9 Results and Discussion

LCI results are presented for B100, B20, and petroleum diesel. These results allow the reader to make a nominal comparison of biodiesel and petroleum diesel. By nominal, we mean that LCIs calculated for each fuel reflect generic "national average" models. The only exception to this statement is soybean agriculture data, which are provided state-by-state basis for the 14 key soybean-producing states. Implicit in such a nominal comparison is that there are no regional differences that could affect any stage of each fuel's life cycle. There will, of course, be differences that will affect each fuel.

In most cases, biodiesel is interchangeable with petroleum diesel without any need to modify today's diesel engine. However, one key issue for biodiesel use that should be explicitly stated up front is the effect of regional climate on the performance of the fuel. This fuel's cold flow properties may limit its use in certain parts of the country during Winter. This caveat should be kept in mind. Means of mitigating biodiesel's cold flow properties are being evaluated by researchers, though no clear solution is at hand. Low-sulfur #2 diesel fuel has similar limitations that are currently addressed today with the use of additives and by blending this fuel with #1 diesel fuel.

These results include estimates of:

- Overall energy requirements
- CO_2 emissions
- Other regulated and nonregulated air emissions
- Water emissions
- Solid wastes.

This section is divided into two main subsections: base case results and sensitivity analyses.

Base Case Results: A comparison of petroleum diesel and biodiesel is presented using the base-case assumptions for each fuel described in the previous sections.

Sensitivity Studies: The purpose of conducting sensitivity studies on the life cycle of biodiesel is to establish the potential range for improvement in the fuel and to establish the range of possible error associated with the assumptions made in the model. The LCI assumes a "current" time frame—that is, we are looking at the extant structure of agriculture, soybean oil recovery, conversion technology, and engine technology within a short-term horizon. This sets realistic limitations on the bounds of the assumptions used in the model. In each step in the life cycle, we have considered where the potential for near-term improvement is. Two main areas were identified. First, we felt it was important to understand the impact of location on biodiesel production. This allows us to consider the benefits of the best of agricultural productivity available in the United States and the shortest distances for transport of fuel and materials. This sets an upper bound on biodiesel benefits from the perspective of current agricultural practices and transportation logistics. Second, we identified the conversion of soybean oil to biodiesel as an aspect of the life cycle that has significant impact on energy use and emissions and that has a broad range of efficiencies, depending on the commercial technology used. Changes in engine technology may also be an avenue for improving biodiesel on a life cycle basis. We opted to forego this area in our sensitivity analysis. Thus, we present in this report the results of two sensitivity studies.

- The base case for B100 is compared with the LCI for an optimal biodiesel location (Chicago). The choice of optimal location is based on an evaluation of regions with the most efficient production of soybeans and with close access to soybean production and end-use markets for urban buses.
- Results for a range of high and low energy demands for soybean conversion to biodiesel are compared to determine the impact of this stage of the biodiesel life cycle on overall emissions and energy flows. Low and high values for energy consumption were based on a survey of technical literature on the most recent technology commercially available.

9.1 Base Case Results

The LCIs for B100, B20, and 100% petroleum diesel are summarized in the following subsections. All of the energy and environmental flows for these fuels are allocated on a mass basis among the various coproducts that result from each process in the fuels' life cycles. For a more detailed discussion of the mass allocation rule used in this study, see section 3.4. For a comparison of the total primary energy flows of biodiesel and petroleum diesel with and without application of the allocation rules, see the results presented in Figure 24 through Figure 27 in section 3.4.2.

9.1.1 Life Cycle Energy Balance

LCIs provide an opportunity to quantify the total primary energy requirements and the overall energy efficiencies of processes and products. Understanding the overall energy requirements of biodiesel is key to our understanding the extent to which biodiesel made from soybean oil is a "renewable energy" source. Put quite simply, the more fossil energy required to make a fuel, the less we can say that this fuel is renewable. Thus, the renewable nature of a fuel can vary across the spectrum of "completely renewable" (i.e., no fossil energy input) to nonrenewable (i.e., fossil energy inputs as much or more than the energy output of the fuel)[94]. Energy efficiency estimates help us to determine how much additional energy must be expended to convert the energy available in raw materials used in the fuel's life cycle to a useful transportation fuel. The following sections describe these basic concepts in more detail, as well as the results of our analysis of the life cycle energy balances for biodiesel and petroleum diesel.

9.1.1.1.1 Types of Life Cycle Energy Inputs

In this study, we track several types of energy flows through each fuel life cycle. For clarity, each is defined below.

- *Total Primary Energy*. All raw materials extracted from the environment can contain[95] energy. In estimating the total primary energy inputs to each fuel's life cycle, we consider the cumulative energy content of all resources extracted from the environment.

[94] This last statement is an oversimplification. We consider the energy trapped in soybean oil to be renewable because it is solar energy stored in liquid form through biological processes that are much more rapid than the geologic time frame associated with fossil energy formation. Also, other forms of nonrenewable energy besides fossil fuel exist.

[95] The energy "contained" in a raw material is the amount of energy that would be released by the complete combustion of that raw material. This "heat of combustion" can be measured in two ways: as a higher heating value or a lower heating value. Combustion results in the formation of CO_2 and water. Higher heating values consider the amount of energy released when the final combustion products are gaseous CO_2 and liquid water. Lower heating values take into account the loss of energy associated with the vaporization of the liquid water combustion product. Our energy content is based on the lower heating values for each material.

