Life Cycle Impact of Soybean Production and Soy Industrial Products

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Prepared for

The United Soybean Board

By

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Additional data tables as well supplemental technical information are available on request.
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Introduction

Objectives

The past decade has witnessed an increased consumer and government interest in replacing petroleum based products with those made from or with biobased resources. As the array of biobased products has increased, so too has the interest in evaluating the energy and environmental impacts of these products. One common method of measuring those impacts is to conduct a life cycle assessment (LCA).

To conduct a credible LCA, it is critical to use good quality, current data on all raw materials, energy, and processing aids used as well as the environmental outputs associated with producing a product because this information becomes the platform for performing the life cycle inventories (LCIs) which are the basis for the LCA. The existing databases for soybean agriculture and processing were, in many cases, over 10 years old and no longer representative of current energy use or raw material production processes.

The United Soybean Board[1] commissioned Omni Tech International, Ltd. to perform an update of the data for soybean production and processing and soy feedstocks for the purpose of calculating LCAs and for other life cycle related tools. The LCA modeling was performed by Four Elements Consulting, LLC. The main objective of the project was to update the cradle-to-gate data for soybean production and conversion of soybean oil and meal into key soy-derived feedstocks (methyl soyate, soy lube base stock, soy polyol, and soy resin) used in fuel and industrial products in order to calculate life cycle inventories (LCIs).

These updated data sets are now available and will be placed into the U.S. Life Cycle Inventory (U.S. LCI) Database, which is managed by the Department of Energy's National Renewable Energy Laboratory (NREL). Until now, only soybean production data have been included in the U.S. LCI Database; as a result of this study, data on soybean processing, refining, and conversion into key soy-derived feedstocks can be added to the Database.

Standards Used

This study has been conducted in accordance with the International Standards Organization (ISO) standards on LCA, including:

- ISO 14040:2006, the International Standard of the International Standardization Organization, Environmental management. Life cycle assessment. Principles and framework.

[1] The United Soybean Board (USB) is made up of 68 farmer-directors who oversee the investments of the soybean checkoff on behalf of all U.S. soybean farmers. As stipulated in the Soybean Promotion, Research and Consumer Information Act, USDA's Agricultural Marketing Service has oversight responsibilities for USB and the soybean checkoff.

- ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

Peer Review

The study has been peer reviewed by a group of international reviewers to verify that the project was performed in accordance with ISO 14040 and 14044 standards to ensure credibility and objectivity of the data and results. Reviewers included: Dr. Martin Patel of Utrecht University (chairperson) and Michael Levy of the American Chemistry Council.

Scope Definition and Methodology

General System Overview

The following table summarizes the system components of the study:

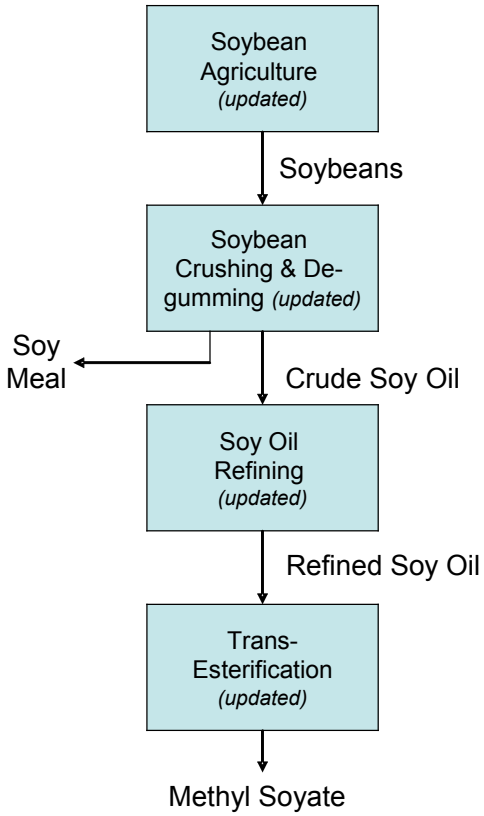
Table 1 Systems Studied

Soy-related unit processes (cradle-to-gate LCIs produced)	Soy agriculture
	Soy crude oil and soy meal production (crushing)
	Soy oil refining
	Methyl soyate (biodiesel)[2]
Comparisons (cradle-to-gate LCIs and LCIAs produced)	Soy biodiesel vs. Petroleum diesel
	Soy-based oil for lubricant vs. Petroleum-based oil for lubricant
	Soy-based polyol vs. Petroleum-based polyol
	Soy-based resin vs. Petroleum-based resin

ISO defines a unit process as the "smallest element of a product system for which data are collected when performing a life cycle assessment."[3] The unit processes updated for this study include: soybean growing/agriculture, crushing into crude soybean oil and meal, refining, and methyl soyate production by transesterification, shown in the figure below. Transportation aspects for each unit process are included. Unit processes to represent the manufacturing of other soy-based products and intermediate materials for other product/material comparisons in this study have also been built. For each analysis, some or all of these unit process stages are linked together to form the basis of the LCIs and Life Cycle Impact Assessments (LCIAs) for soy-based products and intermediate materials. Diagrams representing each system studied are presented in each of the respective sections in the Modeling & Assumptions section of this report.

[2] Methyl soyate and biodiesel are being used interchangeably in this study.
[3] ISO 14040, Sec 3.45.

Figure 1 Unit Process Stages Updated



Cut-Off Criteria: Inclusion in the System Boundaries

ISO 14044 requires a cut-off criterion to be defined for the selection of materials and processes to be included in the system boundary. Several criteria are used in LCA practice to decide which inputs are to be studied, including mass, energy and environmental relevance.[4] The mass criterion was applied, and a cut-off goal of 99% of material inputs was defined.

Detailed information on the materials required for each unit process stage were collected, and every effort was made to include life cycle data for the production of these materials or to find suitable surrogate data (i.e., if data on that material was not included). Despite a defined cut-off criteria based on mass, an attempt was still made to collect all materials and energy inputs to the systems, regardless of mass contribution, in order to capture all materials that may be environmentally relevant.

Exclusion of Data from the System Boundaries

The scope and boundaries exclude impacts for human activities associated with production of the feedstocks and products that are outside the facility boundaries, such

[4] ISO 14044, Section 4.2.3.3.

as employee travel to and from work. Impacts for facility construction and capital equipment are also excluded, as these impacts typically are negligible when allocated over the total quantity of product manufactured over the life cycle of the facilities and equipment.[5] Packaging of the final products has also been excluded since it is assumed that the products are packaged similarly and net differences in the results would therefore be small.

Function and Functional Unit

In order to conduct a proper LCA under the ISO guidelines, product results are run based on a unit summarizing their function or service. This allows for the comparison of different industrial products performing the same function. The cradle-to-gate unit process data on soy feedstocks are modeled on a mass basis since these data are used as building blocks to other LCA systems. All results are run based on 1000 kg of output.

The function of the product comparisons is the use of soy-based products and their petroleum-based alternatives in fuel and industrial products. The comparisons have been run on 1000 kg of each, with the assumption that the materials compared perform generally the same on an equivalent weight basis. It should be noted that for some of the products compared, while they generally can be used interchangeably in many applications, the precision of this one-to-one replacement in terms of actual performance is difficult to assess since every formulation using such materials may have different requirements and functions. It is out of the scope of this work to evaluate each product on the basis of very precise applications. So users of the results should understand that this is a limitation in the results, and that decisions made for the use of these products should be based on appropriateness and applicability of each material as well as the trade-offs of the environmental impacts being evaluated.

Allocation

Mass allocation was used as the main allocation rule for the baseline analysis in this study. However, the data used to build the LCIs are available in unallocated form and these are the data that will be submitted to the U.S. LCI database. This will allow the LCA practitioner or other data user to decide upon an allocation rule appropriate for his/her study.

In LCA, when allocation is necessary, the key to robust modeling is to determine the basis for the allocation (e.g., based on mass, economic value, etc.). It was decided for this study that allocation based on the mass of the products and coproducts would be made for the baseline results. There is a careful rationale behind this methodological decision. Physical partitioning was done because it made the most sense and had the least set of uncertainties. The economics of soy oil and soy meal values are volatile, requiring data to be updated frequently. Also using system boundary expansion was found not to be a viable option for this analysis. Finally, mass allocation has been used for the LCAs performed on biobased products evaluated for the Federal BioPreferred Program. Nonetheless, a sensitivity analysis was conducted using economic allocation. The results of the sensitivity analysis as well as more information on the allocation

[5] Note that capital equipment is included where data sets in the software do contain that information.

decision rationale are found in Appendix A (Allocation Determination and Economic Sensitivity Analysis).

Modeling Tools

The LCA model was built in SimaPro 7, a commercially available LCA software product.[6] This software contains U.S. and European databases on a wide variety of materials in addition to an assortment of European- and U.S.-developed impact assessment methodologies.

Data Categories and Life Cycle Impact Assessment

Life Cycle Inventory (LCI)

Cradle-to-gate life cycle models for the intermediate and final products were constructed in SimaPro and LCI results were generated

Life Cycle Impact Assessment (LCIA)

LCI results for the product comparisons are classified into impact categories, that is, categories in which a set of related flows may contribute to impacts on human or environmental health. The Building for Environmental and Economic Sustainability (BEES) set of impacts were used for the following reasons:

- BEES has adopted the U.S. EPA-developed Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI)[7], a set of peer-reviewed U.S.-based LCIA methods;
- BEES has a comprehensive set of impacts to meet ISO's requirements for a range of impact categories;
- BEES has a recognized and accepted methodology to ensure a level playing field in terms of its methodological approach; and
- The BEES framework and impact categories are used for other government programs, such as the USDA's BioPreferred program.[8]

[6] PRé Consultants: *SimaPro 7.0 LCA Software*. 2006. The Netherlands.
[7] U.S. Environmental Protection Agency, Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User's Guide and System Documentation, EPA/600/R-02/052, U.S. EPA Office of Research and Development, Cincinnati, OH, August 2002.
[8] See http://www.bfrl.nist.gov/oae/software/bees/please/USDA/bees_please.html.

The following table presents the LCIA categories included.

Table 2 LCIA Categories

Impact Category	Units
Global Warming	CO_2 equivalents
Acidification	H^+ equivalents
Eutrophication	N equivalents
Fossil Fuel Depletion	MJ surplus energy
Water Intake [notes 1,2]	liters of water
Criteria Air Pollutants	microDALYs
Smog	NO_x equivalents
Ecological Toxicity	2,4-D equivalents
Ozone Depletion	CFC-11 equivalents
Human Health – Cancer	C_6H_6 equivalents
Human Health – NonCancer	C_7H_8 equivalents
Total Fuel Energy [notes 3,4]	MJ

Note 1: Total water usage is specific to BEES and is not included in TRACI.
Note 2: For example: water used in agriculture is from irrigation (rainfall would not be included in this figure). Water intake for other process stages means water used for all process steps including steam generation and cooling where applicable.
Note 3: fuel energy values are based on lower heating values.
Note 4: Total fuel energy is all energy related to what was used as fuel in the whole system. The fossil fuel depletion category accounts for only the coal, natural gas, and crude oil in the system.

LCIA has limitations, and users of this study must understand these limitations:

1. Spatial and temporal resolution is lost in an LCA. When emissions are put in terms of a functional unit, the system becomes a snapshot in time and space. So all temporal and geographical characteristics which are needed to assess local environmental impacts, i.e., human and/or ecological health-related, are lost. LCA results do not distinguish between emissions released instantaneously and locally and those released over a large geographical area over a long period of time. Also, amplifying and/nor attenuating effects of toxic chemicals may not be taken into account.

2. Threshold effects are lost in an LCA. LCA is based on a linear extrapolation of mass loadings with the assumption that this loading contributes to an environmental effect. This is contrary to threshold-driven environmental and toxicological mechanisms. Thus, while the linear extrapolation of mass loadings is a reasonable approach for more global and regional impact categories such as GWP and acidification, it is not as appropriate a measure for human health- and toxicity- related impacts.

In addition, readers should recognize that human health- and toxicity-related impacts do not include all toxic chemicals at this time. In light of these limitations, LCA results for human health- and toxicity- related impacts, such as human cancer and non-cancer potentials and ecotoxicity, should be used with caution. Results for these categories should be understood to be more limited than some other categories.

Modeling & Assumptions

Data and Energy Used

Both primary data (collected from a manufacturing plant) and secondary data (publicly-available, literature sources) can be used for LCAs. This study contains a mix of primary and secondary data, and this is detailed below in the specific modeling and data quality sections.

All energy data in this study comes from the U.S. LCI database. Unless otherwise specified, the average U.S. electricity grid is used, containing 53% coal, 16% natural gas, 20% nuclear, 3% heavy fuel oil, 7% hydropower, and 1% other biomass renewables)[9]. A line loss factor of 9.91% which represents the difference between electricity generated and electricity sold is accounted for. All power quantities provided in the data tables in this study come from the electricity grid and not facility-specific combined heat and power (CHP) units. Steam is generated from natural gas unless otherwise specified.

