-06	15.44%
Nitrogen oxides	kg	air	low population density	4.54E-06	9.16%
Particulates, < 2.5 um	kg	air	unspecified	3.37E-06	6.80%
Particulates, < 2.5 um	kg	air	high population density	3.06E-06	6.17%
Nitrogen oxides	kg	air	unspecified	1.64E-06	3.31%
Sulfur dioxide	kg	air	unspecified	1.63E-06	3.29%
Nitrogen oxides	kg	air	high population density	1.52E-06	3.07%
The rest	kg			8.86E-08	0.18%

Conventional Gasoline

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total HRE (%)
Sulfur dioxide	kg	air	low population density	2.09E-05	49.50%
Sulfur dioxide	kg	air	high population density	1.01E-05	24.02%
Particulates, < 2.5 um	kg	air	unspecified	3.09E-06	7.35%
Particulates, < 2.5 um	kg	air	low population density	2.54E-06	6.02%
Particulates, < 2.5 um	kg	air	high population density	1.85E-06	4.39%
Nitrogen oxides	kg	air	unspecified	1.37E-06	3.25%
Nitrogen oxides	kg	air	low population density	1.36E-06	3.23%
Nitrogen oxides	kg	air	high population density	5.59E-07	1.33%
The rest	kg			3.82E-07	0.91%

Soybean Diesel (BD100)

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total HRE (%)
Sulfur dioxide	kg	air	high population density	6.31E-06	25.98%
Sulfur dioxide	kg	air	low population density	4.42E-06	18.20%
Particulates, < 2.5 um	kg	air	unspecified	4.34E-06	17.88%
Particulates, < 2.5 um	kg	air	low population density	3.43E-06	14.12%
Nitrogen oxides	kg	air	unspecified	2.23E-06	9.19%
Nitrogen oxides	kg	air	low population density	1.83E-06	7.52%
Sulfur dioxide	kg	air	unspecified	8.73E-07	3.60%
Particulates, < 2.5 um	kg	air	high population density	4.62E-07	1.90%
Nitrogen oxides	kg	air	high population density	3.62E-07	1.49%
The rest	kg			2.79E-08	0.11%

Conventional Diesel

Substance	unit	Category	Sub-category	Emissions (kg/MJ)	Percent contribution to total HRE (%)
Sulfur dioxide	kg	air	low population density	1.77E-05	51.34%
Sulfur dioxide	kg	air	high population density	5.96E-06	17.23%
Particulates, < 2.5 um	kg	air	unspecified	3.86E-06	11.15%
Particulates, < 2.5 um	kg	air	low population density	2.42E-06	7.00%
Nitrogen oxides	kg	air	unspecified	1.60E-06	4.64%
Nitrogen oxides	kg	air	low population density	1.33E-06	3.85%
Particulates, < 2.5 um	kg	air	high population density	1.12E-06	3.24%
The rest	kg			5.32E-07	1.54%

Appendix D. Sensitivity Analysis (for Dominant Substance)

Sensitivity Analysis - corn ethanol

Human cancer

Atrazine to soil (agricultural)

% reduction in substance use	% Reduction in Human Cancer Effects		
	Max	Mean	Min
25	9.8%	14.4%	19.5%
50	19.6%	28.8%	39.0%
100	39.3%	57.6%	78.0%

Human non-cancer

Lead to water (river)

% reduction in substance use	% Reduction in Human Non-cancer Effects		
	Max	Mean	Min
25	14.4%	13.7%	11.1%
50	28.8%	27.3%	22.3%
100	57.6%	54.7%	44.5%

Ecological Toxicity

Aluminum to air (unspecified)

% reduction in substance use	% Reduction in Ecological Toxicity		
	Max	Mean	Min
25	10.8%	10.4%	9.4%
50	21.6%	20.8%	18.8%
100	43.2%	41.6%	37.6%

Sensitivity Analysis - Soy diesel

Human cancer

Arsenic to air (low population)

% reduction in substance use	% Reduction in Human Cancer Effects		
	Max	Mean	Min
25	9.8%	10.9%	12.6%
50	19.6%	21.8%	25.3%
100	39.2%	43.5%	50.5%

Human non-cancer

Lead to water (river)

% reduction in substance use	% Reduction in Human Non-cancer Effects		
	Max	Mean	Min
25	16.1%	14.9%	12.9%
50	32.2%	29.8%	25.9%
100	64.3%	59.6%	51.8%

Ecological Toxicity

Aluminum to air (unspecified)

% reduction in substance use	% Reduction in Ecological Toxicity		
	Max	Mean	Min
25	14.4%	14.4%	14.6%
50	28.8%	28.9%	29.1%
100	57.7%	57.7%	58.2%