3 Life Cycle Scope and Methodology

This section provides an overview of the biodiesel and petroleum diesel life cycle project. It describes the background, the approach taken for conducting the study, the selection of models and methodologies, and describes major components of LCAs and includes subsections on:

- ***3.1 Background:***Defines and describes LCAs and the two fuels are analyzed in this report.
- ***3.2 Purpose of this Study:*** Describes why an LCA was necessary to answer specific questions.
- ***3.3 Project Scope:*** Describes the temporal and geographic assumptions used in the study. It also describes the type of information collected on energy and environmental flows. Also, some major assumptions are highlighted here.
- ***3.4 System Boundaries:*** Describes in more detail how data were manipulated. Specifically, this section describes how allocation decisions were made and handled.
- *Error! Reference source not found. Error! Reference source not found.**:*** Outlines the partners involved in this study and the tools used for completing the analysis.

3.1 Background

3.1.1 Life Cycle Assessment Overview

LCA is an analytical tool used to comprehensively quantify (within the limits of available data) and interpret the flows to and from the environment. These include air emissions, water effluents, solid waste, toxicity, and the consumption/depletion of energy and other resources, over the entire life cycle of a product or process, commonly referred to as "cradle-to-grave." LCAs can include production and extraction of raw materials, intermediate products manufacturing, transportation, distribution, use, and a final "end-of-life" stage, which often includes multiple parallel paths such as recycling, incineration, or landfilling.

An LCA involves two main steps: (1) the *Inventory*, in which the material and energy inputs and outputs from a life cycle are calculated and tabulated; and (2) the *Interpretation*, which describes the implications to decision makers that may be gleaned from an analysis of the inventory data. The methodology of LCI analysis can be standardized and its practitioners and users commonly accept these standardized approaches. Approaches to the interpretation step are much more varied.

In the most straightforward and transparent approach to LCI interpretation, the LCI results may be used ***as-is*** to help identify and prioritize opportunities for pollution prevention or increases in material and energy efficiency for processes within the life cycle. A particular advantage of LCI applied in this way is its comprehensiveness. LCAs help detect the shifting of environmental burdens from one life cycle stage to another (e.g., lower energy consumption during use, achieved at the cost of much higher manufacturing energy consumption), or from one medium to another (e.g., lower air emissions at the cost of increased solid waste).

Because the resulting number of flows calculated during an LCI analysis often exceeds 100, subsets of the flows are sometimes consolidated or aggregated into stages, such as production or transportation, to facilitate interpretation, especially when two or more products or processes are being compared using LCA.

Finally, because the results of an LCI are influenced by a significant number of assumptions and uncertainties, the interpretation phase should include some sensitivity analyses to assess the robustness of the baseline results and conclusions. Sensitivities can also highlight potentially influential assumptions, methodological choices, future scenarios, and uncertainties.

Further information about LCA methodology is provided in a number of publications from SETAC (SETAC, 1991, 1993a, 1993b, 1994), EPA (USEPA, 1993a, 1993b, 1995) and a variety of European sources (Heijungs, et al., 1992 and SETAC-Europe, 1992).

3.1.2 Biodiesel and Petroleum Diesel Fuels

This life cycle study evaluates changes in energy, resource use, emissions, and wastes resulting from the use of new diesel fuel substitutes and additives in the U.S. transportation sector. Developing new fuels can provide a wide range of potential social benefits, such as diversifying fuels that have few current substitutes, reducing dependence of the transportation sector on vulnerable fuel supplies, improving the environmental characteristics of the transportation sector, or improving its energy efficiency. This study compares the life cycle flows of material, energy, and outputs of biodiesel, a renewable transportation fuel, with petroleum diesel from fossil crude oil supplies.

In the early stages of developing the diesel engine one century ago, Rudolf Diesel tested vegetable oils as a fuel. In the 1930s and 1940s vegetable oils were occasionally used as diesel fuels, generally in emergency situations (Shay, 1993). However, unmodified vegetable oils are glycerol esters, and when used in engines designed for petroleum diesel fuel, the glycerol poses engine wear and performance problems caused by higher viscosity and lower volatility (Biomass Digest, 1993)[19].

To mitigate these problems numerous processes have been researched and demonstrated for converting oil glycerides to molecular forms more similar to petroleum-based diesel fuels, including thermal and catalytic cracking, transesterification, and electrolysis (Shay, 1993). During the past couple of years, biodiesel has become defined as the mono alkyl esters of long chain fatty acids derived from renewable lipid feedstocks, such as vegetable oils or animal fats, for use in compression ignition (diesel) engines. In other words, biodiesel is composed of an ester of a fatty acid chain from vegetable oil or animal fats and an alcohol molecule. However, not all alkyl esters can be used as transportation fuels. In order for the alkyl ester product to be considered a “biodiesel” for transportation fuel, it should meet proposed quality standards from the National Biodiesel Board (NBB). There are many challenges for the biodiesel industry in distinguishing itself from the industrial chemical alkyl ester industries. In this study we examine the processes necessary to make a transportation fuel quality biodiesel.

A variety of biodiesels (various fats and oils and several types of alcohol) has been demonstrated in numerous road transport applications worldwide countries (EC Directorate, 1994; Hemmerlein, 1991; NBB, 1994). In the United States, biodiesel has been tested in nearly 8 million miles of use involving more than 1,500 vehicles in fleets, particularly in urban buses. Much greater use of biodiesel occurs currently in Europe, where a methyl ester made from rapeseed oil receives near-total exemption from highway-use taxes in several European Community (EC) countries (NBB, 1994). The use of biodiesel in aquatic transportation applications has been suggested as a result of tests demonstrating that biodiesel fuels biodegrade relatively rapidly in aquatic environments (Zhang, et al, 1995). There are other potential markets for biodiesel (stationary power, industrial equipment, aviation fuel), but this study compares the relative merits of biodiesel as an on-road transportation fuel with those of petroleum diesel.

[19] See discussion in section 5.5 for additional references on the problems of using unmodified fats and oils in diesel engines.

3.2 Purpose of this Study

Several potential environmental benefits of biodiesel have been cited in the literature, including:

- Reduced (or zero) emissions of SO_x at the point of end-use
- More rapid biodegradability in aquatic environments
- Low or negative flows of CO_2 to the environment over the full product life cycle (when accounting for the CO_2 uptake during the feedstock growing stage).