- *Feedstock Energy*. Energy contained in raw materials that end up directly in the final fuel product is termed "feedstock energy." For biodiesel production, feedstock energy includes the energy contained in the soybean oil and methanol feedstocks that are converted to biodiesel. Likewise, the petroleum directly converted to diesel in a refinery contains primary energy that is considered a feedstock energy input for petroleum diesel. Feedstock energy is a subset of the primary energy inputs.
- *Process Energy*. The second major subset of primary energy is "process energy." This is limited to energy inputs in the life cycle exclusive of the energy contained in the feedstock (as defined in the previous bullet). It is the energy contained in raw materials extracted from the environment that does not contribute to the energy of the fuel product itself, but is needed in the processing of feedstock energy into its final fuel product form. Process energy consists primarily of coal, natural gas, uranium, and hydroelectric power sources consumed directly or indirectly in the fuel's life cycle.
- *Fossil Energy*. Because we are concerned about the renewable nature of biodiesel, we also track the primary energy that comes from fossil sources specifically (coal, oil, and natural gas). All three of the previously defined energy flows can be categorized as fossil or nonfossil energy.
- *Fuel Product Energy*. The energy contained in the final fuel product, which is available to do work in an engine, is what we refer to as the "fuel product energy." All other things being equal, fuel product energy is a function of the energy density of each fuel.

9.1.1.1.2 Defining Energy Efficiency

We report two types of energy efficiency. The first is the overall "life cycle energy efficiency." The second is what we refer to as the "fossil energy ratio." Each elucidates a different aspect of the life cycle energy balance for the fuels studied.

The calculation of the life cycle energy efficiency is simply the ratio of fuel product energy to total primary energy:

Life Cycle Energy Efficiency = Fuel Product Energy/Total Primary Energy

It is a measure of the amount of energy that goes into a fuel cycle, which actually ends up in the fuel product. This efficiency accounts for losses of feedstock energy and additional process energy needed to make the fuel.

The fossil energy ratio tells us something about the degree to which a given fuel is or is not renewable. It is defined simply as the ratio of the final fuel product energy to the amount of fossil energy required to make the fuel:

Fossil Energy Ratio = Fuel Energy/Fossil Energy Inputs

If the fossil energy ratio has a value of zero, then a fuel is not only completely nonrenewable, but it provides no useable fuel product energy as a result of the fossil energy consumed to make the fuel. If the fossil energy ratio is equal to 1, then this fuel is still nonrenewable. A fossil energy ratio of one indicates that no loss of energy occurs in the process of converting the fossil energy to a useable fuel. For fossil energy ratios greater than 1, the fuel actually begins to provide a leveraging of the fossil energy required to make the fuel available for transportation. As a fuel approaches being "completely" renewable, its fossil energy ratio approaches "infinity." In other words, a completely renewable fuel has no requirements for fossil energy.

From a policy perspective, these are important considerations. Policy makers want to understand the extent to which a fuel increases the renewability of our energy supply. Another implication of the fossil energy ratio is the question of climate change. Higher fossil energy ratios imply lower net CO_2 emissions. This is a secondary aspect of the ratio, because we are explicitly estimating total CO_2

emissions from each fuel's life cycle. Nevertheless, the fossil energy ratio serves as a check on our calculation of CO_2 life cycle flows (since the two should be correlated).

9.1.1.2 Petroleum Diesel Life Cycle Energy Consumption

Table 122 and Figure 87 show the total primary energy requirements for all the key steps in the production and use of petroleum diesel. The LCI model shows that 1.2007 MJ of primary energy is used to make 1 MJ of petroleum diesel fuel. This corresponds to a life cycle energy efficiency of 83.28%.

The distribution of the primary energy requirements for each stage of the petroleum diesel life cycle is shown in Table 122. In Figure 87 stages of petroleum diesel production are ranked from highest to lowest in terms of primary energy requirements. 93% of the total primary energy is for the extraction of crude oil from the ground. About 88% of the energy shown for crude oil extraction is associated with the energy value of the crude oil itself. The crude oil refinery step for making diesel fuel dominates the remaining 7% of the primary energy usage.

Table 122: Primary Energy Demand for the Petroleum Diesel Life Cycle Inventory

Stage	Primary Energy (MJ per MJ of Fuel)	Percent
Domestic Crude Production	0.5731	47.73%
Foreign Crude Oil Production	0.5400	44.97%
Domestic Crude Transport	0.0033	0.28%
Foreign Crude Transport	0.0131	1.09%
Crude Oil Refining	0.0650	5.41%
Diesel Fuel Transport	0.0063	0.52%
Total	1.2007	100.00%

Removing the feedstock energy (of the crude oil) from the total primary energy demand allows us to analyze the relative contributions of the remaining process energy from each step of the life cycle. Process energy used in each stage of the petroleum life cycle is shown in Figure 88. Process energy demand represents 20.1% of the energy ultimately available in the petroleum diesel fuel product. About 90% of the process energy consumed is in refining (60%) and extraction (29%). The next largest contribution to process energy demand is for transport of foreign crude oil to domestic petroleum refiners.

There are some significant implications in the process energy results shown in Figure 88 regarding trends for foreign and domestic crude oil production and use. Transportation of foreign crude oil carries with it a fourfold penalty for energy consumption compared to domestic petroleum transport. The reason for this is overseas transport of foreign oil by tanker increases the travel distance for foreign oil by roughly a factor of four, relative to the distances required for transport of domestic fuel (see Figure 89).