Note that except where specified, the air emissions outputs in the data tables below are process-related, and not related to energy use. The emissions resulting from energy use/combustion are accounted for in upstream data sets.

Accounting for Carbon Sequestration

In this cradle-to-gate study, the sequestration of carbon is taken into account, based on the quantity of biomass carbon embedded in each of the final products (see Table 13). In the results, the biomass carbon content, in terms of its quantity in CO2, is subtracted from the GWP total. It should be noted that this accounting of embodied carbon is the same, regardless of choice of allocation used.

The reader should be reminded that the carbon sequestered in feedstocks may or may not be released during use or the end-of-life phase of the end product (depends on the end-use application).

Soybean Growing/Agriculture

Data for the agricultural processes to produce soybeans is based on average U.S. soybean production practices in the U.S., and data are based mainly on the years 2001 through 2007. These soybean agriculture data are an update of the existing soybean data that are currently published in the U.S. LCI database.[10]

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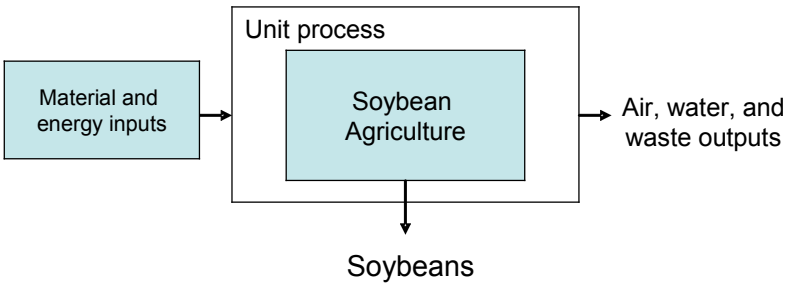
[9] U.S. LCI Database process information for the U.S. average electricity grid. Found at http://www.nrel.gov/lci/database/default.asp.

[10] The U.S. LCI current data comes from the soybean growing data in National Renewable Energy Laboratory's (NREL's) LCA study on biodiesel use in an urban bus, some of which was updated by Omni Tech International and other experts in 2003. The NREL study, hereinafter referred to as "Biodiesel Report", is cited as follows: Sheehan, J. et al., **Life Cycle Inventory of Biodiesel and Petroleum Diesel**

The soybean agriculture data are provided as a single unit process (see figure below), and include:

- Use of farm tractors;
- Irrigation (only consumptive use taken into account);
- Use of nitrogen, phosphorous, and potash fertilizers and air emissions and water effluents associated with those inputs. Note: the influence of a previous year crop has been taken into account through the actual quantities of fertilizer/pesticide used in the current year;
- Use of pesticides and herbicides and air emissions and water effluents associated with those inputs;
- Other energy and materials requirements, including energy to grow seedlings; and
- Transportation of the material inputs to the farm.

Figure 2 Soy Agriculture Unit Process



The updated information is summarized below. Where there was no change in data from the original soy agriculture data set ("NC"), refer to the documentation on the U.S. LCI database website.

Table 3 Updated Soy Agriculture Inputs

Inputs	Quantity per 1000 kg soybeans[Note 1]	Source
Energy inputs[11]		
Diesel (farm tractor) (l)	14.3	5
Electricity (MJ elec.)	25	5
Gasoline (farm tractor) (l)	4.5	5
LPG (MJ)	32	5
Natural gas (MJ)	48	5
Material inputs		
Agrochemicals (kg)	0.52	1
Nitrogen Fertilizer (NH4NO3 as N) (kg)	1.6	1
Phosphorous Fertilizer (TSP as P2O5) (kg)	5.0	1
Potash Fertilizer (K2O) (kg)	9.3	1
Quick lime (kg)	94	2,3

for Use in an Urban Bus, NREL/SR-580-24089 (Washington, DC: U.S. Department of Agriculture and U.S. Department of Energy, May 1998).

[11] Note that the energy in this and other tables in this report is reported as unit process energy, and not, for example, for energy related to material inputs (that energy is captured upstream).

Water (from river) (l)[note 2]	15855	4
Water (from well) (l)[note 2]	34725	4
Land use information		
Cropland (Conservation Tillage) (m2.yr)	2034	NC
Cropland (Conventional Tillage) (m2.yr)	850	NC
Cropland (Reduced Tillage) (m2.yr)	723	NC

Note 1: The average yield of soybeans for the years 2004 through 2007 was 1120 kg/acre. U.S. soybean data from United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) database found at www.nass.usda.gov, and US soybean seed data from USDA/Economic Research Service (ERS) Crop Production Practices database, found at www.ers.usda.gov.
Note 2: A report that has recently been published contains irrigation data consistent with that in the table (The Keystone Center, "Environmental Resources Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States", First Report, January 2009, p.44, found at http://keystone.org/files/file/SPP/Field-to-Market_Environmental -Indicator_First_Report_with_Appendices_01122009.pdf)

Source 1: USDA NASS Agricultural Chemical Usage Field Crops Summary Reports for 2006, 2005, 2004, 2002 and 2001, found at www.nass.usda.gov.
Source 2: Agricultural Resources & Economic Indicators, 2006 edition/EIB-16/Economic Research Services/USDA, p. 97. Based on 2002 survey by the Economic Research Services of the USDA, approximately 80% of the soybean acres in the 10 major producing states use corn-soybean rotation. The average lime application rate was allocated to soybeans based on the ratio of soybean and corn usage.
Source 3: Personal communication (email), James Duffield to James Pollack, September 9, 2008 with attachment "devLime data published.doc".
Source 4: USDA Farm & Ranch Irrigation Survey reports for 1994, 1998, and 2003, found at www.agcensus.usda.gov.
Source 5: Argonne National Lab report ANL/ESD/08-02, pp. 14-17. Specifically, the data was retrieved from USDA, 2007b, Data Sets: Commodity Costs and Returns, available at http://www.ers.usda.gov/Data/CostsAndReturns/Fuelbystate.xls, accessed Nov. 2007. Current data was pulled from Ag resource and management survey (ARMS), Economic Research Service, USDA, for year 1997.

Transportation of materials to the field has been accounted for, and an average distance of 300 miles is used, and the materials are transported by truck. For modeling in SimaPro of this and all the input data for this study, data for energy and transportation come from the U.S. LCI database. Data for materials are from secondary sources from the following databases (in order of preference and data availability): the U.S. LCI database, the EcoInvent database,[12] and the SimaPro database which contains data sets with varying levels of data quality in terms of representativeness of technology, age of data, and geography of the processes.

[12] Generally reputed to be current, representative data on processes and chemicals, the EcoInvent database is a for-purchase database developed by the Swiss Center for Life Cycle Inventories. EcoInvent is used in conjunction with other databases in the SimaPro software. More information can be found at www.ecoinvent.org.

The output data from soybean production includes biomass CO2 (-1,560,995 grams per 1,000 kg soybeans[13]), nitrous oxide (350 grams per 1,000 kg soybeans[14]), and air and water emissions associated with fertilizer, agrochemicals, and other agriculture activities. This full data set will be available as part of the submission to the U.S. LCI database.

Some components of soybean agriculture were excluded either due to general LCA practice or lack of available data, including:

- Capital equipment for farm machinery and buildings
- Farmer-related impacts, such as production and consumption of food
- Micronutrients
- Nitrification inhibitors

Soybean Processing to Produce Soy Crude Oil and Meal

The data for soybean processing were collected and aggregated by the National Oilseed Processors Association (NOPA).[15] To the degree possible, NOPA has provided updated data for specific energy and material "inputs" and "outputs" set forth in a May 1998 Final Report issued by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) entitled "Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus."

The data in the 1998 NREL Report were obtained from a single soybean processing plant. These data were not representative of either other individual soybean processing plants or the soybean processing industry as a whole.

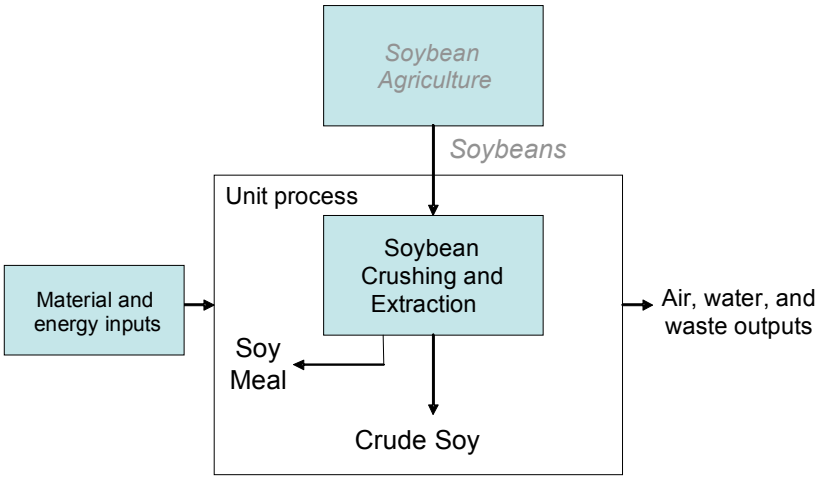
NOPA's data, obtained by surveying its 15 member companies in mid-December 2008 for data reflective of each company's most recent fiscal year, do not reflect the performance of any single soybean processing plant. Rather, the data reflect company-supplied data that NOPA received on 50 of the 60 soybean processing plants that it represents, and are broadly reflective of energy and material inputs and outputs for soybean processing plants similar in general design and processes to the plant that was evaluated in the 1998 Report. The data that NOPA received were provided as full-facility inputs and outputs on a per-soybean input basis, and cover soybean processing via solvent extraction through crude oil degumming.

[13] Calculated based on soybean carbon content of 42.6%.

[14] Calculated using 2006 **IPCC Guidelines** and **U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2005,** DAYCENT and CENTURY models, Global Change Program Office, Office of the Chief Economist, USDA, 2008.

[15] David Ailor, Vice President of Regulatory Affairs for the National Oilseed Processors Association, Washington, D.C., provided the aggregated data in January 2009, following a data collection effort that he undertook in December 2008 and January 2009 via NOPA's "Technical and Research, Environmental, Security, and Safety, Health & Loss Prevention" (TESH) Committee.

Figure 3 Soybean Crushing and Extraction Process



The updated soybean processing data are summarized in the table below.

Table 4 Soybean Processing Updated Data (per 1000 kg Oil)

Inputs	Biodiesel Study	NOPA Updates	Notes
Energy inputs			
Electricity (kWh)	410	289	
Natural Gas (kcal)	1,569,000	---	
Steam (kcal)	1,296,000		
% NG (NOPA)	---	65%	Fuel types were not broken down this specifically in Biodiesel study
% #2 FO (NOPA)	---	0.5%	
% #6 FO (NOPA)	---	1%	
% Coal (NOPA)	---	32%	
% Biomass (NOPA)	---	1%	
% LF gas (NOPA)	---	0.5%	
Total kcal of heat	*2,865,000*	*1,502,729*	NOPA data do not include data from six plants that do not produce steam onsite.
Material inputs			
Soybeans (kg)	5,891	5,236	NOPA note: 1000 bushels of soybeans
Hexane (kg)	11.9	2.96	See **note 1** below.
Water (kg)	19.4	2,547	See **note 2** below.
Outputs			
Products (kg)			
Soy Meal Produced (% by mass)	4,478 (82%)	4,131 (80.5%)	Based on five-year (2003-2007) average yields that NOPA has provided to USDA. Also see **note 3** below.
Soybean Oil Produced (% by mass)	1000 (18%)	1000 (19.5%)	
Air Emissions (kg)			
Hexane	10.15	2.96	See **note 1** below.
Water Effluents (kg)			
Water	453	1,383	For NOPA: the difference between the water input and output is primarily evaporation losses.

Fats, oils, and grease	5.0	<0.14	
Triglycerides	4.9	---	Not broken out by NOPA
Unsaponifiable Matter	0.08	---	
Free Fatty Acids	0.04	---	
Nonhaz. solid waste (kg)	46	8.7	

Note 1: NOPA's hexane input and air emissions numbers are based on EPA's Vegetable Oil MACT limit of 0.2 gallon of hexane lost/ton of soybeans processed with an assumed specific gravity of hexane of 5.65 pounds/gallon. The MACT limit is a "total loss" limit that reflects total hexane disappearance, the vast majority of which is via air emissions.
Note 2: NOPA data reflect individual facility metered water use, which includes water used in cooling towers, steam production, and other process-related equipment. NOPA believes the current data are more accurate than the water use data contained in the 1998 lifecycle inventory.
Note 3: In 1998 it took 5,891 kilograms of soybeans to produce 1,000 kilograms of oil, but the new data show only 5,236 kilograms of soybeans needed to produce 1,000 kilograms of oil, representing an 11% increase in efficiency. In 1998, 1,316 kilograms of soybeans produced 1,000 kilograms of meal but the new data show only 1,267 kilograms of soybeans needed to produce 1,000 kilograms of meal, representing a 4% increase in efficiency.