Solving one problem can unintentionally create others. A life cycle analysis can provide a holistic view of environmental issues.

The purpose of this study is to conduct an LCI to quantify and compare the comprehensive sets of environmental flows (to and from the environment) associated with both biodiesel and petroleum-based diesel, over their entire life cycles.

In addition to the purpose stated, this LCA was initiated to provide the necessary information that could be used to answer the following questions that have been posed by policy makers:

- What are the carbon balances for biodiesel and petroleum diesel fuels? Does one fuel provide a benefit over the other?
- What are the energy efficiencies of biodiesel and petroleum diesel fuels? Does one fuel provide a benefit over the other?
- What are the total contributions of regulated emissions to the environment from producing and using biodiesel and petroleum diesel? Does one fuel provide a benefit over the other?
- Are there potential benefits in some life stages of these fuels that are offset by potential burdens in other stages?
- Can the benefits or burdens of specific life cycle stages, which are created by using biodiesel and diesel fuel, be altered without increasing the net burdens of the entire life cycle?

3.3 Project Scope

This section defines the parameters considered during the scoping phase of the project. This phase had significant stakeholder input. We followed the sequence shown in Figure 22. The outcome of the scoping process was summarized in a report made available to all stakeholders (NREL, 1995).

Project Parameters

3.3.1.1 Environmental Issues Considered

This report will describe only the LCI flows of biodiesel and petroleum-based diesel fuels and discuss the implications of the data. The actual environmental impacts created by these flows depend on site-specific conditions and are best considered in models designed for those purposes. As a result, this report will not consider environmental damages, economic impacts, or long-term environmental consequences of using biodiesel or petroleum diesel fuel. Table 10 presents the list of LCI flows considered in this project.

The inventory flows shown in Table 10 were selected because they were common to both biodiesel and petroleum diesel fuel life cycles; for example, natural resources used during the life cycle of either biodiesel, petroleum diesel fuel, or both. Specific air emissions and water effluents are also found in both life cycles. In addition, these data are most often collected and reported by regulatory agencies and thus, provide a common framework for the inventories. Input from stakeholders was used early in the process to identify important emissions and life cycle flows that needed to be included in our study.

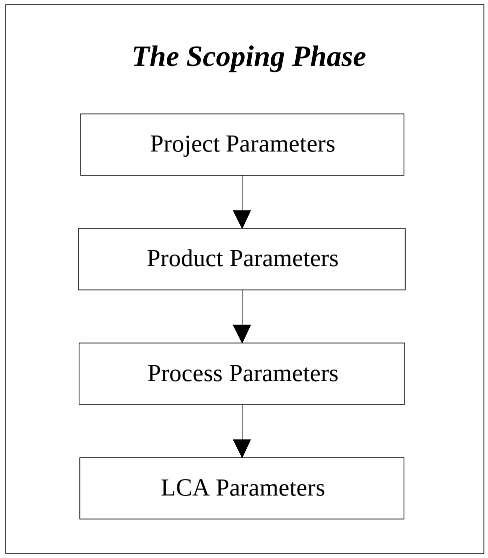

Figure 22: Elements of the Scoping Phase for LCA

Table 10: LCI Items Considered

Natural Resources	Air Emissions
Coal	Fossil Carbon Dioxide (CO_2 fossil)
Oil	Biomass Carbon Dioxide (CO_2 biomass)
Natural Gas	Methane (CH_4)
Iron (Fe, ore)	Nitrous Oxide (N_2O)
Phosphate Rock	Nitrogen Oxides (NO_x)
Potash (K_2O)	Sulfur Oxides (SO_x)
Uranium (U, ore)	Ammonia (NH_3)
Limestone ($CaCO_3$)	Hydrogen Chloride (HCl)
Sand	Hydrogen Fluoride (HF)
Sodium Chloride (NaCl)	Particulate Matter (PM)
Water Used (total)	Hydrocarbons (HC)
Water Effluents	Carbon Monoxide (CO)
Chemical Oxygen Demand (COD)	Benzene
Nitrates	Formaldehyde
Biochemical Oxygen Demand (BOD)	Solid Waste
Agrochemicals	Hazardous
Ammonia (as N)	Nonhazardous
Metals	

The list of air emissions selected was also based on the potential harm to the environment. Trace emissions of benzene and formaldehyde were included in the inventory list because of their potentially toxic nature, and some of the acid gas emissions (HCl, HF) were chosen because of their potential contribution to acid deposition. However, the inventory information on these flows is not consistent throughout the life cycle. Trace HC emissions of benzene and formaldehyde are only known for volatile emissions during crude oil extraction; data on these emissions from other combustion sources are sparse.

These, and other similar types of data, should be used with care because some sources may not be accounted for because of data gaps.

Energy use is tracked throughout the life cycle of both biodiesel and petroleum-based diesel fuel. Total energy efficiency, process energy efficiency, and fossil energy efficiency ratios are calculated in the section presenting results. The ratios are used to evaluate the consumption of nonrenewable energy resources. The carbon balance for each fuel cycle is also modeled and evaluated to estimate the impact, if any, on controversial greenhouse gas and global warming issues.

Some of the values estimated for inventory flows are highly uncertain for a variety of reasons: scarce data, poorly characterized processes or natural systems, proprietary data, etc. When the uncertainty of the data characterizing a particular inventory flow is large, the results are not included in the final inventory tabulation to prevent compromising reliable data and misinterpreting the results. However, the data and their quality are discussed in detail in the relevant sections describing specific life cycle stages.

3.3.1.2 Temporal Scope

A near-term time frame has been selected for this study. Because of capital stock lifetimes, a study reflecting current technologies should remain relevant into the next decade. Also, a study of current end-use technologies based on empirical data provides a robust LCI that becomes the most logical starting point for future projections or extrapolations.

The biodiesel LCA required us to postulate a hypothetical biodiesel industry in its infancy, based on today's soybean production and crushing industries, U.S. and European methyl ester transesterification technology, and methyl ester and diesel fuel transportation infrastructure. The details that describe the basis for these and other assumptions are provided in the sections describing the details of the biodiesel life cycle stages.