At the same time, domestic crude oil extraction is more energy intensive than foreign crude oil production. Advanced oil recovery practices in the United States represent 11% of the total production volume, compared to 3% for foreign oil extraction. Figure 90 shows the overall contributions of advanced and conventional oil extraction to primary energy demand for domestic crude oil production. Advanced oil recovery uses twice as much primary energy per kg of oil compared to conventional extraction. Advanced crude oil extraction requires almost 20 times more process energy than onshore domestic crude oil extraction per kg of oil out of the ground (Figure 91) because the processes employed are energy intensive and the amount of oil recovered is low compared to other practices. Domestic crude oil supply is essentially equal to foreign oil supply (50.26% versus 49.74%, respectively) in our model, but its process energy requirement is 62% higher than that of foreign crude oil production.

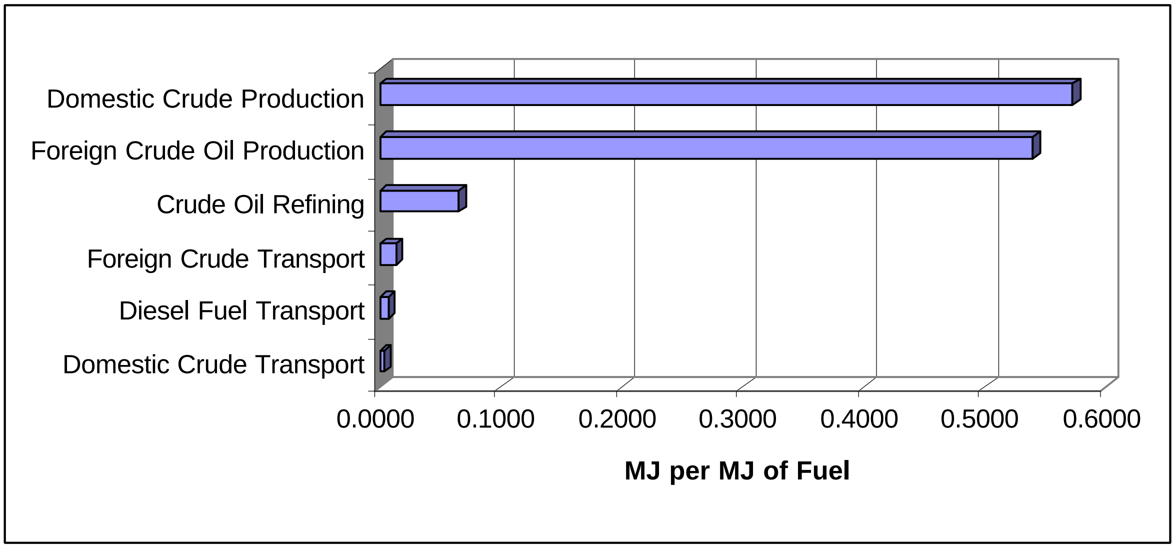
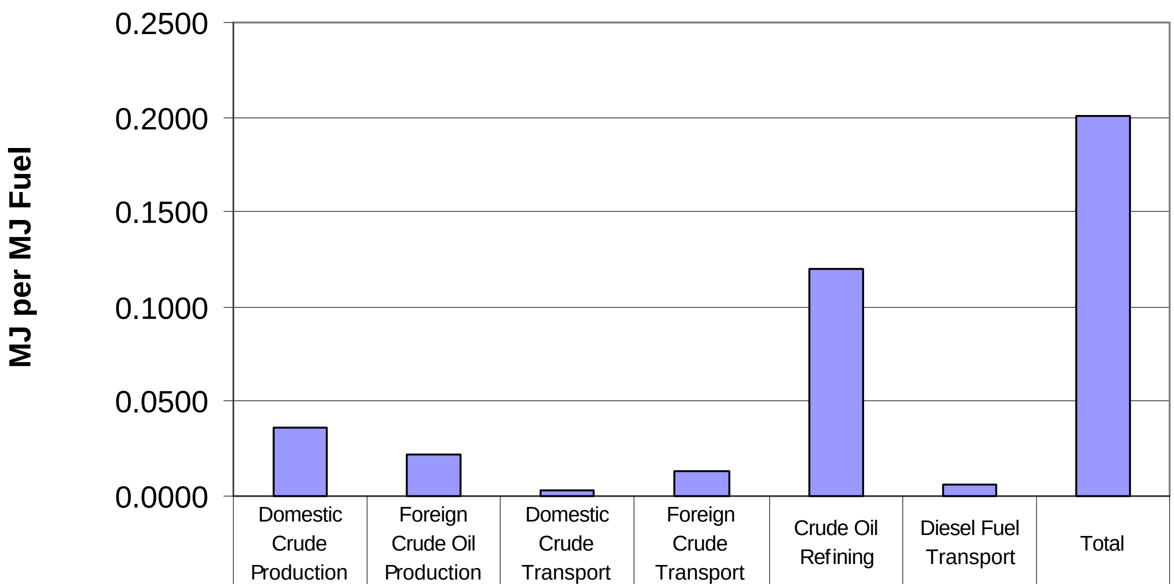


Figure 87: Ranking of Primary Energy Demand for the Stages of Petroleum Diesel Production



	Domestic Crude Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Total
Process Energy	0.0361	0.0223	0.0033	0.0131	0.1198	0.0063	0.2009

Figure 88: Process Energy Demand for Petroleum Diesel Life Cycle

If our present trend of increased dependence on foreign oil continues, we can expect the life cycle energy efficiency of petroleum diesel to worsen due to the higher energy costs of transporting foreign crude to the United States. In addition, as the practice of advanced oil recovery increases in the United States, domestic crude oil extraction may become less energy efficient.