Soybeans are modeled as being transported 75 miles to the crushing facility.[16] The products from soybean crushing/processing include degummed soy oil and soybean meal.

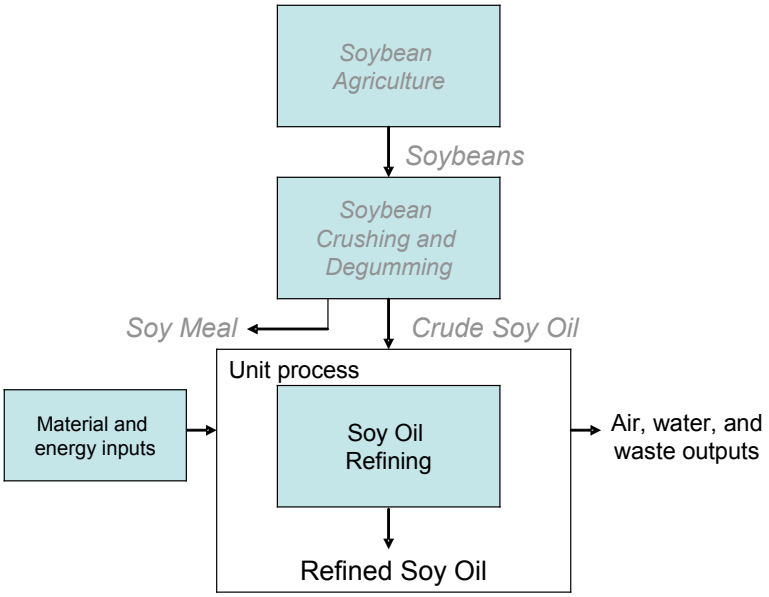
It is important to note that the data in Table 4 are unallocated data. Because there are multiple product outputs (or coproducts), the process inputs and outputs have to be divided or allocated among all products in order to fairly assign environmental impacts to each product. In LCA, when allocation is necessary, the key to robust modeling is to determine how an allocation is to be made (e.g., based on mass, economic value, etc.). It was decided for this study that allocation based on the mass of the products and coproducts would be made for the baseline results.

Crude Soy Oil Refining

Soy oil refining is modeled using the alkaline refining process. **[Note: If one is planning to model methyl soyate go to the next section.]** For this process, caustic soda is added to degummed crude oil, which reacts with the free fatty acids (FFA) to form soap stock. The oil/soap mixture is separated using a centrifuge, and filtration may be done to further clarify the oil from the soap. According to the Biodiesel study, 0.72% of total crude oil input is lost as FFA,[17] and a mass allocation has been made on refined soy oil and soap stock. For the economic allocation for sensitivity, the oil was given an allocation percentage of 100 since soap stock has a minimal value, especially relative to oil. The refining unit process relative to upstream production is as follows:

[16] Biodiesel Report, Sec. 5.2.1.
[17] Biodiesel study, Table 88.

Figure 4 Soy Oil Refining Unit Process



For this model, typical soy oil refining electrical and steam energy were provided by a large agro-processor in the U.S.[18] The other data used for soy oil refining were extrapolated from the Biodiesel report since it contained information on the alkaline refining processes occurring prior to transesterification into biodiesel.[19] The table below summarizes the inputs and outputs associated with production of refined soy oil.

Table 5 Refining Crude Soybean Oil

	Input or Output	Quantity per 1000 kg refined soy oil
Inputs	Crude, degummed soy oil (kg)	1042
	Caustic soda (kg)	2.3
	Water (l)	156
	Electrical energy (Btu)	15,223
	Steam energy (Btu)	56,644
Outputs	Refined soybean oil (kg)	1000
	Soap stock (kg)	7.4
	Wastewater (kg)	123
	- Water (kg)	*90.1*
	- Unsaponifiable matter and lost glycerides (kg)	*14.9*
	- Saponifiable oils and fats (kg)	*18.0*

Bleaching and deodorizing refined soybean oil is only done to produce food grade oil and these steps are not included in this model. Transportation of materials to the refining facility has been accounted for, and 200 miles by truck has been assumed for

[18] Company name not released for confidentiality purposes.
[19] Biodiesel report, Section 5.5.

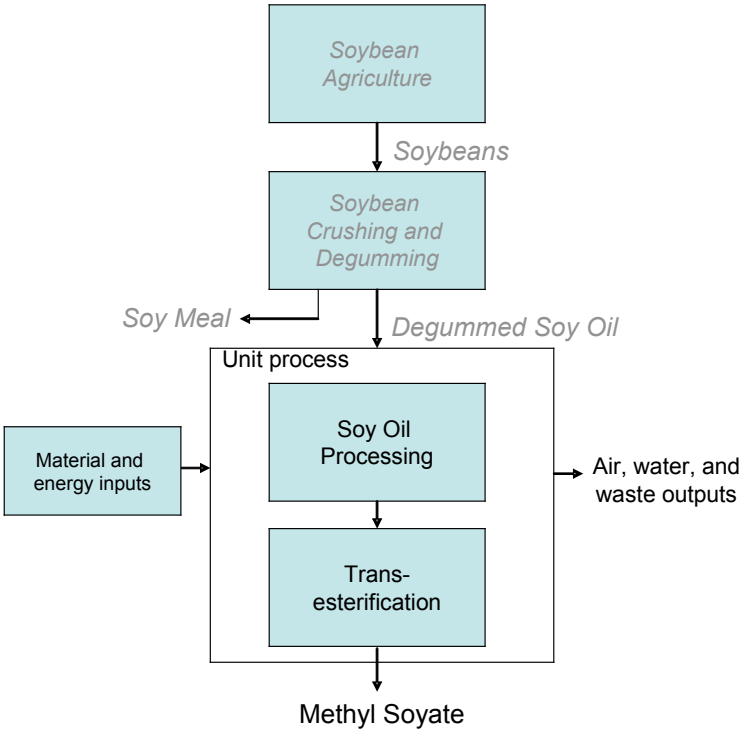
the caustic soda. It is important to note that the data in Table 5 are unallocated data. For this study, mass allocation was made for oil (99.3%) and the soap stock (0.7%).

NOTE: Table 6 for methyl soyate (biodiesel production) below includes the soy oil processing (refining) data. Therefore, when modeling methyl soyate, use the data in Table 6 in lieu of data in Table 5 to avoid double counting.

Methyl Soyate (Biodiesel) Production

For this model, methyl soyate is produced by transesterification, in which a simple alcohol is reacted with the triglycerides in soybean oil to produce methyl soyate and glycerin. The following figure presents the cradle-to-gate system boundaries for methyl soyate. The "unit process" box represents the biodiesel production data described in this section.

Figure 5 Methyl Soyate Production Unit Process



Responding to requests for biodiesel production data from academic institutions and government agencies such as the US Department of Agriculture, the National Biodiesel Board (NBB), the trade association representing the US biodiesel industry, surveyed 2008 energy and material use data from its member companies' commercial biodiesel production plants located in the U.S. NBB developed a survey that was sent to its entire membership, including 230 biodiesel producing companies. In order to design a survey instrument capable of accurately capturing the most relevant data, NBB sought input from organizations such as Argonne National Laboratories, developer of the GREET life cycle model.

According to NBB, 2008 was a record year for the volume of biodiesel production in the U.S., reaching nearly 700 million gallons.[20] The survey data returned by U.S. producers represents 37% of that volume, and as such, this is the first survey of biodiesel production primary data that represents such a substantial volume. Also, due to the good participation rate in this survey, the values represent an excellent cross section of biodiesel plant size, biodiesel production technologies, and biodiesel feedstocks.

[20] From http://www.biodiesel.org/resources/faqs/. Data originates from the Energy Information Administration.

One obstacle to acquiring this type of process-specific data is the reluctance of private companies to reveal trade secrets in a highly competitive market. Previous estimates of the energy used during biodiesel production had to rely on process modeling and data from a very small number of plants using older technology. The results reported from the NBB survey include no modeling and represent actual energy consumption measured and materials used at operating biodiesel facilities. For this reason, this updated, primary information is considered to be excellent quality and timely for this study.

The table below presents the industry-weighted average of energy and material inputs and products and other outputs. The data reported here were weighted against actual 2008 production volumes.[21]

Table 6 Biodiesel Production

	Input or Output	Quantity per 1 gal. Biodiesel
Inputs		
Feedstock	Virgin oil (lb)[note 1]	7.3285
Energy	Electricity (kWh)	0.12
	Natural Gas (Btu)[note 2]	2,763
Materials	Methanol (lb)	0.6735
	Sodium Methylate (lb)	0.1712
	Sodium Hydroxide (lb)	0.0072
	Hydrochloric Acid (lb)	0.3214
	Phosphoric Acid (lb)	0.0047
	Citric Acid (lb)	0.0054
	Water Usage (gal) [note 3]	0.30
Outputs		
	Biodiesel (gal) [note 4]	1.0
	Glycerin (lb)	0.8881
	Wastewater (gal)	0.0426
	Fatty Acids in w. water (lb)	0.0153

Note 1: Data here represents Biodiesel plants' data for both canola and soybean oils. According to NBB, very little variation was found between plants that used virgin oils, and that canola and soybean oil required similar energy inputs.
Note 2: Natural gas input is 2.69 standard cubic feet (SCF), with 1027 Btu per SCF
Note 3: This value comes from the Biodiesel study. The water use data from the surveys was not reported consistently enough with which to declare a new industry average. For example, some sites included only process water, while others included process and cooling water, etc.
Note 4: Assumed density: 7.4 pounds per gallon.

[21] Note from NBB documentation: weighting by actual plant production provides the most accurate representation of real-world production and provides a realistic estimate of energy use that can be expected as existing plants increase production volume. New plants and new technology implemented at existing plants can be expected to improve energy efficiency, just as has been demonstrated in recent years. No estimates for future energy improvements are included in this analysis.

It is important to note that the data in Table 6 are unallocated data. For this study, a mass allocation was made on the biodiesel and glycerin (89% and 11%, respectively).

Most of the facilities reported their incoming soy feedstock as general feedstock and did not distinguish between already refined oil, crude oil, or degummed crude oil. However, it was found that the difference in plant energy usage for plants reporting crude vs. refined was small (averaging to 170 Btu/gal). For plants that also crush beans and share a steam generation plant for both facilities, the steam going to the biodiesel plant was measured and then back-calculated to come up with the amount of natural gas consumed for biodiesel only. This was needed to be done for only a few facilities, and it was done to keep the biodiesel plant system boundaries consistent. The industry average does not include energy used to refine glycerin to pharmaceutical grade done at some plants. Transportation of materials is included in the model. All materials except crude soy oil are assumed to be transported 100 miles by diesel truck. The soy oil is assumed to be transported 570 miles by diesel locomotive, the same assumption used in the Biodiesel Study.

In terms of robustness of the data, each survey was reviewed by NBB's Professional Engineer. When necessary, clarifying questions were asked of the producers via phone or email to verify that all the data was reported consistently, and that the data accurately represent the actual energy used to produce the reported volume for each plant. In terms of precision, the range of numbers reported was relatively narrow. Wherever a potential outlier was identified, numbers, units, and/or measurements were double checked, and an explanation was requested. When the explanation was reasonable and numbers had been checked, the data point was kept.