3.3.1.3 Geographical Scope

The focus of the project is, in generic terms, to "evaluate biodiesel and petroleum diesel applications in the United States." However, the geographic scope of particular data or product life cycle stages will depend on the locations dictated by actual plant locations, feedstock origins, sources of electricity, and end-uses. Often, our choice of using site-specific, industry, or national average data is limited by the completeness of each type of data set available, and whether the choice of data made for one stage of the life cycle can be followed through into the sequential stages of the life cycle. Because most firm and industry data are proprietary, LCAs are often limited to national public data, which generally consist of national, regional, or industry averages. Table 11 outlines the geographic scope and types of data sets available for each petroleum diesel fuel life cycle stage modeled in this study. International crude oil extraction is included because almost half the crude oil used in the United States is of foreign origin. Table 12 outlines the geographic scope and type of data sets used for each biodiesel fuel life cycle stage modeled in this study.

U.S. national averages for soybean oil conversion and biodiesel production were based on modeled engineering systems because little industry specific information was available. Biodiesel transportation and storage systems had to be modeled as well, because biodiesel distribution infrastructure has not yet been developed.

The relevance of data is explained in each section of this report. Whenever possible data are regionalized to allow for more detailed site-specific comparisons. For example, crude oil transportation distances and methods are separated by Petroleum Administration for Defense District (PADD), and soybean agriculture is separated by state.

Table 11: Geographic Scope of Petroleum Diesel Fuel Modeling

Life Cycle Stage	***Geographic Scope***
Crude Oil Extraction	International average based on the consumption of crude oil in the United States
Crude Oil Transportation	International average transportation distances to the United States
Crude Oil Refining	U.S. national average
Diesel Fuel Transportation	U.S. national average
Diesel Fuel Use	U.S. national average based on urban bus use

Table 12: Geographic Scope of Biodiesel Modeling

Life Cycle Stage	***Geographic Scope***
Soybean Agriculture	Average based on the 14 states growing soybeans
Soybean Transportation	U.S. national average
Soybean Crushing	U.S. average based on modeled data
Soybean Oil Transport	U.S. national average
Soybean Oil Conversion	U.S. average based on modeled data
Biodiesel Transportation	U.S. national average
Biodiesel Fuel Use	U.S. national average based on urban bus use

3.3.2 Product Parameters

3.3.2.1 Fuels Studied

The petroleum diesel studied is low-sulfur #2 diesel. A comparison with 100% biodiesel is selected as the baseline for this study. However, among biodiesel blend ratios, 20% biodiesel blend with #2 diesel has been extensively studied and has been recommended by industry groups as a fuel blend that provides reasonable environmental benefits for a reasonable cost (NBB, 1994). This type of study is an appropriate venue for quantifying some of those environmental flows. The three fuels studies in this report are:

- Low-sulfur #2 diesel for on-road applications (often referred to simply as petroleum diesel)
- 100% biodiesel made from soybean oil and methanol using transesterification technology (referred to as B100)
- A blend of 20% biodiesel 80% low-sulfur #2 diesel fuel (referred to as B20).

3.3.2.2 End-Use

The end-uses of the fuels modeled in this study are characterized by the following:

- Use of biodiesel and low-sulfur diesel fuel in modern urban diesel buses
- Fleet use only (a consequence of the previous assumption)
- Engine-specific comparisons.

It is important to limit the end-uses of the fuels to a single application. Transit bus applications are among the most heavily studied biodiesel applications in the United States to date. Limiting the end-use to bus applications allows us to introduce the best-characterized empirical database on biodiesel available. Urban buses operations are characterized as "fleets" and establishes the use of central fueling in the modeling.

Engine-specific comparisons of the two fuel alternatives (biodiesel and petroleum diesel) are highly important. Data on engine performance for diesel and biodiesel have shown considerable variability in emissions and performance characteristics among different engine designs. Therefore, comparisons must pertain to a given engine, and must clearly state the engines to which the results correspond.

Many bus fleets use four-stroke engines (e.g., the Detroit Diesel Series 60) today to meet particulate emission rules imposed by EPA. No one specific engine is chosen as the representative urban bus engine, because of the variability in emissions and performance among engines, *all engines suitable for transit buses for which reliable emissions test data are available for both fuels are included in the study.*

3.3.2.3 Functional Unit

Different industrial systems can be compared only if they perform the same function or service to society. In this case, that service is to provide bus transportation to an urban population.

Once this shared function is defined, a unit has to be chosen to compare the systems on the same quantitative basis. End-use emissions data are generally available in terms of grams of emissions per brake-horsepower-hour (g/bhp-h), as the result of standardized EPA transient cycle testing procedures, designed to characterize emissions from real driving. Therefore, the functional unit to be used in this study is ***brake-horsepower-hour***. By using this functional unit, the LCA will compare the two fuels in terms of actually delivered work from combustion within real engines under tests designed to reflect realistic operating conditions.

All the energy and mass flows in the inventory are normalized to this functional unit. In other words, the LCI data will be tabulated and reported as units of environmental flows per brake-horsepower-hour.

3.3.3 Process Parameters

The establishment of project and product parameters leads logically to the development of the process parameters, which describe the fuel technologies chosen.

3.3.3.1 Biodiesel

We assume that the LCIs will be based on current data and technology; this dictates some of the assumptions concerning fuel production and feedstock supplies. The primary feedstock for biodiesel production is soybeans because soybean oil supplies exceed the total combined supply of all other oils and fats produced in the United States today. Based on its dominant supply position and widespread availability, it is the most likely biodiesel fuel to dominate the U.S. market in the near term. Other oil seed crops would require a significant amount of time to expand production and achieve dominance, which eliminates them from consideration in the near term. Animal fats used for biodiesel have yet to establish their market acceptance, and that too eliminates them from near-term consideration. In addition, most of the research and data available for characterizing biodiesel are based on a soy oil methyl ester. Therefore, soy oil and soybean feedstock production were logical choices for characterizing near-term biodiesel production.

USDA data characterizing the chemical, land, energy, water, and other inputs to soybean production in the United States are used to establish current performance characteristics for soybean production and harvesting. Also, to the maximum extent supportable by reliable data, outflows of the agricultural system will include the use, production, and fates of chemicals used, including fertilizers, herbicides, etc.

Soybean crushing and soy oil production technologies are widespread, although characterization data were not easily found in the literature. Cooperation with industrial partners allowed NREL engineers to recreate an engineering model of this technology. Sources and distribution of soybean oil are identified for each region studied. Available end-use data on soy-derived biodiesel are based on refined oils.