Table 123 and Figure 92 summarize the fossil energy inputs with respect to fuel product energy output. Petroleum diesel uses 1.1995 MJ of fossil energy to produce 1 MJ of fuel product energy. This corresponds to a fossil energy ratio of 0.8337[96]. Because the main feedstock for diesel production is itself a fossil fuel, this ratio is almost identical to the life cycle energy efficiency of 83.28%. In fact, fossil energy associated with the crude oil feedstock accounts for 93% of the total fossil energy consumed in the life cycle. Fossil fuel use is slightly less than the total primary energy consumption because there is a very small contribution to the total primary energy that is met through hydroelectric and nuclear power supplies related to electricity generation.

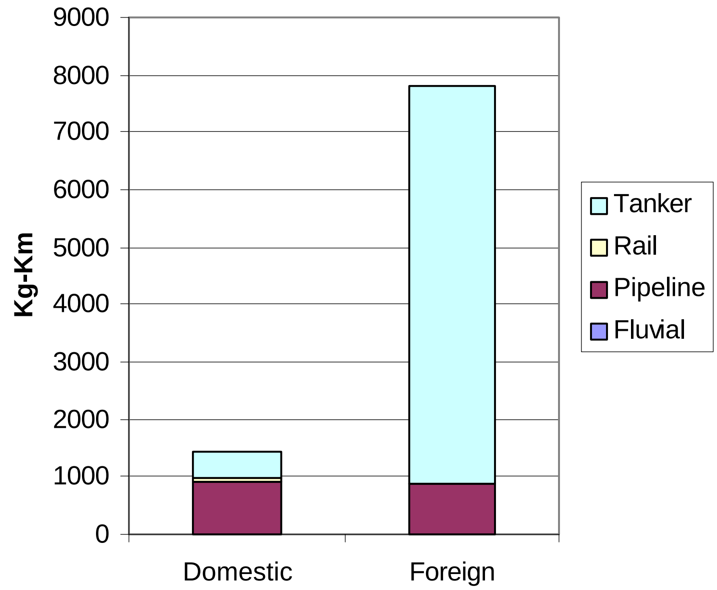
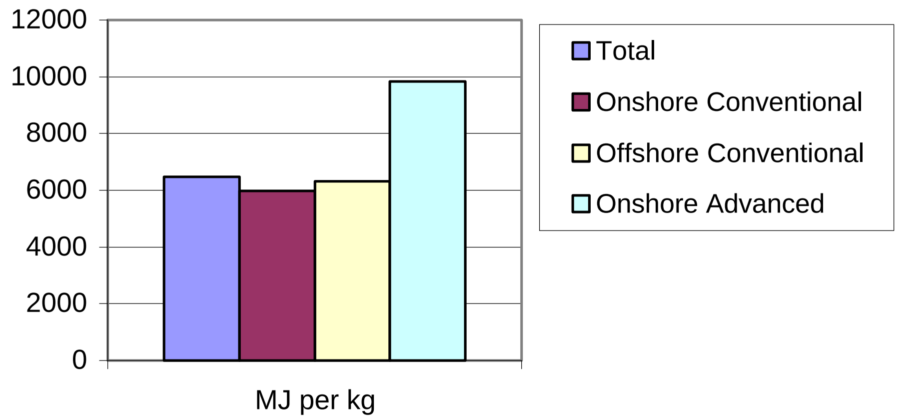


Figure 89: Transport Distances for Domestic and Foreign Crude Oil (kg-km)[97]



[96] Fossil Energy Ratio = 1 MJ of Fuel Product Energy/1.1995 MJ of Fossil Energy Input.

[97] The transport distances are calculated in the LCI model using PADD data for modes of transportation and distances.

Figure 90: Primary Energy Demand of Advanced versus Conventional Crude Recovery

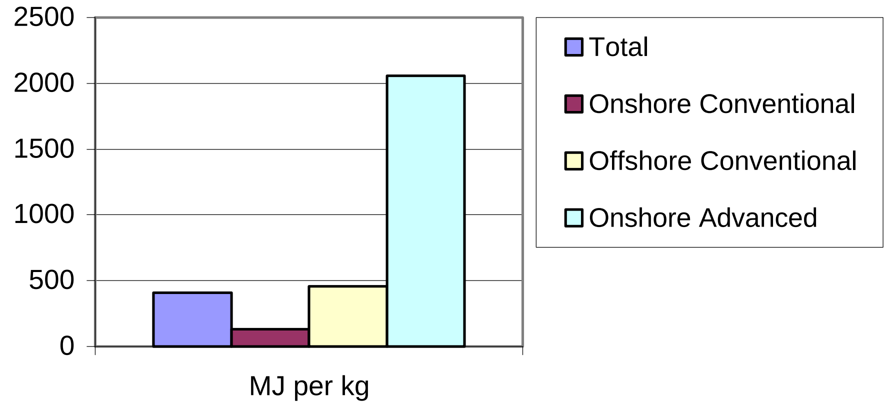


Figure 91: Process Energy Requirements of Advanced versus Crude Oil Extraction

Table 123: Fossil Energy Requirements for the Petroleum Diesel Life Cycle

Stage	Fossil Energy (MJ per MJ of Fuel)	Percent
Domestic Crude Production	0.572809	47.75%
Foreign Crude Oil Production	0.539784	45.00%
Domestic Crude Transport	0.003235	0.27%
Foreign Crude Transport	0.013021	1.09%
Crude Oil Refining	0.064499	5.38%
Diesel Fuel Transport	0.006174	0.51%
Total	1.199522	100.00%