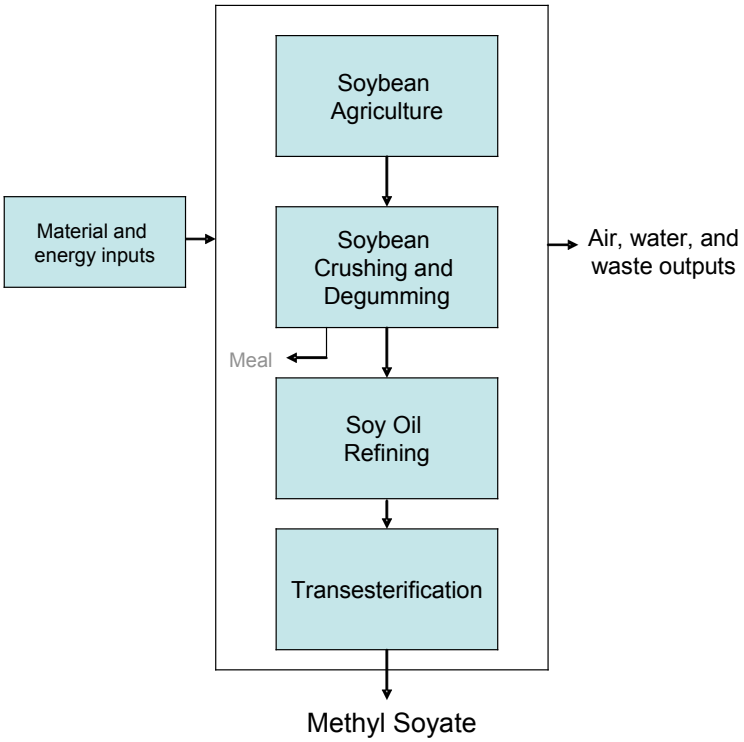
Product Comparisons

Diesel Comparison

Methyl Soyate Production

The main processes to produce methyl soyate have been described above – with all the above unit processes linked together to produce the LCA model, as shown in the figure below:

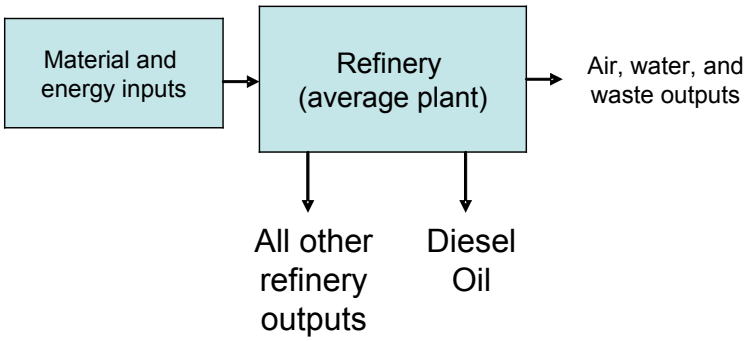
Figure 6 Methyl Soyate System Boundaries



Petroleum Diesel Oil Production

The data for diesel oil production comes from the U.S. LCI database on North American average refinery operations, which convert crude oil into petroleum products using physical and/or chemical processing technology. System boundaries of the diesel production data are as follows:

Figure 7 Diesel Oil System Boundaries



The petroleum refining data in the U.S. LCI database is based on production of 1000 pounds of general refinery product, and is summarized as follows:

Table 7 Inputs and Outputs of Petroleum Refining

	Input or Output	Quantity per 1000 lbs refined petroleum	Source
Inputs	**Raw materials**		
	Crude oil	1034 lbs	3
	Process energy		
	Electricity	64.9 kWh	1
	LPG	0.14 gal	1
	Natural Gas	178 cu-ft	1
	Residual Oil	3.26 gal	1
	Water (process and cooling)	249 gal	5
Outputs	**Air emissions**		
	Aldehydes	0.042 lbs	1,3
	Ammonia	0.021 lbs	1,3
	Carbon monoxide	13.3 lbs	1,3
	Carbon tetrachloride	1.2E-08 lbs	1,3
	CFC12	1.2E-07 lbs	1,3
	Hydrocarbons (other than methane)	2.03 lbs	1,3
	Methane	0.071 lbs	1,2,3
	NOx	0.33 lbs	1,3
	Particulates (unspecified PM)	0.24 lbs	1,3
	SOx (unspecified)	2.35 lbs	1,3
	Trichloroethane	9.7E-08 lbs	1,3

	Water effluents		
	BOD5	0.034 lbs	1
	COD	0.23 lbs	1
	Chromium (hexavalent)	3.7E-05 lbs	1
	Chromium (unspecified)	5.7E-04 lbs	1
	Nitrogen (as ammonia)	0.015 lbs	1
	Oil and Grease	0.011 lbs	1
	Phenolic Compounds	2.3E-04 lbs	1
	Sulfide	1.9E-04 lbs	1
	Total Suspended Solids	0.028 lbs	1
	Solid Waste		
	Solid waste (unspecified)	5.60 lbs	4

Source 1: Energy and Environmental Profile of the U.S. Petroleum Industry. U.S. Department of Energy Office of Industrial Technologies. December 1998.
Source 2: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000. Table 2-29: CH4 Emissions from Petroleum Systems. U.S. EPA Office of Atmospheric Programs, Washington, DC. April 15, 2002.
Source 3: Energy Information Administration, Annual Energy Review 2001, Table 5.8: Refinery Input and Output
Source 4: Estimating Externalities of Oil Fuel Cycles, Oak Ridge National Laboratory and Resources for the Future, August 1996.
Source 5: Water in refining process - 1 to 2.5 gal range per refined fuel. From U.S. DOE Dec 2006, Energy Demands on Water Resources: Rpt to Congress on the Interdependency of Energy and Water, page 20. Report says refinery use of water for processing and cooling is about 1 to 2.5 gallons of water for every gallon of product (Gleick, 1994).

Data for crude oil production comes from the U.S. LCI database. Transportation of crude oil and process fuels to the refinery is also included in the refinery model. Other sources of data for the refinery include personal communication with industry experts, U.S. EPA,[22] Worldbank Group,[23] and Association of Oil Pipelines.[24]

Data for specific refinery outputs, including diesel fuel, were obtained by allocating the overall refinery inputs and outputs to specific refinery outputs. Allocation has been made on a mass basis, based on the percent by mass of each product produced at the refinery. The following table provides the percent by mass of the refinery outputs:[25]

[22] AP-42, Chapter 5, Petroleum Refining, U.S. Environmental Protection Agency, January 1995.
[23] Petroleum Refining, Pollution Prevention and Abatement Handbook, WORLD BANK GROUP, 1998.
[24] Association of Oil Pipelines Annual Report 2000.
[25] US LCI Database: Data Module Report on Petroleum Refining, February 2004, specifically: Energy Information Administration, **Annual Energy Review 2001**, Table 5.8: Refinery Input and Output.

Table 8 Production (by Mass Percent) of Refinery Products

Fuel / Refinery product	Percent mass of refinery output
Gasoline	42.1 %
Diesel (distillate fuel oil)	21.9 %
Kerosene (jet fuel)	9.1 %
Petroleum coke	6.0 %
Residual fuel oil	4.9 %
Still Gas	4.5 %
Asphalt	3.7 %
LPG	2.7 %
Lubricant[26]	1.3 %
Other refinery outputs	3.9 %
Total	**100 %**

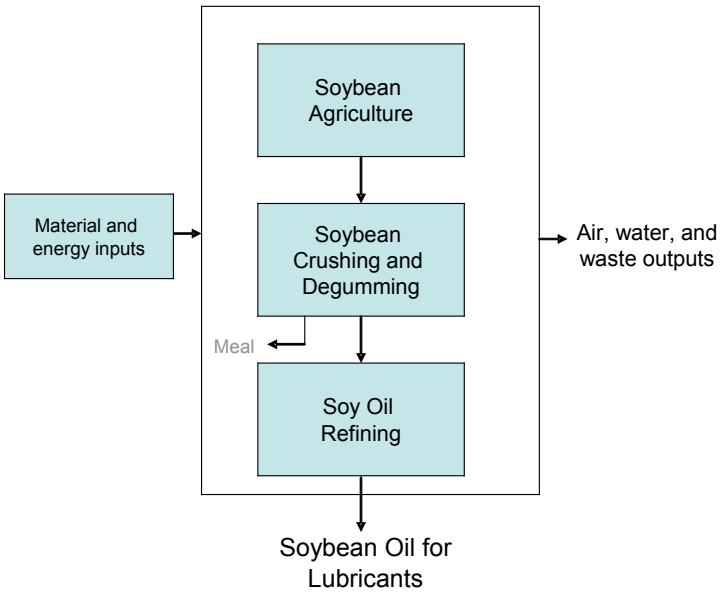
Oil for Lubricants Comparison

Soybean Oil for Lubricants

A soybean-based oil for lubricants is a high oleic soybean oil, which is produced from soybeans whose seeds have been genetically modified to have increased levels of oleic acid, and decreased levels of linoleic and linolenic acid. According to soybean GMO testing done by the DuPont Company, Pioneer, high oleic soybean was found to be no different than conventional soybean for both "yield and agronomic and other relevant characteristics."[27] The soybean growing model already factors in an energy consumption of growing seed, but no data were available to account for producing these GM seeds. Despite that, it is assumed that most of the energy is accounted for in the conventional soybean growing model. Thus, the conventional model is used to produce the soy oil for lubricants, presented in the figure below:

[26] Note: in the U.S. LCI documentation, lubricants are included in the "other outputs" category. The 1.3% for lubricants comes form the Biodiesel study, which provides a more detailed list of refinery outputs.
[27] Butzen, Steve and Steve Schnebly, *High-Oleic Soybean*, from the Pioneer®, a DuPont Company, website, at: http://www.pioneer.com/web/site/portal/menuitem.666b80f644978322a0030d05d10093a0/.

Figure 8 Soybean Oil for Lubricants System Boundaries

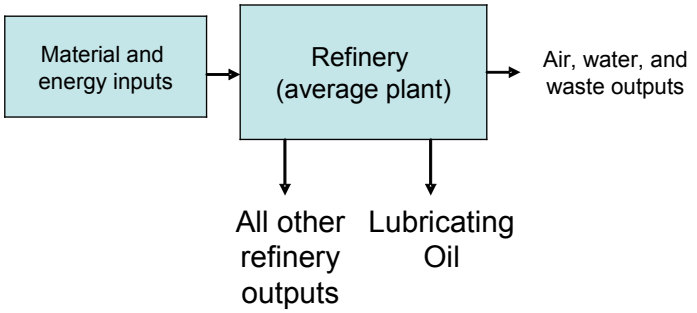


These data include the production of base oil only, and not further downstream material.

Lubricant Production

Because petroleum-based lubricant is produced at a refinery, the same model for diesel fuel (described above) has been applied. The exception to this is the allocation factor for these refinery outputs (see Table 8).

Figure 9 Petroleum Oil for Lubricants System Boundaries



Resin Comparison

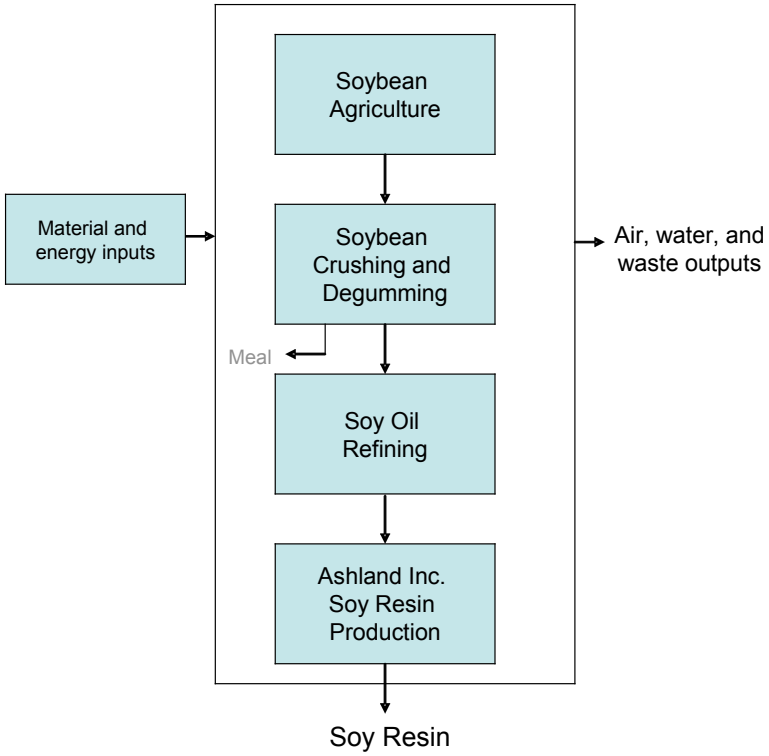
Soy Resin Production

Soy resin production data was provided by Ashland Composite Polymers. Specifically, Ashland provided process energy and formulation data to produce their ENVIREZ 1807 soy-based resin product, an intermediate material used by customers to make end-products such as John Deere combine panels. ENVIREZ 1807 is an unsaturated

polyester resin (UPR); this resin has a double bond available to use as a reaction (cross-link) site.

The soy resin is produced by reacting refined soybean oil, ethanol, and other materials to produce the resin.[28] Water and ethanol distillates produced in the process are burned through an oxidizer. The reacted resin is then diluted in styrene to produce the mixture as sold to customers. The only other process input is water for cooling, and total make-up water amounts to 0.01 gal/lb resin. No air emissions, solid waste, or other by-products are produced. The following figure represents the soy resin LCA model:[29]

Figure 10 Soy Resin System Boundaries



Both electrical and natural gas energy are used to manufacture the resin at Ashland's plant, and these data were provided by Ashland. The reported energy is net energy consumed – and includes fuel to run the thermal oxidizers and their heat recovery, plus any on-site utility energy consumption such as that used by the cooling tower. The following table provides the electrical and natural gas requirements for the soy resin production at Ashland's facility (the final unit process stage in the figure above):

[28] For confidentiality purposes, the names and quantities for all materials in this product are omitted from this report.

[29] Note: for confidentiality purposes, results are fully aggregated and life cycle stages (e.g., unit processes) and not broken down.