The most popular current biodiesel production technology is transesterification using methanol as the alcohol input. The U.S. capacity dedicated to biodiesel production for the transportation market (excluding methyl ester industry chemical producers) is approximately 30 million annual gallons, most of which use some variation of the transesterification process. This technology also dominates the European market for biodiesel. Methanol is the most common alcohol used because it provides some process efficiencies and is relatively inexpensive compared to its second most common alternative, ethanol.

3.3.3.2 Petroleum Diesel Fuel

Petroleum diesel produced domestically from U.S. and foreign sources of crude oil is the second largest source of transportation fuel in the U.S. Energy Information Administration data characterizing the split between foreign and domestic crude oil supplies are used to characterize diesel fuel feedstocks. Oil production technologies are characterized by public data, as is crude oil transportation. Regional differences in crude oil supplies, refined product production, and product distribution modes are taken into account where data are available. National average data supplied by the EPA are used to characterize refining technologies. Some of these data may be out of date given the large advances in refining technology demonstrated by the industry in recent years. Industry and government studies characterizing refining and other petroleum life cycle flows were sought out and provided valuable data for assumptions and environmental flows. Mass and energy balances were developed for these stages to give confidence to the analysis, similar to the same effort conducted for biodiesel life cycle stages.

3.3.4 LCA-Specific Parameters

Biomass carbon in this study is a specific case that requires special attention when performing an LCI. The carbon content of the biomass portion of the biodiesel is derived from the CO_2 absorbed by plants while growing (photosynthesis). These carbon atoms are released as CO_2, CO, HC, or particulate emissions during biodiesel combustion. The biomass-derived CO_2 releases are offset by the CO_2 uptake or sequestering during plant growth[20].

A portion of the biodiesel consists of methanol that is derived from natural gas, a fossil fuel source. The total CO_2 emitted from the bus tailpipe consists of both fossil and biomass CO_2; therefore, these two

[20] Implicit in this discussion is the fact that we have ignored the dynamic effect of carbon sequestration in the soil on the level of atmospheric carbon. A significant amount of carbon can be stored in the soybean plant root systems. Soil microorganisms eventually return this carbon to the atmosphere, but at a relatively slow rate. We have chosen not to take credit for any of this additional sequestering of carbon. See sections 9.1.2.1 for a more detailed description of how we account for biological cycling of carbon.

sources of CO_2 are reported and tracked separately throughout the biodiesel life cycle. Actually, a carbon balance is calculated for the biodiesel life cycle showing all the sources and final deposition of both fossil and biomass carbon.

3.4 System Boundaries

3.4.1 LCA Principle for Setting System Boundaries

System boundaries define the relevant processes to be included or excluded from the LCA. The common ones that are generally considered are construction and disposition stages, the flows associated with producing the inputs consumed in life cycle stages, accounting for duplicate stages common to both life cycles, and the rules for allocating life cycle contributions between coproducts of production processes. Arguments associated with each of the three common system boundary decisions are provided below.

- The LCA theoretical principle implies that *each* material and constituent be studied and traced *back* to natural resources, and *forward* through final disposal. The strict application of this principle would lead to the study of almost every industrial process, as all industrial operations work within a complex network. To keep the LCA focused on the primary flows that provide significant contributions to the LCI, quantitative rules are applied to exclude the constituents and ancillary materials whose impacts are estimated to be negligible compared to those of the overall studied system.
- As the project focuses on a comparison, steps that are functionally equivalent for the compared products could be excluded from both systems. On the other hand, steps or operations that are not functionally equivalent for the compared products should be taken into account, i.e., included in the system boundaries. If the life cycle is to prepare a comprehensive inventory rather than a comparison, common activities to both life cycles should be included.
- Economic activities that result in more than one product that are subsequently introduced into commerce (i.e., not disposed of) should allocate the environmental flows associated with those processes between the coproducts in a rational or equitable manner. A wide variety of "rational and equitable" approaches is available and each has its particular impact on the results of an LCA. Whatever choice is made for one life cycle should be applied to another if the two are being compared. In addition, whatever choice is made for one stage or process in an LCA should be carried through to other processes and stages. In practice, these rules of consistency create difficult choices and unintentional trade-offs.

The principle for defining the system boundaries within an LCA study is illustrated in Figure 23.

For this study, the life cycle environmental flows associated with producing capital equipment and facilities used to extract, transport, and refine crude oil are excluded based on results from prior studies that suggest their contribution is small. Likewise, the life cycle environmental flows associated with producing capital equipment and facilities used to grow, transport, crush, and convert soybeans are excluded.[21]

The energy used in the construct large energy facilities and other equipment used in fuel cycles (including electric power plants, oil wells, oil tankers, and hydroelectric plants) is negligible (less than 1%)

[21] See, for example, Boustead, 1997. Boustead states that the flows from large equipment and facilities construction are less than 0.01% for any product. He does suggest two exceptions to this—oil well construction and road transport. Delucchi suggests that oil well contributions are small (Delucchi, 1993). The complexity of modeling road transport equipment production necessitated our ignoring this effect in our analysis. Quantification of life cycle flows from capital equipment production should be considered as a future area of study for improving the quality of our results.

compared with the energy produced or carried by that equipment over its useful life (DeLucchi 1993). These results indicate that, for the petroleum fuel cycle in this study, the life cycle flows associated with capital equipment and facilities are negligible[22].