9.1.1.3 Biodiesel Life Cycle Energy Demand

Table 124 and Figure 93 present LCI results for the total primary energy requirements of each stage of the biodiesel life cycle. One MJ of biodiesel requires an input of 1.2414 MJ of primary energy, resulting in a life cycle energy efficiency of 80.55%. Biodiesel is only slightly less efficient than petroleum diesel in the conversion of primary energy to fuel product energy (80.55% versus 83.28%). The largest contribution to primary energy is the soybean oil conversion step because this is where we have chosen to include the feedstock energy associated with the soybean oil itself[98]. The conversion step consumes 87%

[98] Energy contained in the soybean oil itself represents, in effect, the one place in the biodiesel life cycle where input of solar energy is accounted for. Total radiant energy available to soybean crops is essentially viewed as "free" in the life cycle calculations. It becomes an accountable element of the life cycle only after it has been incorporated in the soybean oil itself. This is analogous to counting the feedstock energy of crude petroleum as the point in its life cycle where solar energy input occurs. Petroleum is essentially stored solar energy. The difference between petroleum and soybean oil as sinks for solar energy is their time scale. While soybean oil traps solar energy on a rapid ("real time") basis, petroleum storage represents a process that occurs on a geologic time scale. This

of the total primary energy in the biodiesel life cycle. As with the petroleum life cycle, the stages of the life cycle that are burdened with the feedstock energy overwhelm all other stages. Had the soybean oil energy been included with the farming operation, soybean agriculture would have been the dominant consumer of primary energy. This is analogous to placing the crude oil feedstock energy in the extraction stage for petroleum diesel fuel. The next two largest uses of primary energy are for soybean crushing and soybean oil conversion. They account for most of the remaining 13% of the total demand.

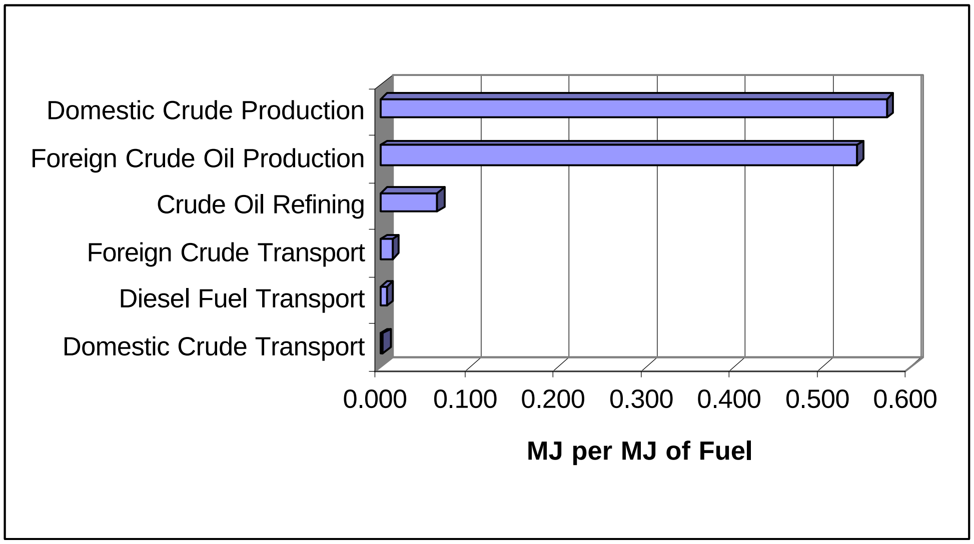


Figure 92: Ranking of the Fossil Energy Demand for Stages of the Petroleum Diesel Life Cycle

Table 124: Primary Energy Requirements for Biodiesel Life Cycle

Stage	Primary Energy (MJ per MJ of Fuel)	Percent
Soybean Agriculture	0.0660	5.32%
Soybean Transport	0.0034	0.27%
Soybean Crushing	0.0803	6.47%
Soy Oil Transport	0.0072	0.58%
Soy Oil Conversion	1.0801	87.01%
Biodiesel Transport	0.0044	0.35%
Total	1.2414	100.00%

difference in the dynamic nature of solar energy utilization is the key to our definitions of renewable and nonrenewable energy. See section 2.4.1.2.1 for an analogous discussion of carbon utilization dynamics for soybean oil versus fossil fuels.