Table 9 Soy resin production energy

Energy sources	Quantity per lb of resin
Electricity	0.117 kWh
Natural gas boiler	1497 Btu

The formulation for ENVIREZ 1807 is current and assumed to be representative of a soy resin. However, it is uncertain how representative this product is amongst all soy resins of this nature available in the marketplace. Data are based on 2008 figures.

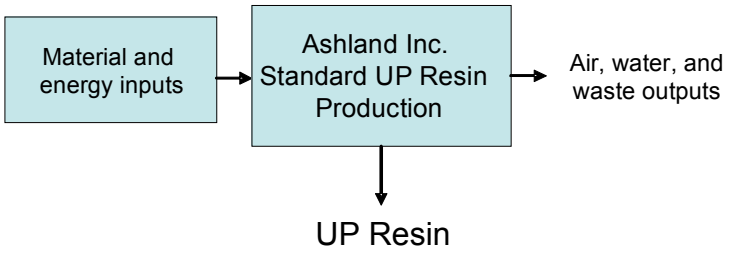
The soy resin model includes transportation of refined soy oil and other materials to Ashland's resin manufacturing plant. Packaging of the final product is not included, nor is transportation to downstream customers or any transportation of the resin into the final end-use product.

Standard Unsaturated Polyester (UP) Resin Production

The data for an alternate unsaturated polyester resin, the petroleum-based alternative to the soy resin, were provided by Ashland Composite Polymers company. Specifically, Ashland provided process energy and formulation data to produce their propylene glycol maleate.

The PG maleate is produced by reacting maleic anhydride, propylene glycol, and other additives to produce the resin.[30] Water as a distillate is burned through an oxidizer. The reacted resin is then diluted in styrene to produce the mixture as sold to customers. The only other process input is water for cooling, and total make-up water amounts to 0.01 gal/lb resin. No air emissions, solid waste, or other by-products are produced. The following figure represents the standard UP resin LCA model:

Figure 11 Standard Resin System Boundaries



Both electrical and natural gas energy are used to manufacture the resin, and this data was provided by Ashland. On-site utility energy consumption, including the cooling tower, was included in Ashland's total energy figures. The following table provides the electrical and natural gas requirements for the standard UP resin production at Ashland's facility (the main unit process stage in the figure above, not including the material and energy inputs):

[30] For confidentiality purposes, the names and quantities for all materials in this product are omitted from this report.

Table 10 Standard UP Resin Production Energy

Energy sources	Quantity per lb of resin
Electricity	0.048 kWh
Natural gas boiler	612 Btu

The formulation for the standard resin is current and can probably be assumed to be representative of other UP resins in the marketplace. Data are based on 2008 figures.

The model includes transportation of input materials to Ashland's resin manufacturing plant. Packaging of the final product is not included, nor is transportation to downstream customers or any transportation of the resin into the final end-use product.

Polyol Comparison

Soy Polyol Production

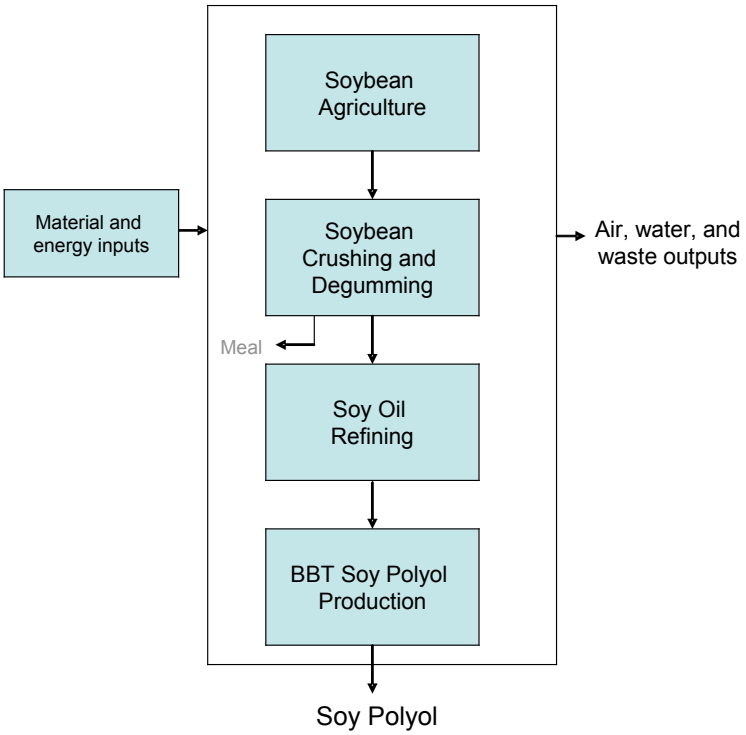
Soy polyol production data was provided by Biobased Technologies, LLC (BBT). Specifically, BBT provided process energy and formulation data to produce their Agrol soy-based polyol product. To produce Agrol, refined soy oil and acidified oxidant[31] are charged to a clean reactor under an inert atmosphere. The reactor contents are heated to reflux with agitation and aged for a specified period of time. After completing the aging step, the reaction mixture is treated to remove impurities and excess of raw materials that are recycled back into the subsequent batch. The pure polyol is then cooled, filtered and stored in a dry inert atmosphere. This is sold to customers.

Other process inputs include water for cooling and nitrogen used for blanketing. Wastewater and air emissions associated with water and material use have been accounted for in the model. There are no coproducts produced in this process. The following figure represents the soy polyol LCA model:[32]

[31] For confidentiality purposes, the names and quantities for all materials in this product are omitted from this report.

[32] Note: for confidentiality purposes, results are fully aggregated and life cycle stages (e.g., unit processes) and not broken down.

Figure 12 Soy Polyol System Boundaries



Both electrical and natural gas energy are used to manufacture Agrol, and these data were provided by BBT on a total batch basis. Energy consumption for the on-site utilities has been included in BBT's total energy figures. The following table provides the electrical and natural gas requirements for Agrol at BBT's facility (the final unit process stage in the figure above):

Table 11 Soy Polyol Production Energy

Energy sources	Quantity per lb of polyol
Electricity	0.188 kWh
Natural gas boiler	957 Btu

The formulation for Agrol is current and may be assumed to be representative of soy polyol production. However, it is uncertain how representative this product is amongst all soy polyols produced in the marketplace. Data are based on 2009 figures.

The soy polyol model includes transportation of refined soy oil and other materials to BBT's plant. Packaging of the final product is not included, nor is transportation to downstream customers.

Petroleum-Based Polyol

The manufacture of polyether polyol begins with the introduction of a potassium hydroxide catalyst to a polyol initiator, such as a triol. This solution is reacted with propylene oxide and ethylene oxide to form an intermediate. Water is then added to this intermediate. A solvent is introduced, which absorbs the polyol from the water/catalyst. The density difference between the aqueous & organic phases is used to separate the two phases. Finally, the polyol is purified of solvent, side products and water through distillation.[33] Its detailed process flow diagram is provided below:[34]

Figure 13 Detailed polyol production flowchart

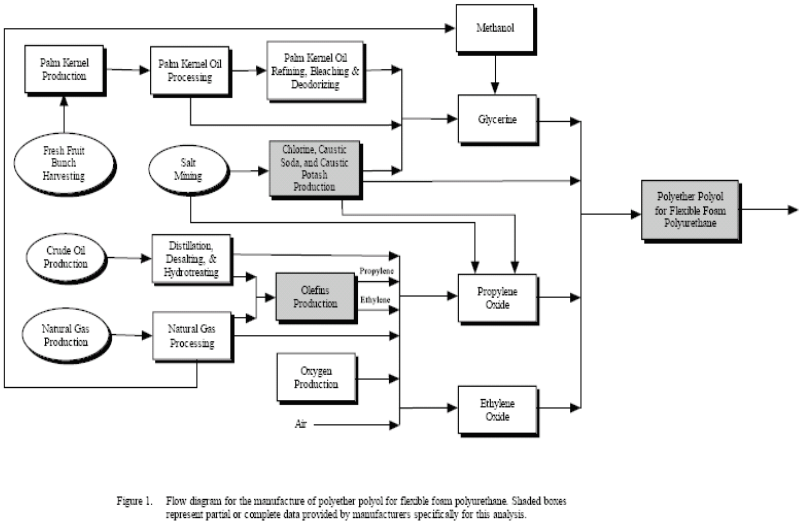
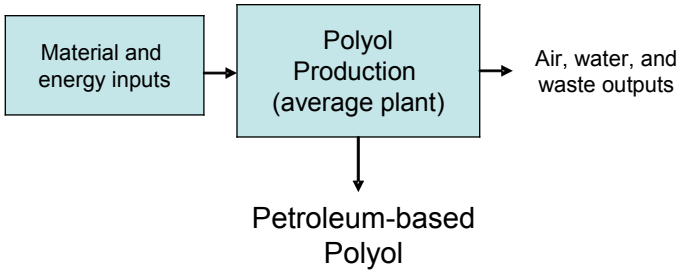


Figure 1. Flow diagram for the manufacture of polyether polyol for flexible foam polyurethane. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

Data for the petroleum polyol, specifically polyether polyol used for flexible foam polyurethane, came from the U.S. LCI database. The figure below presents the polyether polyol unit process flowchart as it is modeled for this study.

Figure 14 Petroleum Polyol System Boundaries



[33] From the "Data Module Report for Polyether Polyol for Flexible Foam Polyurethanes", dated April 18, 2007, found at http://www.nrel.gov/lci/ (hereinafter referred to as "Polyol for Flexible Foam Polyurethane Data Module Report")

[34] Flexible Foam Polyurethane Data Module Report, page 2.

The main material and process energy inputs to polyol production are as follows (gate-to-gate):

Table 12 Inputs to Petroleum-based Polyol Production

Inputs	Quantity per 1000 kg Polyol
Raw Materials	
Propylene oxide (kg)	856
Ethylene oxide (kg)	113
Glycerine (kg)	26
Caustic Potash (kg)	4
Water (as process water) (liter)	451
Energy	
Electricity (grid) (GJ)	0.26
Electricity (cogeneration) (GJ)	0.77
Natural gas (GJ)	2.57

Solid waste, air emissions, and water effluents were also reported in the data sets, and these can be found in the U.S. LCI database.

The US LCI database also provides the transportation needed for the full *cradle-to-gate* production, as follows, for 1000 kgs polyol:

Diesel barge transportation: 11 ton-miles
Residual oil barge transportation: 37 ton-miles
Diesel ocean freighter transportation: 111 ton-miles
Residual oil ocean freighter transportation: 995 ton-miles
Pipeline-petroleum products: 665 ton-miles
Pipeline-natural gas: 697 ton-miles
Diesel combination truck transportation: 187 ton-miles
Diesel single unit truck transportation: 2 ton-miles
Diesel Locomotive transportation: 90 ton-miles

According to the Polyol for Flexible Foam Polyurethane Data Module Report, primary (site-specific) data were provided by five producers (5 plants) in North America and represent the years 2003 and 2005. As of 2002, it is estimated that for all polyurethane applications, there were 7 polyether polyol producers and 9 polyether polyol plants in the U.S. The polyether polyol data collected represents a majority of the total North American production of polyether polyol for flexible foam polyurethane. Additionally, the polyol producers who provided data for this module verified that the characteristics of their plants are representative of a majority of the North American production. The final, averaged dataset was reviewed and accepted by all polyether polyol data providers.[35] Data quality for the collection methods, technology, industry representation, time period, and geography were extensively assessed. Note that since the data that were collected from the producers represented a good sample size, it is likely that the submitted data represent a wide range of molecular weights, creating truly an industry-wide average polyol.

[35] Polyol for Flexible Foam Polyurethane Data Module Report; The Resin Review. The Annual Statistical Report for the U.S. Plastics Industry. American Plastics Council. 2003, backed by research by Franklin Associates on each polyol producing companies' website.

The upstream material and energy data for polyol inputs come from secondary sources, namely the U.S. LCI database, EcoInvent, and the SimaPro database. Glycerine is a co-product of palm oil methyl ester production, according to the same data source as the polyol production data (Franklin Associates Limited), and these FAL data were used.[36] Upstream palm kernel production comes from EcoInvent.

Results and Interpretation

Results tables are presented in this section of the report and are based on 1000 kg of each output (e.g., soybeans, lubricant, polyol, etc.). It is important to remind the reader that the *application* of these products has not been evaluated. These results are cradle-to-gate, so depending on the use and end of life phases of the products, results could change.

In terms of understanding the tables, readers should be aware that most impact categories are independent from one another so the data in the tables should be read across rather than down. It is not appropriate to compare results for one impact category to a different category, e.g., to directly compare GWP impacts with acidification impacts.