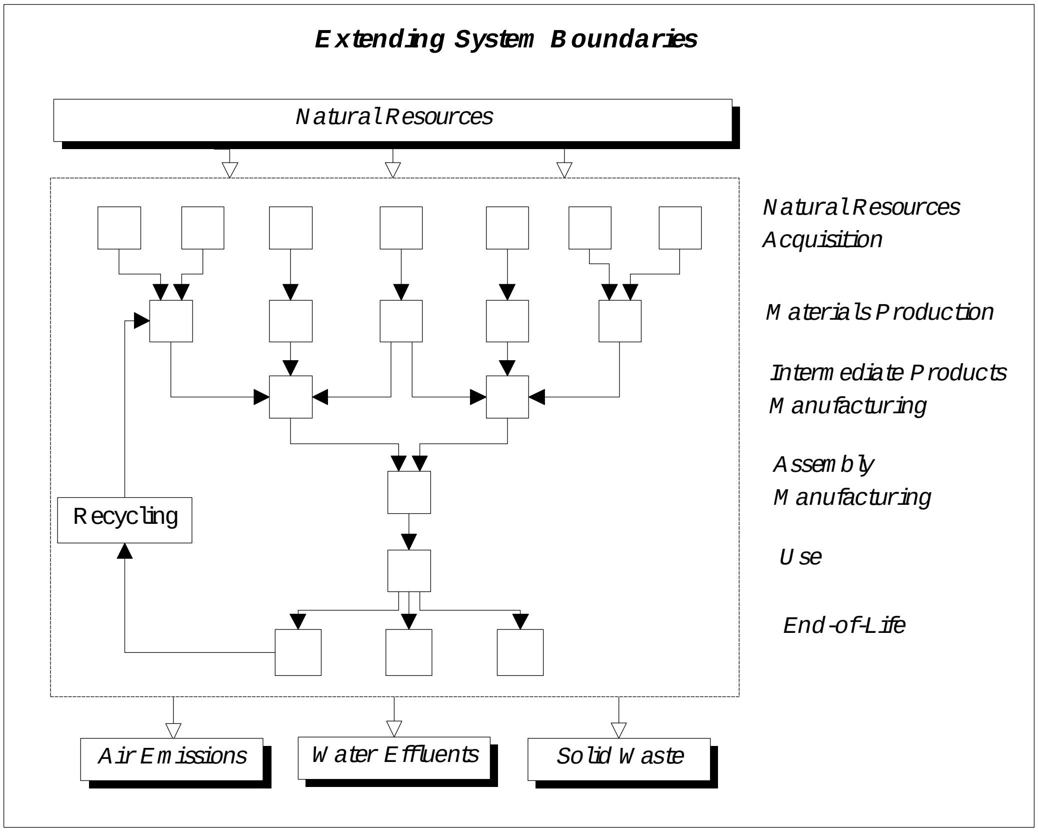

Figure 23: LCA System Boundary Principles

This may not be the case, however, for the biodiesel life cycle. The biomass resources used to produce biodiesel are often less energy dense and less concentrated than fossil fuels. They also often require more transportation and processing equipment and facilities. In some cases, the energy embodied in the construction of equipment used in biofuels compared with the energy produced or carried by that equipment over its useful life is an order of magnitude higher than petroleum fuel cycles (~10%) (Delucchi 1993). However, to be consistent with the petroleum fuel cycle, the life cycle flows associated with construction of capital equipment and facilities used in biodiesel life cycle are excluded from this study.

The environmental flows associated with inputs consumed in the life cycle stages are traced back to their original components and their production and extraction wherever possible.

Both the biodiesel and the petroleum diesel life cycles employ a mass balance allocation rule throughout.[23] A number of alternatives were considered and discarded because they introduced major practical problems in their implementation or interpretation.

[22] The only case for which this may not be negligible is offshore oil platform construction.

3.4.2 How Allocation Rules are Used in Our Study

Several processes within the biodiesel and the petroleum diesel life cycles produce more than one product. This life cycle study is concerned only with the portion of the environmental flows that is attributable to the biodiesel or petroleum-based diesel LCIs. Therefore, the original LCI flows of a process (emissions, energy and material requirements, etc.) that produce more than one coproduct are split between the various products produced. As previously discussed, a mass based allocation is used for the baseline comparison of biodiesel and petroleum-based diesel fuel.

The following example shows how a mass allocation works in the case of allocating the soybean conversion into biodiesel environmental flows between multiple coproducts:

First, the overall environmental flows are determined for a specific process, as shown in Table 13 for soybean conversion into biodiesel.

Table 13: Environmental Inflows and Outflows for the Biodiesel Conversion Process

	Environmental Flow	*Units*	*Value*
IN:	Soybean Oil (degummed)	kg	1.04
	Sodium Hydroxide (NaOH, 100%)	kg	0.0023
	Methanol (CH_3OH)	kg	0.096
	Electricity	MJ elec	0.23
	Steam	kg	1.03
	Water Used (total)	L	0.36
	Sodium Methoxide (CH_3ONa)	kg	0.024
OUT:	Biodiesel (neat, kg)	kg	1
	Crude Glycerine	kg	0.15
	Soapstock	kg	0.00054
	Water (chemically polluted)	L	0.38
	Waste (total)	kg	0.012

Next, the mass percent of each coproduct produced is calculated, as shown in Table 14:

Table 14: Mass Percent of the Various Conversion Co-Products

Coproducts	*Units*	*Value*	*Mass Percent of Total*	
Biodiesel (neat, kg)	kg	1	87%	
Crude Glycerine	kg	0.15	13%	
Soapstock	kg	0.00054	0%	(negligible)
Total:	kg	1.15	100%	

[23]The choice of allocation rules can be quite controversial. The assumption of a mass allocation rule applied to multi-product processes was a subject of real debate among the stakeholders. The mass allocation approach was seen as the least problematic approach to use.

Finally, the overall environmental flows are allocated to only the production of biodiesel, as shown in Table 15.

Table 15: Mass Allocated Conversion Results for Biodiesel

	Environmental Flow	***Units***	***Total Process Values***	***Biodiesel Only Allocation***	***Biodiesel Only Results***
IN:	Soybean Oil (degummed)	kg	1.04	x 0.87 =	0.90
	Sodium Hydroxide (NaOH, 100%)	kg	0.0023	x 0.87 =	0.0020
	Methanol (CH_3OH)	kg	0.096	x 0.87 =	0.083
	Electricity	MJ	0.23	x 0.87 =	0.20
	Steam	kg	1.03	x 0.87 =	0.89
	Water Used (total)	kg	0.36	x 0.87 =	0.31
	Sodium Methoxide (CH_3ONa)	kg	0.024	x 0.87 =	0.021
OUT:	Biodiesel (neat, kg)	kg	1	x 1 =	1
	Crude Glycerine	kg	0.15	x 0 =	0
	Soapstock	kg	0.00054	x 0 =	0
	Water (chemically polluted)	kg	0.38	x 0.87 =	0.33
	Waste (total)	kg	0.012	x 0.87 =	0.010

Similarly, a mass based allocation can be performed for the production of crude glycerine, as shown in Table 16. We don't actually carry out the calculations for allocation of life cycle flows to glycerine in our model because our analysis is concerned with those flows allocated only to biodiesel. We show this calculation to demonstrate that the mass balance for all flows is not violated by the application of allocation factors, as long as all coproducts are treated the same way when flows are allocated to them. In this example, in other words, combining the final columns of Table 15 and Table 16 will yield the overall results for biodiesel conversion as shown in Table 17.