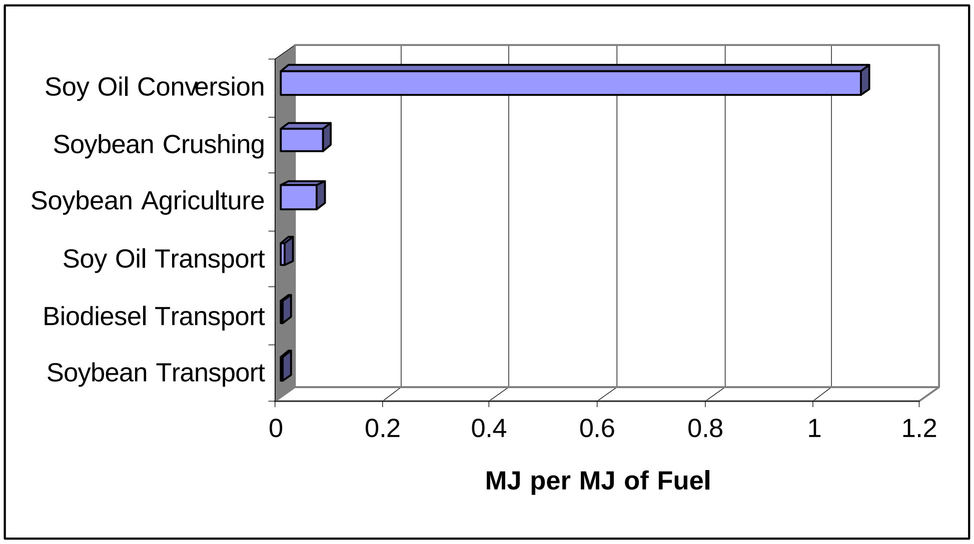


Figure 93: Ranking of Primary Energy Demand for the Stages of Biodiesel Production

When we look at process energy separately from primary energy, we see that process energy demands is not dominated by soybean oil conversion (Figure 94). The soybean crushing and soy oil conversion steps use the most process energy (34.25 and 34.55%, respectively, of the total). Agriculture accounts for the most of the remaining process energy consumed in life cycle for biodiesel (almost 25% of total demand). Each transportation step is only 2%-3% of the process energy used in the life cycle.

Table 125 and Figure 95 summarize the fossil energy requirements for the biodiesel life cycle. Because 90% of its feedstock requirements are renewable (that is, soybean oil), biodiesel's fossil energy ratio is favorable. Biodiesel uses 0.3110 MJ of fossil energy to produce one MJ of fuel product; this equates to a fossil energy ratio of 3.215. In other words, the biodiesel life cycle produces more than three times as much energy in its final fuel product as it uses in fossil energy. Fossil energy used for the conversion step is almost twice that of its process energy consumption, making this stage of the life cycle the largest contributor to fossil energy demand. The use of methanol as a feedstock in the production of biodiesel accounts for this high fossil energy use[99]. We have counted the feedstock energy of methanol coming into the life cycle at this point, assuming that the methanol is produced from natural gas. This points out an opportunity for further improvement of the fossil energy ratio by substituting natural gas-derived methanol with renewable sources of methanol, ethanol or other alcohols.

9.1.1.4 Effect of Biodiesel on Life Cycle Energy Demands

Compared on the basis of primary energy inputs, biodiesel and petroleum diesel are essentially equivalent. Biodiesel has a life cycle energy efficiency of 80.55%, compared to 83.28% for petroleum diesel. The slightly lower efficiency reflects a slightly higher demand for process energy across the life of cycle for biodiesel. On the basis of fossil energy inputs, biodiesel enhances the effective use of this finite energy resource. Biodiesel leverages fossil energy inputs by more than three to one.

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[99] Fossil energy can be used in the form of feedstock energy or process energy. Generally, for biodiesel production, process energy is the main consumer of fossil energy. However, methanol used in the conversion process energy which contains fossil energy that shows up as feedstock energy. Thus, the usage of fossil energy in the conversion step is much higher than the total process energy consumed in this step.