Carbon Sequestration in the Results

As mentioned previously, for the GWP category, the sequestration of carbon is taken into account based on the quantity of biomass carbon embedded in each of the soybean-based final products, as shown in the table below..[37] In the results, the following carbon contents are subtracted from the GWP total

Table 13 Biobased carbon content in 1000 kg of each output

Product or output	% carbon	Biomass carbon (kg)	Corresponding biomass CO2 (kg)
Crude soy oil	77%	770	2823
Meal	48%	480	1760
Refined oil	80.6%	806	2955
Biodiesel	77%	770	2823
Soy oil used for lubricants	80.6%	806	2955
Soy-based polyol (oil is 91% of product)	80.6% * 91% = 73.4%	733	2689
Soy-based resin (oil is 12% of product)	80.6% * 12% = 9.7%	97	355

[36] Franklin Associates, Revised Final Appendices: Cradle-to-Gate LCI of Nine Plastic Resins and Two Polyurethane Precursers prepared for Plastics Division of ACC, December 2007, Tables L-5 and L-6.
[37] Carbon contents for the refined oil, biodiesel, polyol, and resin were calculated by an Omni Tech chemical engineer, based on the molecular formulas for each output. Crude oil was estimated based on oil content and "impurities" in the crude that are non-carbon in nature. The meal carbon content has been estimated.

Soybean Production Results

Table 14 Soybean Production (1000 kg output)

Impact category	Unit	Total Soybean Production
Global warming potential	kg CO2 eq	-1.2 E+03
Acidification Potential	milmole H+eq	9.4 E+04
Eutrophication Potential	kg N eq	2.9 E+00
Fossil Fuel Depletion	MJ Surplus	1.9 E+02
Water Intake	Liters	5.1 E+04
Criteria Air Pollutants	microDALYs	2.5 E+01
Ozone Depletion Potential	kg CFC-11 eq	8.0 E-07
Smog Formation Potential	g NOx eq	2.0 E+03
Total Fuel Energy	MJ	1.8 E+03
Ecotoxicity	g 2,4-D eq	1.1 E+04
Human Toxicity - Cancer	g C6H6 eq	1.9 E+02
Human Toxicity - Noncancer	g C7H8 eq	3.8 E+05

Product comparisons

The next tables present the comparisons of soy-based products to petroleum-based products. In the first two data columns, the tables present the overall result for each impact category. The third data column presents the ratio of the petroleum-based product to the soy product. As noted by the color key with each table, when values are within 10% (+/-) of each other, the results are considered equivalent. Ratios above 1 are better for soy and ratios below 1 are worse for soy. For example, 0.30 means the petroleum product's impact value is 30% of that of the soy product.

When the results are negative numbers, as they are with global warming potential (GWP) for three of the soy-based products, ratios cannot be used. Instead, comparing the absolute values for GWP shows the differences between the alternatives. Thus, "N/A" is shown in the tables in place of a ratio.

Some general remarks about these results:

- Application/use of the end products are not accounted for: These results are cradle-to-gate, so depending on the use and end of life phases of the products, the results could change.

- Limited impact categories: In light of the limitations of very localized types of impact categories, the ecological toxicity potential and two human health potential sets of results should be used with caution (see previous discussion for more detail). In addition, for both soy-based and petroleum-based products, the ozone depletion potential numbers are extremely small.

Diesel Comparison Results

Table 15 Methyl Soyate vs. Petroleum-based Diesel (1000 kg output)

Impact category	Unit	Methyl Soyate Total	Petroleum-based Diesel Oil Total	Petro to soy ratio
Global warming potential	kg CO2 eq	-2.1 E+03	6.6 E+02	N/A
Acidification Potential	milmole H+eq	4.1 E+05	5.0 E+05	1.20
Eutrophication Potential	kg N eq	2.8 E+00	4.5 E-01	0.16
Fossil Fuel Depletion	MJ Surplus	1.5 E+03	7.3 E+03	5.00
Water Intake	Liters	4.8 E+04	2.2 E+03	See Note
Criteria Air Pollutants	microDALYs	1.1 E+02	1.1 E+02	0.95
Ozone Depletion Potential	kg CFC-11 eq	1.8 E-06	1.7 E-07	0.09
Smog Formation Potential	g NOx eq	5.0 E+03	1.0 E+04	2.04
Total Fuel Energy	MJ	8.7 E+03	8.1 E+03	0.93
Ecotoxicity	g 2,4-D eq	1.4 E+04	4.9 E+03	0.35
Human Toxicity - Cancer	g C6H6 eq	7.5 E+02	1.9 E+03	2.59
Human Toxicity - Noncancer	g C7H8 eq	1.0 E+06	1.4 E+06	1.40

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Oil for Lubricants Comparison Results

Table 16 Soy-based Oil for Lubricant vs. Petroleum-based Oil for Lubricant (1000 kg output)

Impact category	Unit	Soy-based Lubricant Total	Petroleum-based Diesel Oil Total	Petro to soy ratio
Global warming potential	kg CO2 eq	-2.4 E+03	6.6 E+02	N/A
Acidification Potential	milmole H+eq	1.8 E+05	5.0 E+05	2.82
Eutrophication Potential	kg N eq	3.1 E+00	4.5 E-01	0.14
Fossil Fuel Depletion	MJ Surplus	4.3 E+02	7.3 E+03	16.99
Water Intake	Liters	5.4 E+04	2.2 E+03	See Note
Criteria Air Pollutants	microDALYs	4.9 E+01	1.1 E+02	2.23
Ozone Depletion Potential	kg CFC-11 eq	1.9 E-06	1.7 E-07	0.09
Smog Formation Potential	g NOx eq	3.0 E+03	1.0 E+04	3.42
Total Fuel Energy	MJ	4.3 E+03	8.1 E+03	1.90
Ecotoxicity	g 2,4-D eq	1.3 E+04	4.9 E+03	0.37
Human Toxicity - Cancer	g C6H6 eq	2.9 E+02	1.9 E+03	6.62
Human Toxicity - Noncancer	g C7H8 eq	7.5 E+05	1.4 E+06	1.86

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Polyol Comparison Results

Table 17 Soy-based Polyol vs. Petroleum-based Polyol (1000 kg output)

Impact category	Unit	Soy-based Polyol Total	Petro-based Polyol Total	Petro to soy ratio
Global warming potential	kg CO2 eq	-1.4 E+03	4.1 E+03	N/A
Acidification Potential	milmole H+eq	5.1 E+05	1.5 E+06	3.04
Eutrophication Potential	kg N eq	3.0 E+00	1.1 E+01	3.80
Fossil Fuel Depletion	MJ Surplus	1.7 E+03	1.1 E+04	6.50
Water Intake	Liters	6.8 E+04	7.6 E+04	See Note
Criteria Air Pollutants	microDALYs	1.4 E+02	4.3 E+02	3.06
Ozone Depletion Potential	kg CFC-11 eq	1.4 E-05	4.0 E-06	0.28
Smog Formation Potential	g NOx eq	5.6 E+03	1.6 E+04	2.81
Total Fuel Energy	MJ	1.6 E+04	5.5 E+04	3.48
Ecotoxicity	g 2,4-D eq	1.4 E+04	6.8 E+04	4.87
Human Toxicity - Cancer	g C6H6 eq	7.9 E+02	2.1 E+03	2.63
Human Toxicity - Noncancer	g C7H8 eq	1.3 E+06	1.2 E+07	9.55

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Resin Comparison Results

Table 18 Soy-based Resin vs. Petroleum-based Resin (1000 kg output)

Impact category	Unit	Envirez Resin Total	Standard Resin Total	Petro to soy ratio
Global warming potential	kg CO2 eq	4.1 E+03	5.2 E+03	**1.28**
Acidification Potential	milmole H+eq	1.6 E+06	1.7 E+06	**1.03**
Eutrophication Potential	kg N eq	6.8 E+00	7.0 E+00	**1.04**
Fossil Fuel Depletion	MJ Surplus	1.1 E+04	1.2 E+04	**1.11**
Water Intake (see note)	liters	4.4 E+04	4.9 E+04	See Note
Criteria Air Pollutants	microDALYs	4.2 E+02	4.4 E+02	**1.03**
Ozone Depletion Potential	kg CFC-11 eq	1.7 E-06	1.7 E-06	**0.99**
Smog Formation Potential	g NOx eq	5.6 E+04	2.0 E+04	**0.36**
Total Fuel Energy	MJ	4.3 E+04	4.7 E+04	**1.08**
Ecotoxicity	g 2,4-D eq	2.2 E+04	2.8 E+04	**1.28**
Human Toxicity - Cancer	g C6H6 eq	3.3 E+03	3.3 E+03	**1.01**
Human Toxicity - Noncancer	g C7H8 eq	4.3 E+06	6.2 E+06	**1.46**

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Data Quality Requirements and Evaluation

Overview of ISO Data Quality

This LCA adheres to the ISO standards on data quality to help ensure consistency, reliability, and clear-cut evaluation of the results. The following aspects of the study's data quality are described in accordance with ISO 14044.[38]

- **Representativeness** of the data in the study, which includes an assessment of the temporal, geographical, and technological coverage of the model;
- **Consistency** – the qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis;
- **Reproducibility** – the qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study;
- **Precision** – the measure of the variability of the data values for each data category expressed;
- **Completeness** – the percentage of flow that is measured or estimated;
- **Sources of data**; and
- **Uncertainty of information**.

Data Quality as Applied to this Study

Representativeness

Representativeness includes the following:

- Time/temporal coverage – describes the age of data and the minimum length of time (e.g., one year) over which data are collected;
- Geographical coverage – describes the geographical area from which data for unit processes are collected to satisfy the goal of the study; and
- Technological coverage – describes the technology mix of the data sets, which may include weighted average of the actual process mix, best available technology, or worst operating unit.

Table 19 provides a detailed analysis of the temporal, geographical, and technological coverage for all aspects of this study.

[38] ISO 14044 Section 4.2.3.6

Table 19 Temporal, Technological, Geographical Coverage & Data Sources

	Temporal Information	Technological coverage	Type of data	Geographical coverage	Source of data
Data sets for input materials in each unit process and product	Data sets range primarily from mid-1990s through the 2000s. No data older than 1990 is used (if any).	For generic materials, the most representative technology is used wherever possible. Most data sets represent average technologies	Secondary data	U.S. data is preferable, but where U.S. data are not available or if the quality is low, European data sets are used (**see note below**)	U.S. LCI database, elements of the SimaPro and EcoInvent databases.
Energy and fuel data sets	2000s	The most representative technologies	Secondary data	U.S. data, average US grid mix.	U.S. LCI database
Transportation data sets	2000's data	Average technologies	Secondary data	Represents U.S. production	U.S. LCI database
Soybean agriculture	2000's data	Industry average technologies	Secondary data	Represents U.S. production	Various sources; see body of the report
Soybean processing	Mid 2000's data, some 2007 data	Industry average technologies	Primary data	Represents U.S. production	NOPA
Soybean oil refining	2000's data	Industry average technologies	Secondary data	Represents U.S. production	Various sources; see body of the report
Biodiesel production	2008	Industry average technologies	Primary data	Represents U.S. production	NBB
Soy-based polyol production	2009	BBT technologies	Primary data	BBT U.S. production	BBT
Soy-based resin production	2008	Ashland Composite Polymers technologies	Primary data	Ashland Composite Polymers U.S. production	Ashland Composite Polymers

Petroleum diesel production	2000's	Average technologies	Secondary data	North America	U.S. LCI Database
Petroleum-based lubricant production	2000's	Average technologies	Secondary data	North America	U.S. LCI Database
Petro-based polyol production	2000's	Average technologies	Primary data from several producers that has been made public	North America	American Plastics Council; U.S. LCI Database
Petro-based resin production	2008	Ashland Composite Polymers technologies	Primary data	Ashland Composite Polymers U.S. production	Ashland Composite Polymers

Note on geographical coverage of the data sets: In LCA it is quite common to use a mix of data sets from different geographical locations, for several reasons. First, data for all materials are not always available for all geographies. Also, available data from a preferred geographical location may be very poor in quality (may be outdated, based on faulty emissions factors, based on old or non-representative technologies, based on one plant or a non-representative sample, etc.). Finally, an alternative geography or data set is used because it is better than no data at all. In order to minimize an LCA's margin of error associated with data based on a different geographical location, it is Four Elements' practice to customize the data sets to the preferred geographical location. For example, instead of using a European data as-is, the energy, fuels, and transportation data, all European, are replaced by the corresponding U.S. data sets from the U.S. LCI database, ensuring more U.S. related emissions factors.

Consistency

Consistency is a qualitative understanding of how uniformly the study methodology is applied to the various components of the study. Consistency was maintained in the data collection and modeling of all of the components in the study. The OTI and Four Elements team shared responsibilities which enabled consistent modeling – one set of consultants collected, reviewed and validated the data before life cycle modeling in the software, and then the data were modeled and cross-checked.

Reproducibility

All of the data in this report used for life cycle modeling have been made available. So the level of detail and transparency provided in this report allow the results of this study to be reproduced by another practitioner as long as the production datasets are similar.