Figure 24 through Figure 27 show the allocated and unallocated mass and energy balances for the two systems considered in this study. These figures demonstrate the complexity of the systems we are modeling. A comparison of the allocated and unallocated primary energy inputs for both of these fuels shows that, without allocation, the energy consumption assigned to make each fuel is much higher than the value of the fuel. This is due to the fact that the energy inputs that occur in each life cycle contribute to production of many other products besides petroleum diesel and biodiesel. The application of allocation rules provides an approximate means for assigning energy inputs in the life cycle among all of the products involved.

Table 16: Mass Allocated Conversion Results for Glycerine (not used in this study)

	Environmental Flow	*Units*	*Total Process Values*	*Glycerine Only Allocation*	*Glycerine Only Results*
IN:	Soybean Oil (degummed)	kg	1.04	x 0.13 =	0.14
	Sodium Hydroxide (NaOH, 100%)	kg	0.0023	x 0.13 =	0.00030
	Methanol (CH_3OH)	kg	0.096	x 0.13 =	0.013
	Electricity	MJ	0.23	x 0.13 =	0.030
	Steam	kg	1.03	x 0.13 =	0.14
	Water Used (total)	kg	0.36	x 0.13 =	0.047
	Sodium Methoxide (CH_3ONa)	kg	0.024	x 0.13 =	0.0032
OUT:	Biodiesel (neat, kg)	kg	1	x 0 =	0
	Crude Glycerine	kg	0.15	x 1 =	0.15
	Soapstock	kg	0.00054	x 0 =	0
	Water (chemically polluted)	kg	0.38	x 0.13 =	0.051
	Waste (total)	kg	0.012	x 0.13 =	0.0016

Table 17: Biodiesel Conversion Process Flows per Coproduct

	Environmental Flow	*Units*	*Biodiesel Only Results*		*Glycerine Only Results*		*Total Process Values*
IN:	Soybean Oil (degummed)	kg	0.90	+	0.14	=	1.04
	Sodium Hydroxide (NaOH, 100%)	kg	0.0020	+	0.00030	=	0.0023
	Methanol (CH_3OH)	kg	0.083	+	0.013	=	0.096
	Electricity	MJ	0.20	+	0.030	=	0.23
	Steam	kg	0.89	+	0.14	=	1.03
	Water Used (total)	kg	0.31	+	0.047	=	0.36
	Sodium Methoxide (CH_3ONa)	kg	0.021	+	0.0032	=	0.024
OUT:	Biodiesel (neat, kg)	kg	1	+	0	=	1
	Crude Glycerine	kg	0	+	0.15	=	0.15
	Water (chemically polluted)	kg	0.33	+	0.051	=	0.38
	Waste (total)	kg	0.010	+	0.0016	=	0.012

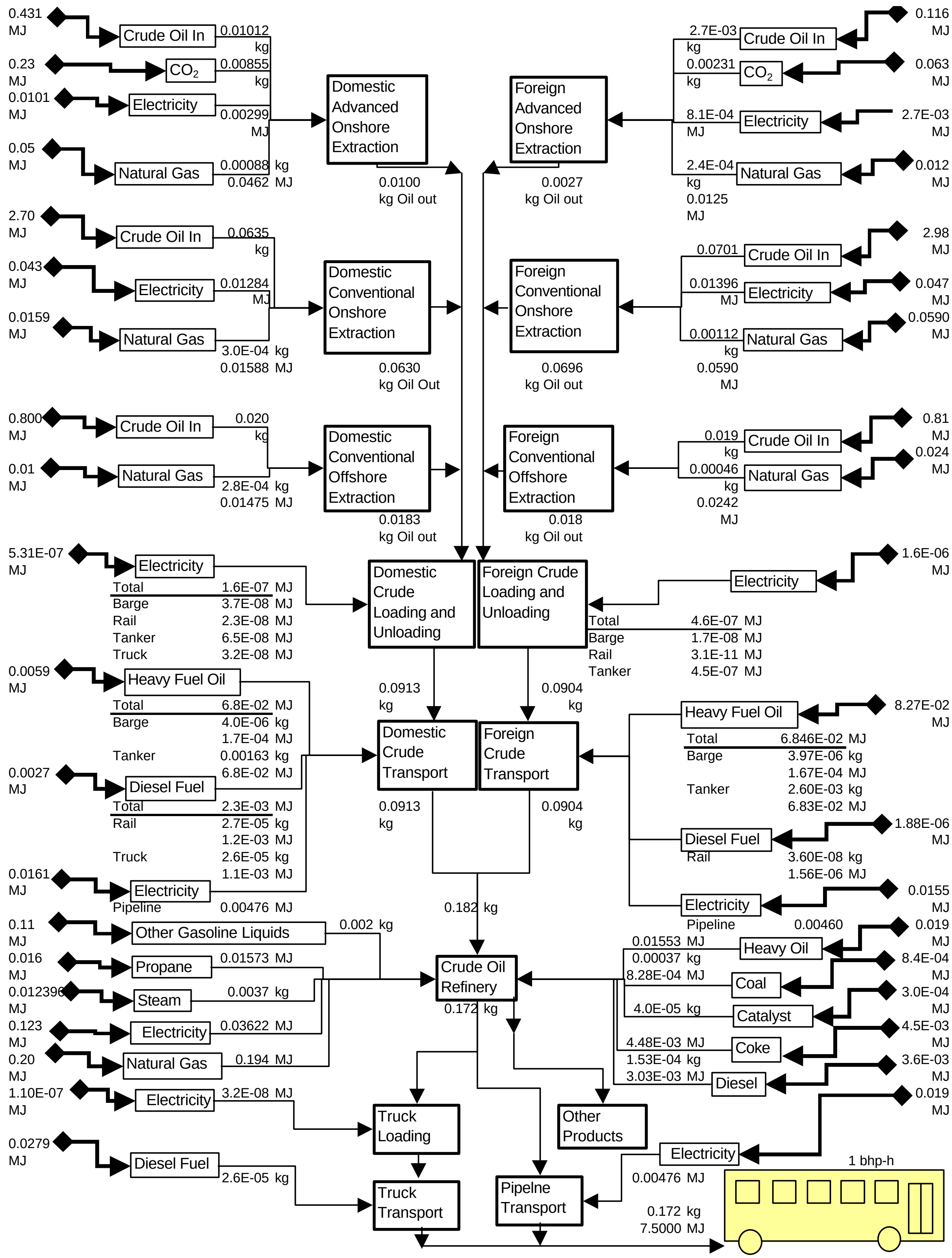

Figure 24: Primary Energy Balance for the Petroleum Diesel Fuel Life Cycle (with Mass Allocation)