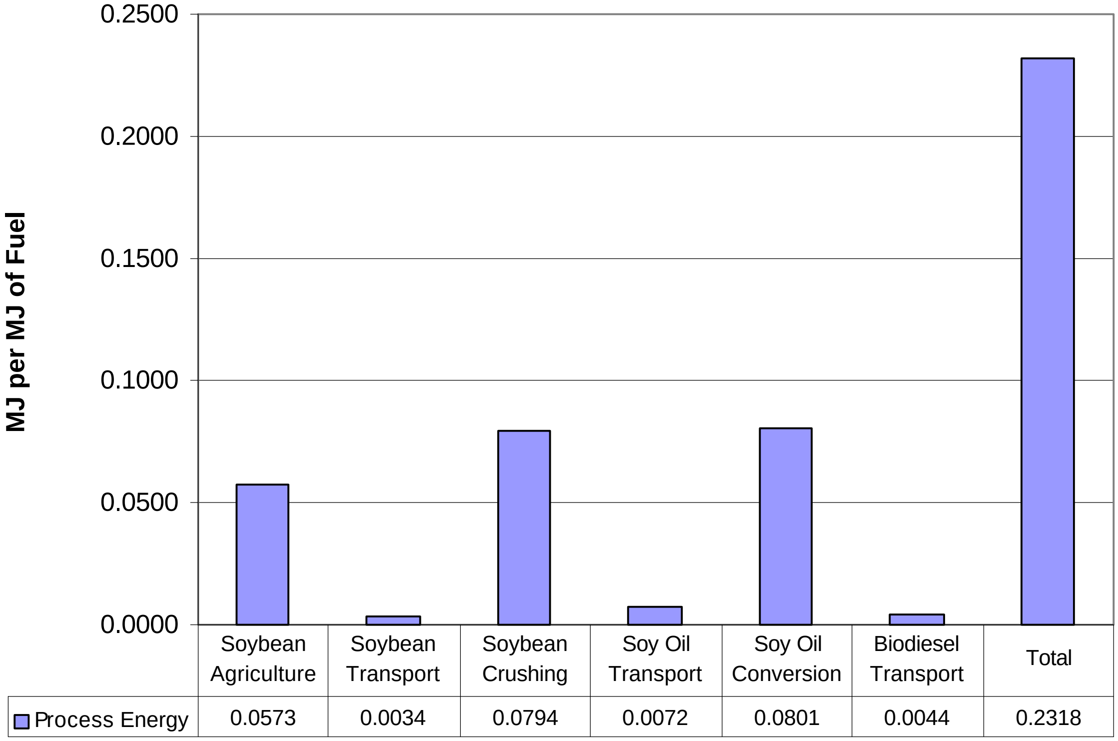


Figure 94: Process Energy Requirements for Biodiesel Life Cycle

Table 125: Fossil Energy Requirements for the Biodiesel Life Cycle

Stage	Fossil Energy (MJ per MJ of Fuel)	Percent
Soybean Agriculture	0.0656	21.08%
Soybean Transport	0.0034	1.09%
Soybean Crushing	0.0796	25.61%
Soy Oil Transport	0.0072	2.31%
Soy Oil Conversion	0.1508	48.49%
Biodiesel Transport	0.0044	1.41%
Total	0.3110	100.00%

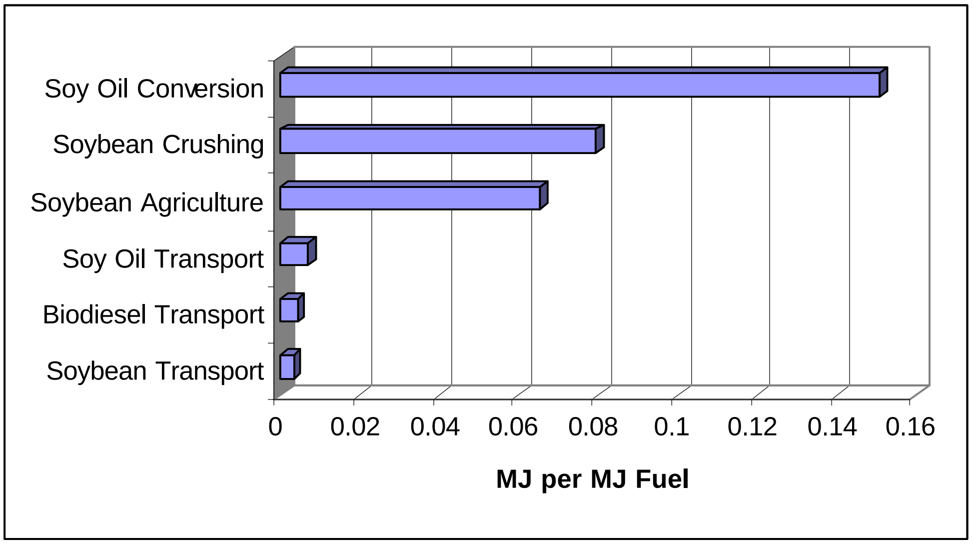


Figure 95: Fossil Energy Requirements versus Fuel Product Energy for the Biodiesel Life Cycle

9.1.2 CO_2 Emissions

9.1.2.1 Accounting for Biomass-Derived Carbon

Biomass plays a unique role in the dynamics of carbon flow in our biosphere. Biological cycling of carbon occurs when plants (biomass such as soybean crops) convert atmospheric CO_2 to carbon-based compounds through photosynthesis. This carbon is eventually returned to the atmosphere as organisms consume the biological carbon compounds and respire. Biomass derived fuels reduce the net atmospheric carbon in two ways. First, they participate in the relatively rapid cycling of carbon to the atmosphere (via engine tailpipe emissions) and from the atmosphere (via photosynthesis). Second, these fuels displace the use of fossil fuels. Combustion of fossil fuels releases carbon that took millions of years to be removed from the atmosphere, while combustion of biomass fuels participates in a process that allows rapid recycle of CO_2 to fuel. The net effect of shifting from fossil fuels to biomass-derived fuels is, thus, to reduce the amount of CO_2 in the atmosphere.

Because of the differences in the dynamics of fossil carbon flow and biomass carbon flow to and from the atmosphere, biomass carbon must be accounted for separately from fossil-derived carbon. The LCI model tracks carbon from the point at which it is taken up as biomass via photosynthesis to its final combustion as biodiesel used in an urban bus. The biomass-derived carbon that ends up as CO_2 leaving the tailpipe of the bus is subtracted from the total CO_2 emitted by the bus because it is ultimately reused produce new soybean oil. In order to ensure that we accurately credit the biodiesel LCI for the amount of recycled CO_2, we provide a material balance on biomass carbon.

The material balance (Table 126 and Figure 97) shows all the biomass carbon flows associated with the delivery of 1 bhp-h of engine work. For illustration purposes, only the case of 100% biodiesel is shown. Lower blend rates proportionately lower the amount of biomass carbon credited as part of the recycled CO_2. Carbon incorporated in the meal fraction of the soybeans is not included in the carbon balance. Only carbon in the fatty acids and triglycerides that are used in biodiesel production are tracked. The calculation of the carbon content of the fatty acids and triglycerides is based on average composition data for soybean oil[100].