Precision

Precision represents the degree of variability of the data values for each data category. Areas where there is data variability are in the use of average data, including average soybean production, average soybean crushing and refining, and some of the average data sets in the U.S. LCI database, including the petroleum-based products. Most of these values have been obtained on a weighted average basis, so while there is variability in the data, it has been averaged on a production-output basis. There may be a high level of variability in the petroleum production data, as the data are older and are not very specific.

Completeness

ISO 14044, section 4.2.3.6 defines completeness as the "percentage of flow that is measured or estimated."[39] This study can be considered complete since much of the data was based on measured or estimated data. In many cases, data were provided by multiple producers. In terms of inclusion of production data of the raw materials, the cut-off criteria of 99% was exceeded, based on what was understood to be inputs to the systems.

[39] ISO 14044:2007, Section 4.2.3.6.

Sources of Data

Both primary and secondary data are used in the modeling. Primary data are the preferred, highest quality data for life cycle modeling. Primary data were gathered from the BBT facility, the Ashland facility, soybean crushing processors, biodiesel producers, and polyether polyol producers. Secondary data including published literature and theoretical models were used for other comparisons. All these have been detailed in the modeling and assumptions sections.

From a practical standpoint it is impossible to collect actual process data for each of the hundreds or thousands of unit processes included in a complete life cycle model, so the use of secondary data in an LCI is normal and necessary. Secondary data have been applied to production of material inputs, production and combustion of fuels used for process energy, and transportation energy throughout the life cycle. Wherever possible, the LCA used the best data that were available, including energy, fuels, transportation, and basic materials from the U.S.-based, recent data from the U.S. LCI database.

Limitations and Uncertainty

General use limitations. It should be borne in mind that LCA, like any other scientific or quantitative study, has limitations and is a far from perfect tool for assessing the environmental impacts and attributes associated with product systems. There is inherently a margin of error due to various limitations such as data quality differences and/or unavailability of potentially relevant data. *Should claims or assertions be made on the environmental performance of the product, the public should be informed of these inherent limitations.*

Product performance. It should be reminded that while generally these materials can be used interchangeably in probably most applications, the precision of this one-to-one replacement in terms of actual performance is difficult to assess. It was out of the scope of this work to evaluate each product on the basis of very precise applications. So users of the results should understand that this is a limitation and that decisions made for the use of these products should be based on appropriateness and applicability of each material as well as the trade-offs of the environmental impacts being evaluated.

Petroleum-based crude oil extraction. The data for petroleum-based crude oil extraction can be considered outdated, especially since even as recently as five to 10 years ago, oil flow was better in some of the North American operations, requiring less inputs into the wells to get the oil out. Now, more energy, water, and equipment are needed to get the same unit quantity of oil of the ground. This is an area that needs to be researched.

Also, more research may be necessary to update the quantity of brine water produced per unit output, other sources of water or other inputs including hot water/steam that is used to extract oil from oil sands and any contamination associated with these (that is released into the environment).

Uncertainty

Both primary and secondary data are used in modeling the materials. Because the quality of secondary data are not as good as primary data, the use of secondary data

becomes an inherent limitation to the study. Secondary data may cover a broad range of technologies, time periods, and geographical locations. Because hundreds of data sets are linked together and because it is often unknown how much the secondary data used deviate from the specific system being studied, quantifying data uncertainty for the complete system becomes very challenging. As a result, it is not possible to provide a reliable quantified assessment of overall data uncertainty for the study.

It should be added that wherever possible, this LCA used the best data that were available, including energy, fuels, transportation, and basic materials from the U.S.-based, recent data from the U.S. LCI database. The U.S. LCI database is considered the best quality data for U.S.-based studies, however, there are limitations to the use of these data for all processes as discussed earlier.

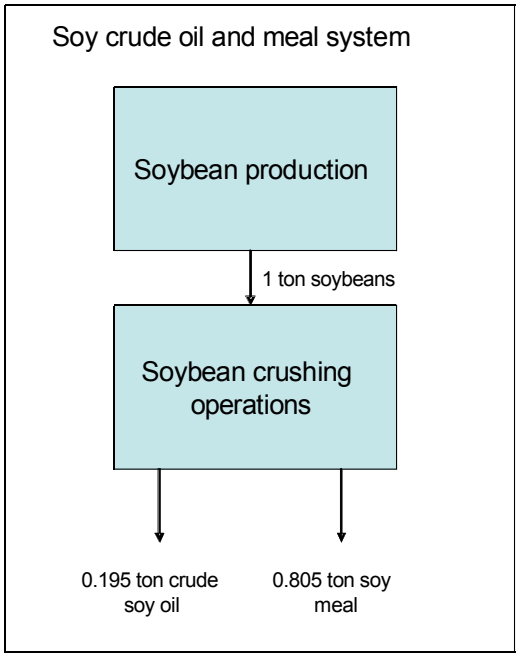
Appendix A

Allocation Determination and Economic Sensitivity Analysis

Allocation Determination

The products from soybean crushing/processing include degummed soy oil and soybean meal, both marketable and useful coproducts, and allocating these has been an ongoing debate. In LCA, when allocation is necessary, the key to robust modeling is to determine the basis for the allocation (e.g., based on mass, economic value, etc.). It was decided for this study that allocation based on the mass of the products and coproducts would be made for the baseline results, and a sensitivity analysis would be performed on their economic value. The below discussion provides the rationale behind this methodological decision. Figure A-1 presents the unallocated production of soy crude oil and soy meal.

Figure A-1 Unallocated Production of Soy Crude Oil and Soy Meal



ISO's preferred approach to allocation is as follows:[40]

1. Wherever possible, allocation should be avoided by:
   1) dividing the unit process to be allocated into two or more subprocesses and collecting the input and output data related to these subprocesses;
   2) expanding the product system to include the additional functions related to the co-products.

2. Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them.

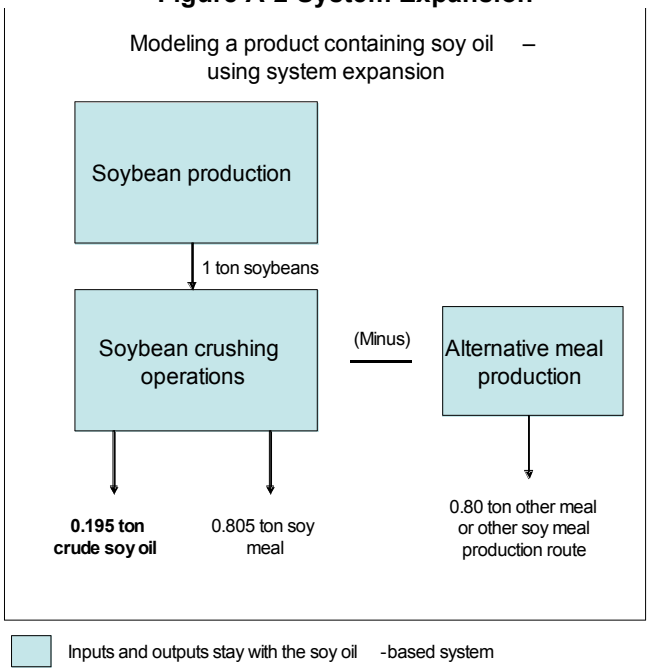
[40] ISO 14044:2006, Section 4.3.4.2.

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

When LCA practitioners are faced with processes having coproducts, they defer to ISO's first preference, i.e., dividing the multiple output process into two or more subprocesses and avoiding allocation altogether. In the case of soybean crushing, this is nearly impossible to do since soybean crushing is quite an integrated process and data is not available to model separately the energy, inputs, and outputs to produce soy meal and crude soy oil. ISO's second preference for dealing with coproducts would be to expand the system boundary, as shown in the figure below.

Figure A-2 System Expansion

Expand the system boundaries by subtracting out a functional equivalent quantity of an alternative animal feed or alternate soy meal production route



Using system expansion was found to be not a viable option for this analysis for the following reasons:

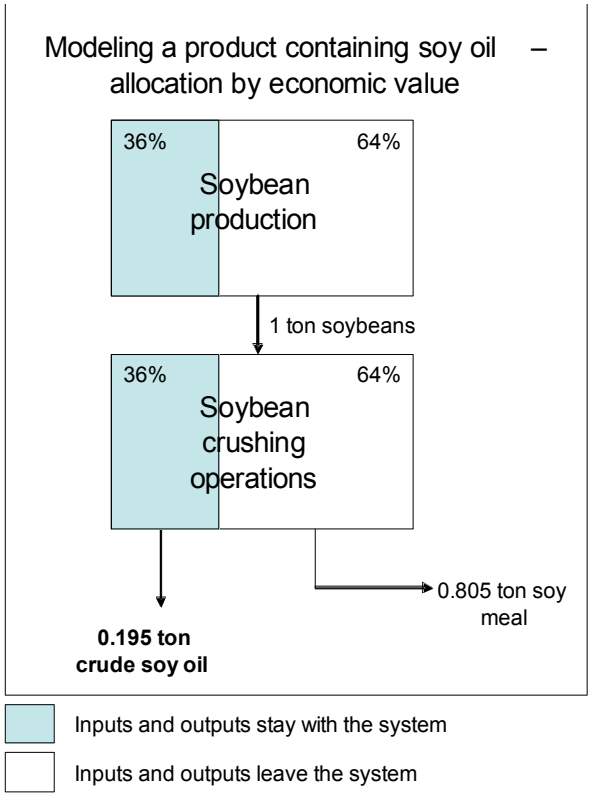
1. No data on an alternate *soy* meal process were available to use for system expansion, so alternate *animal or other vegetable meals* could be used. The composition of common feed rations varies based on species (poultry, swine, fish, beef, dairy etc.), age of species (starter rations, growth rations, finishing rations) and cost of ingredients. Alternative protein sources, if looking at just protein, include other protein meals (canola meal, DDGS, corn steep water, animal by-product meals such as dairy, feather or fish meals, etc.). For these reasons, choosing the most appropriate alternate meal over another would have been a complex process.
2. Some of the alternate meal sources would have made the soy-based polyol option have even lower GHG emissions, because of the N2O and CH4

associated with the animal husbandry. This in itself becomes a decision with a bias toward the soy-based polyol;

3. The data quality on the various alternate meals may not be as high as the other data in this study, so it would not have yielded as robust a set of results; and
4. Often with system expansion, the process data for the alternative product being subtracted out is higher than the process data for the coproduct, resulting in net negative, and very non-intuitive, results. This was the case here, and therefore it was decided that system expansion would not be used.

If avoiding allocation altogether or expanding the system boundary are not practicable, then the inputs and outputs should be allocated based on some sort of other basis, such as market value or physical partitioning. Figure A-3 presents the *economic* value of the coproducts, based on December 2008 price projections.

Figure A-3 Economic Allocation

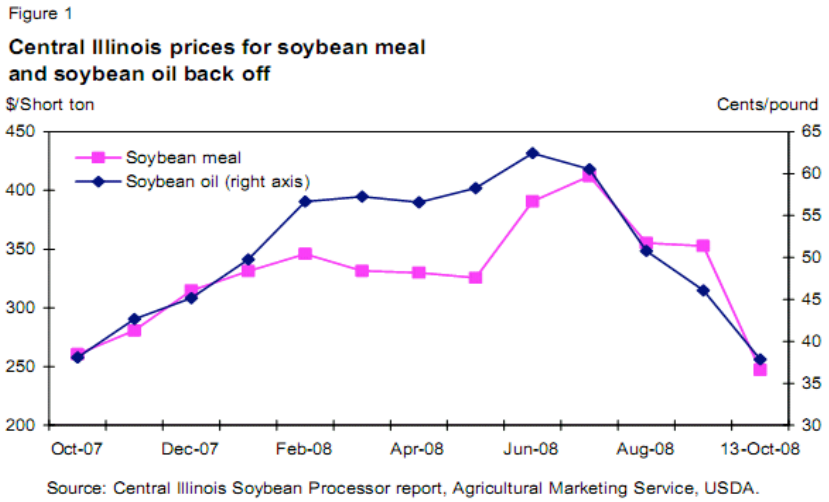


However, allocation based on the economic value of the products is also not a hard and fast choice. As shown in Table A-1 and Figure A-4 the economics of soy oil and soy meal are volatile. It is fairly common to update an LCA or data contained in an LCA every 4 to 6 years. But using allocation based on value would require the LCA to be updated very frequently, which is cost- and time- prohibitive and would not hold water for marketing purposes or for economic programs such as a carbon credit trading system. Economic allocation, nonetheless, is a defensible choice, and many in the LCA field feel that it is a preferred choice. For these reasons, those using this study or data should put a lot of consideration into the allocation choice.