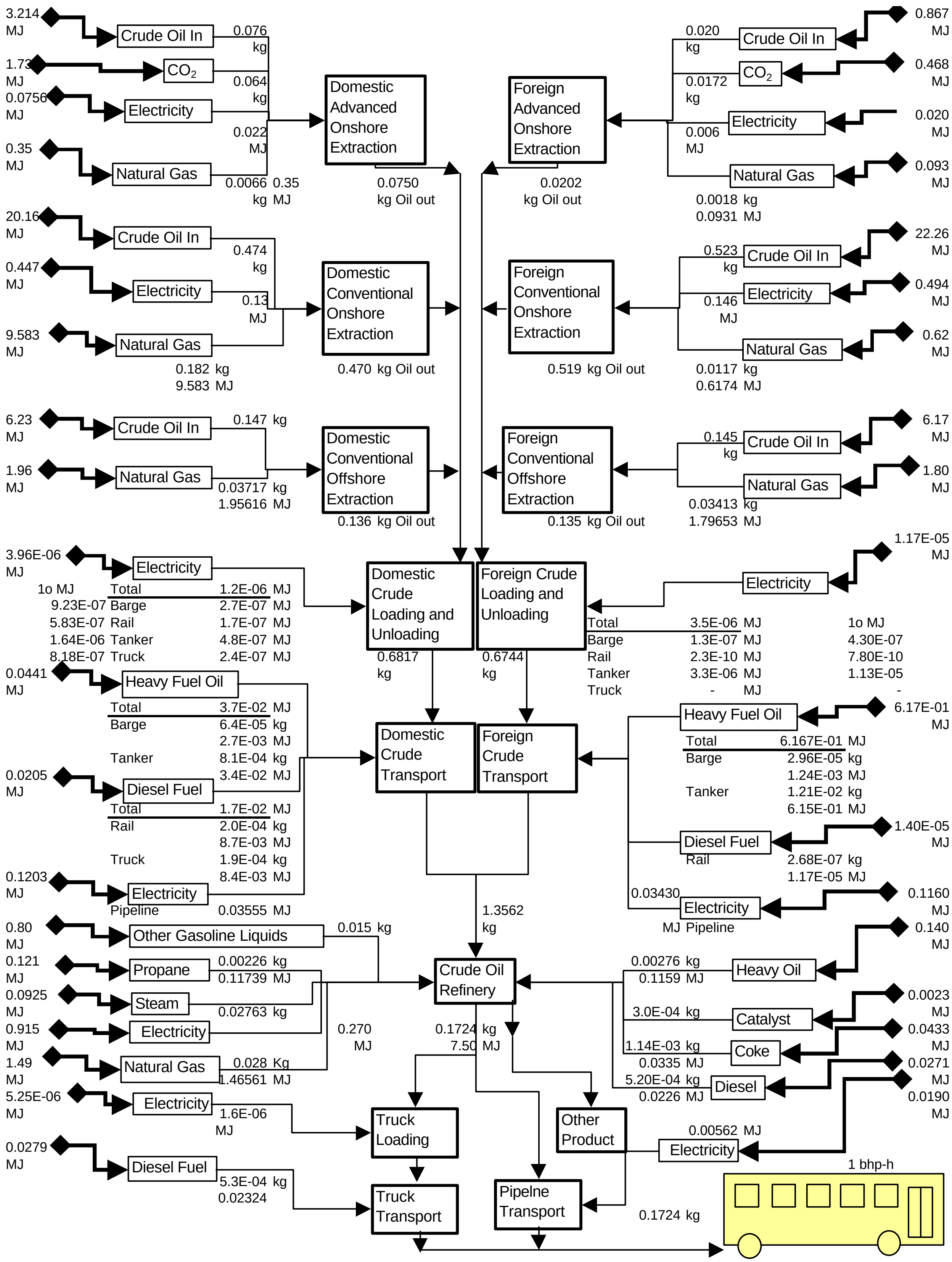

Figure 25: Primary Energy Balance for Petroleum Diesel Fuel Life Cycle (No Mass Allocation)