Table A-1 Soy Oil and Meal Economic Data[41]

Allocation basis	Output	Portion of each output from 1 kg of soybean	Economic value for each output ($/kg)	Total $ in the system	Final allocated value
Economic, 2004 pricing	crude oil	0.195	$0.45	$0.09	36%
	meal	0.805	$0.19	$0.16	64%
Economic, 2005 pricing	crude oil	0.195	$0.46	$0.09	33%
	meal	0.805	$0.23	$0.19	67%
Economic, 2006 pricing	crude oil	0.195	$0.63	$0.12	40%
	meal	0.805	$0.23	$0.18	60%
Economic, 2007 pricing	crude oil	0.195	$1.01	$0.20	39%
	meal	0.805	$0.39	$0.31	61%
Economic, 2008 pricing	crude oil	0.195	$0.68	$0.13	34%
	meal	0.805	$0.32	$0.26	66%
Economic, June 2008	crude oil	0.195	$1.45	$0.28	43%
	meal	0.805	$0.46	$0.37	57%
Economic, Dec '08 pricing	crude oil	0.195	$0.78	$0.15	38%
	meal	0.805	$0.30	$0.24	62%
Economic, July 2009	crude oil	0.195	$0.75	$0.15	30%
	meal	0.805	$0.42	$0.34	70%

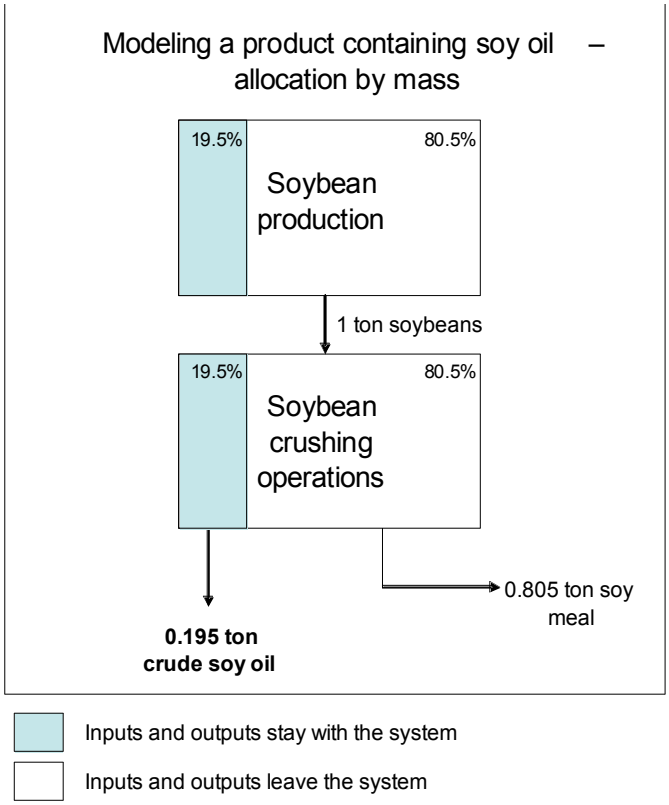
Figure A-4 Soy Oil and Meal Economic Data [42]



[41] Data from Chicago Board of Trade and Wall Street Journal.
[42] Taken from Ash, Mark and Erik Dohlman, **Oil Crops Outlook**, October 14, 2008. Found at www.ers.usda.org.

Finally, an allocation choice based on physical partitioning can be done. Figure A-5 presents the allocation by mass percent of the two coproducts.

Figure A-5 Mass Allocation



The physical breakdown of the quantities of oil and meal coming from soybeans is probably not going to vary more than a few percentage points, so in general, this is uncontested. Since a physical partitioning allocation choice seems to have the least set of uncertainties, this analysis uses mass allocation, and a sensitivity analysis is made using economic allocation. To sum up the decision on allocating coproducts,

1. For this analysis, physical partitioning was done because it made the most sense and was least contentious.
2. The economics of many product systems, including soy oil and soy meal, may be very volatile, and the numbers in Figure A-4 and Table A-1 demonstrate this well.
3. Mass allocation has been used for the LCAs performed on biobased products evaluated for the Federal BioPreferred Program.
4. Results for system expansion may not be intuitive for the user. Also one needs to have good data for the alternative production for system expansion, and data on alternate meal that is comparable to other data in the study.

It should be reminded that the soybean processing data (soy oil and meal production) will be submitted to the U.S. LCI database on an unallocated basis so that LCA practitioners can run results based on goals and scope of their studies.

Sensitivity Analysis: Use of Economic Allocation

The following tables present an analysis on the affect of the mass allocation decision. The value used for the economic sensitivity analysis was 38.5% allocated to oil (the higher end of the range). The petroleum-to-soy ratios have been presented in these tables to evaluate the differences of the ratios of the mass and economic allocation results.

Overall remark: for products that do not contain a significant amount of soy based material (such as resin), the allocation choice does not make as much of a difference. However, for products that contain a significant amount of soy-based material, the allocation choice does make more of a difference.

Diesel Economic Allocation Sensitivity Results

The table below presents the soy biodiesel results using mass allocation, vs. the soy biodiesel results using economic allocation (the petroleum results do not change).

Table A-2 Soy Biodiesel – Mass vs. Economic Allocation

Impact Category	Unit	Methyl Soyate (Mass)	Methyl Soyate (Econ)	Economic to Mass ratio
Global warming potential	kg CO2 eq	-2.1 E+03	-1.5 E+03	0.73
Acidification Potential	milmole H+eq	4.1 E+05	6.2 E+05	1.51
Eutrophication Potential	kg N eq	2.8 E+00	6.1 E+00	2.17
Fossil Fuel Depletion	MJ Surplus	1.4 E+03	2.0 E+03	1.38
Water Intake	liters	4.8 E+04	1.0 E+05	2.16
Criteria Air Pollutants	microDALYs	1.1 E+02	1.7 E+02	1.51
Ozone Depletion Potential	kg CFC-11 eq	1.8 E-06	3.8 E-06	2.14
Smog Formation Potential	g NOx eq	5.0 E+03	8.3 E+03	1.67
Total Fuel Energy	MJ	8.6 E+03	1.3 E+04	1.56
Ecotoxicity	g 2,4-D eq	1.4 E+04	2.8 E+04	2.02
Human Toxicity - Cancer	g C6H6 eq	7.5 E+02	1.1 E+03	1.48
Human Toxicity - Noncancer	g C7H8 eq	1.0 E+06	1.8 E+06	1.80

In all categories, the results for the economic allocation increase. This makes sense, since the crushing and soybean production impacts increased from a nearly 20% allocation to nearly 40%. The GWP category is lower; much of the GWP value stems from the carbon embedded in the product. Thus, the allocation change only affects the non-biomass CO2 impacts. Table A-2 above presents soy biodiesel vs. petroleum-based diesel using economic allocation. But in order to effectively demonstrate how the change in allocation rule affects the overall comparative results, Table A-3 and the subsequent tables present the *ratios* calculated between the mass allocation comparison results and the economic allocation comparison results.

Table A-3 Diesel Comparison Using Economic Allocation

Impact category	Unit	Methyl Soyate Total	Petroleum-based Diesel Oil Total	Petro to soy ratio
Global warming potential	kg CO2 eq	-1.5 E+03	6.6 E+02	N/A
Acidification Potential	milmole H+eq	6.3 E+05	5.0 E+05	0.79
Eutrophication Potential	kg N eq	6.1 E+00	4.5 E-01	0.07
Fossil Fuel Depletion	MJ Surplus	2.0 E+03	7.3 E+03	3.61
Water Intake	liters	1.0 E+05	2.2 E+03	See Note
Criteria Air Pollutants	microDALYs	1.7 E+02	1.1 E+02	0.63
Ozone Depletion Potential	kg CFC-11 eq	3.8 E-06	1.7 E-07	0.04
Smog Formation Potential	g NOx eq	8.4 E+03	1.0 E+04	1.22
Total Fuel Energy	MJ	1.4 E+04	8.1 E+03	0.59
Ecotoxicity	g 2,4-D eq	2.8 E+04	4.9 E+03	0.18
Human Toxicity - Cancer	g C6H6 eq	1.1 E+03	1.9 E+03	1.75
Human Toxicity - Noncancer	g C7H8 eq	1.8 E+06	1.4 E+06	0.77

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Table A-4 Economic Allocation: Soy-based Diesel vs. Petroleum-based Diesel

Impact category	Unit	Mass Allocation - petro to soy ratio	Economic Allocation - petro to soy ratio
Global warming potential	kg CO2 eq	N/A	N/A
Acidification Potential	milmole H+eq	1.20	0.79
Eutrophication Potential	kg N eq	0.16	0.07
Fossil Fuel Depletion	MJ Surplus	5.00	3.61
Water Intake	Liters	See Note	See Note
Criteria Air Pollutants	microDALYs	0.95	0.63
Ozone Depletion Potential	kg CFC-11 eq	0.09	0.04
Smog Formation Potential	g NOx eq	2.04	1.22
Total Fuel Energy	MJ	0.93	0.59
Ecotoxicity	g 2,4-D eq	0.35	0.18
Human Toxicity - Cancer	g C6H6 eq	2.59	1.75
Human Toxicity - Noncancer	g C7H8 eq	1.40	0.77

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Remarks: In general, because the allocation went from 20% to nearly 40%, the ratio decreased for many of the categories, so the soy results are not as favorable when using the economic allocation. Where the soy product was considered equivalent to the petro product in the mass allocation (criteria pollutants and fuel energy), now the soy results are worse than the petroleum results. The GWP ratio increased slightly.

Oil for Lubricants Economic Allocation Sensitivity Results

Table A-5 Economic Allocation: Soy Oil for Lubricant vs. Petroleum-based Oil for Lubricant

Impact category	Unit	Mass Allocation - petro to soy ratio	Economic Allocation - petro to soy ratio
Global warming potential	kg CO2 eq	N/A	N/A
Acidification Potential	milmole H+eq	2.82	1.44
Eutrophication Potential	kg N eq	0.14	0.07
Fossil Fuel Depletion	MJ Surplus	16.99	8.72
Water Intake	liters	See Note	See Note
Criteria Air Pollutants	microDALYs	2.23	1.14
Ozone Depletion Potential	kg CFC-11 eq	0.09	0.04
Smog Formation Potential	g NOx eq	3.42	1.73
Total Fuel Energy	MJ	1.90	0.97
Ecotoxicity	g 2,4-D eq	0.37	0.19
Human Toxicity - Cancer	g C6H6 eq	6.62	3.37
Human Toxicity - Noncancer	g C7H8 eq	1.86	0.95

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Remarks: A couple of the categories where soy was better than the petroleum product (e.g., fuel energy and human toxicity non-cancer), are now equivalent to the petroleum product. Beside that, the overall outcomes did not change.

Polyol Economic Allocation Sensitivity Results

Table A-6 Economic Allocation: Soy-based Polyol vs. Petroleum-based Polyol

Impact category	Unit	Mass Allocation - petro to soy ratio	Economic Allocation - petro to soy ratio
Global warming potential	kg CO2 eq	N/A	N/A
Acidification Potential	milmole H+eq	3.04	2.34
Eutrophication Potential	kg N eq	3.80	1.96
Fossil Fuel Depletion	MJ Surplus	6.50	5.35
Water Intake	liters	See Note	See Note
Criteria Air Pollutants	microDALYs	3.06	2.34
Ozone Depletion Potential	kg CFC-11 eq	0.28	0.25
Smog Formation Potential	g NOx eq	2.81	1.92
Total Fuel Energy	MJ	3.48	2.83
Ecotoxicity	g 2,4-D eq	4.87	2.64
Human Toxicity - Cancer	g C6H6 eq	2.63	1.98
Human Toxicity - Noncancer	g C7H8 eq	9.55	6.29

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Remark: while the ratios have still gone down (with the exception of GWP), overall, the majority of impacts for the soy product are still better than those for the petroleum product.

Resin Economic Allocation Sensitivity Results

Table A-7 Economic Allocation: Soy-based Resin vs. Petroleum-based Resin

Impact category	Unit	Mass Allocation - petro to soy ratio	Economic Allocation - petro to soy ratio
Global warming potential	kg CO2 eq	1.28	1.26
Acidification Potential	milmole H+eq	1.03	1.02
Eutrophication Potential	kg N eq	1.04	0.98
Fossil Fuel Depletion	MJ Surplus	1.11	1.10
Water Intake (see note)	liters	See Note	See Note
Criteria Air Pollutants	microDALYs	1.03	1.02
Ozone Depletion Potential	kg CFC-11 eq	0.99	0.87
Smog Formation Potential	g NOx eq	0.36	0.36
Total Fuel Energy	MJ	1.08	1.07
Ecotoxicity	g 2,4-D eq	1.28	1.19
Human Toxicity - Cancer	g C6H6 eq	1.01	1.00
Human Toxicity - Noncancer	g C7H8 eq	1.46	1.43

"equivalent" (+/- 10%)
soy is better than petroleum
soy is worse than petroleum

Note: Incomplete water usage data for crude oil exploration and production prevents a meaningful comparison for this impact category.

Remark: with this product, more categories are equivalent when the economic analysis is performed.