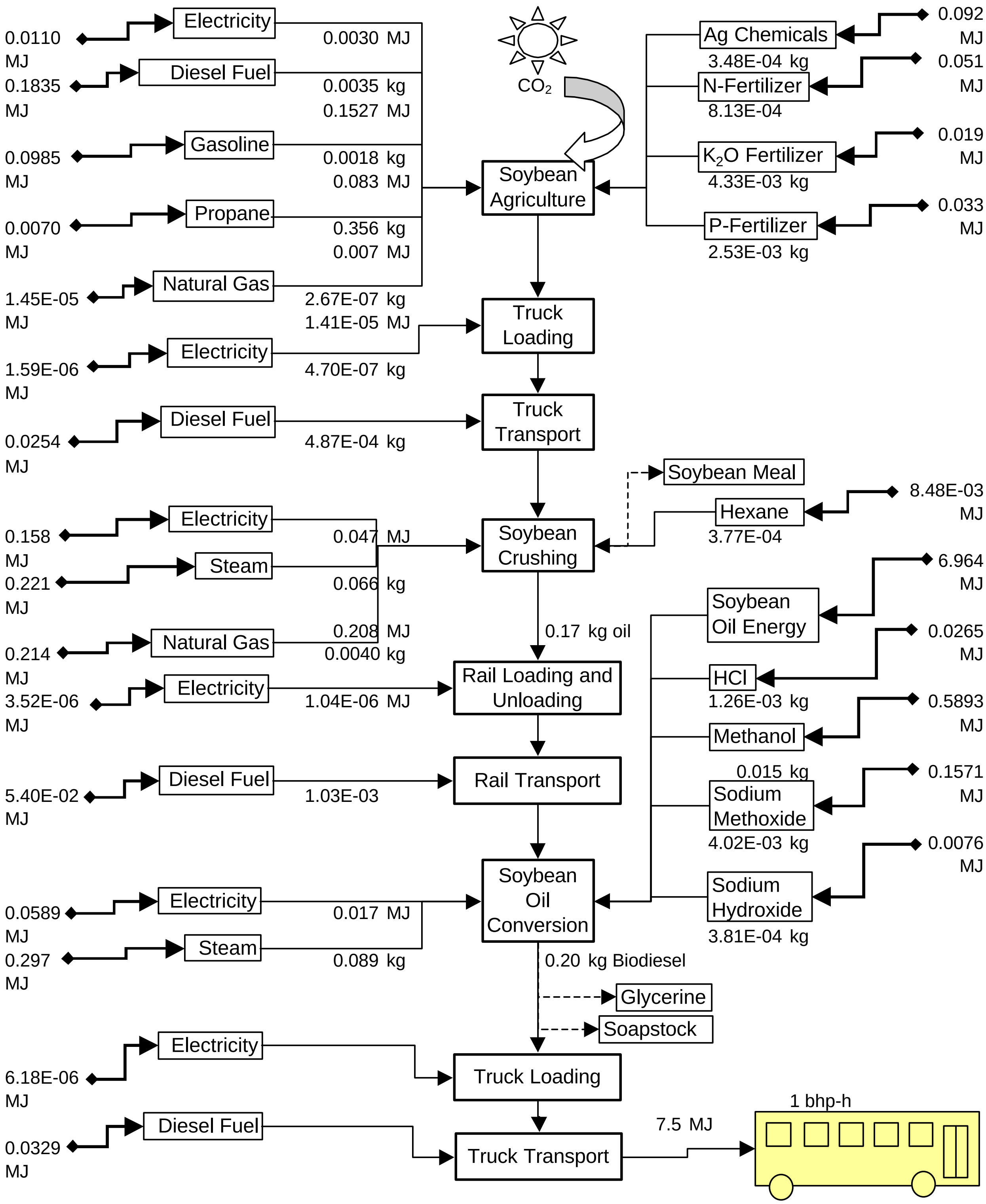

Figure 26: Primary Energy Balance for Biodiesel Fuel Life Cycle (with Mass Allocation)

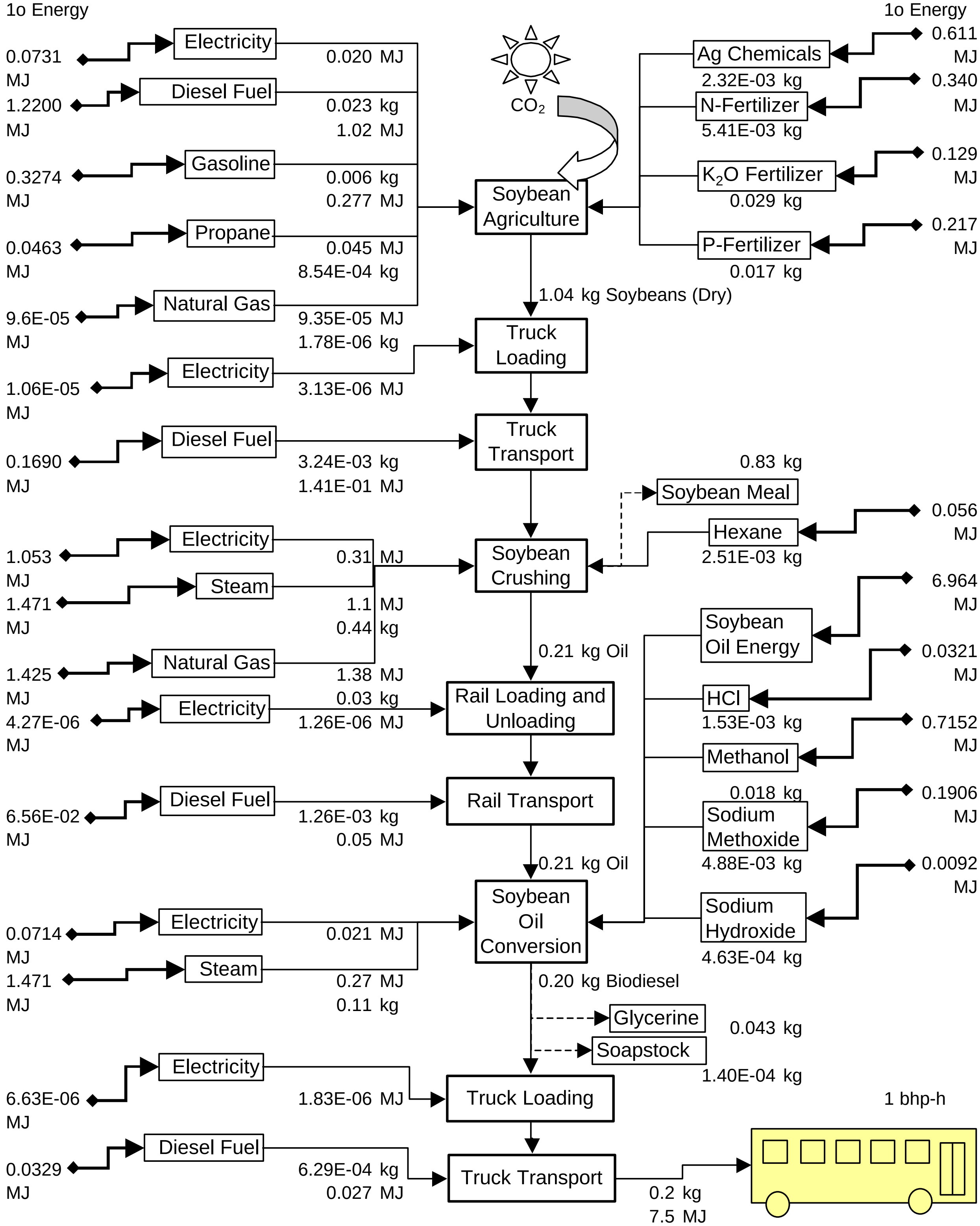

Figure 27: Primary Energy Balance for Biodiesel Fuel Life Cycle (No Mass Allocation)

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