Table 126: Biomass Carbon Balance for Biodiesel Life Cycle (g/bhp-h)[101]

Life Cycle Stage	g carbon per bhp-h	g CO_2/bhp-h
Soybean Production	**169.34**	**621.48**
Uptake of carbon in triglycerides and fatty acids	169.34	621.48
Soybean Crushing	**160.81**	**590.16**
Release of carbon via residual oil in meal	(7.73)	(28.36)
Release of carbon via waste	(0.81)	(2.97)
Biodiesel Production	**148.39**	**544.60**
Release of carbon via glycerine	(8.26)	(30.32)
Release of carbon via wastewater	(2.36)	(8.67)
Release of carbon via solid waste	(1.74)	(6.40)
Release of carbon in soapstock	(0.05)	(0.17)
Combustion in bus		**-**
Release of carbon in biodiesel (total)	(148.39)	(544.60)
Release of carbon in CO_2	(148.05)	(543.34)
Release of carbon in HC	(0.04)	(0.16)
Release of carbon in CO	(0.28)	(1.01)
Release of carbon in PM	(0.02)	(0.08)
Release of carbon in HC, CO, and PM	(0.34)	(1.26)

Not all the carbon incorporated in fatty acids and triglycerides ends up as CO_2 after combustion of biodiesel. Some oil loss occurs in the meal by-product. Glycerol is removed from the triglycerides as a by-product. Finally, fatty acids are removed as soaps and waste. The calculation of carbon released as residual oil in the meal after crushing is described in the section on soybean crushing. Calculation of the carbon released as by-products and waste from biodiesel production is described in the section on soybean oil conversion. Finally, carbon released in combustion ends up as CO_2, CO, HC, and PM. The detailed calculations of carbon distribution in combustion products are discussed in the section on urban bus operations.

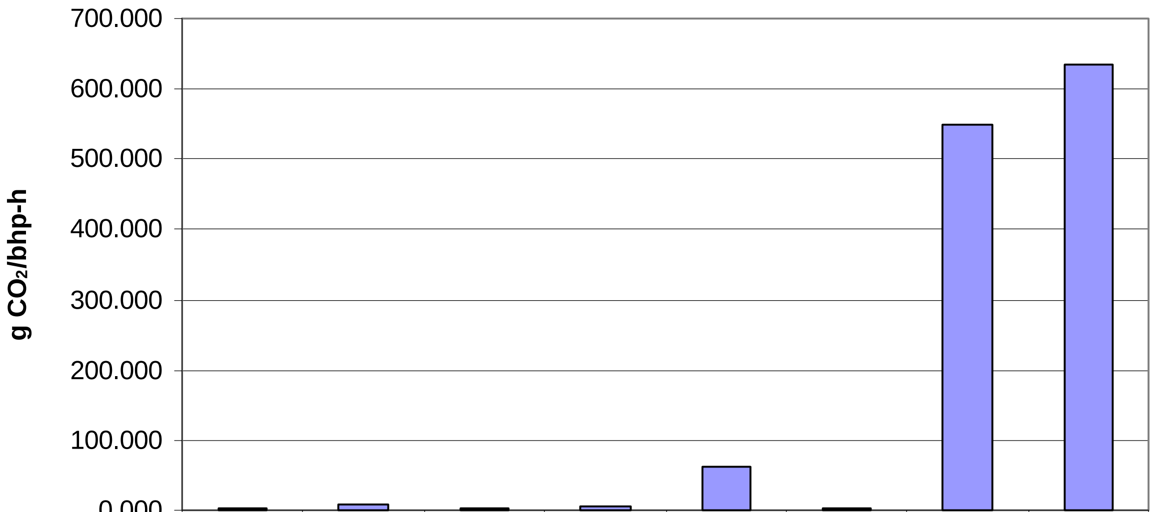
[100] Based on data from Perkins, E., "Composition of Soybeans and Soybean Products," in *Practical Handbook of Soybean Processing and Utilization* (Erickson, D.R., ed.). AOCS Press, Champlain, Illinois, 1995.

[101] Highlighted life cycle stages show cumulative carbon moving through the life cycle. Soybean production shows a net inflow of 169 grams of carbon for 1 bhp-h of engine work. Each subsequent stage consumes carbon, so that, at the point of end-use combustion, the carbon which remains is zero. Inflows of carbon are shown as positive numbers and outflows are shown as negative numbers (in parentheses).

Of the 169.34 grams of carbon absorbed in the soybean agriculture stage, only 148.39 grams (87%) end up in biodiesel. After accounting for carbon that ends up in other combustion products, 148.05 grams of carbon end up as 543.34 grams of tailpipe CO_2. This CO_2 is subtracted from the diesel engine emissions as part of the biological recycle of carbon. No credit is taken for the 13% of the carbon that ends up in various by-products and waste streams.

9.1.2.2 Petroleum Diesel Life Cycle Emissions of CO_2

CO_2 emissions for the petroleum life cycle are shown in Figure 96. CO_2 is shown for biomass- and fossil-derived sources. In the petroleum life cycle, the contribution of CO_2 from biomass is zero. Only combustion of fossil fuel-derived carbon generates CO_2.



	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Oil Transport	Foreign Crude Oil Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Combustion	Overall
Biomass CO2	0	0	0	0	0	0	0	0
Fossil CO2	4.260	7.157	1.634	6.925	62.136	3.148	548.02	633.275

Figure 96: Carbon Dioxide Emissions for Petroleum Diesel Life Cycle

The dominant source of CO_2 is the combustion of petroleum diesel in the bus. CO_2 emitted from the tailpipe of the bus represents 86.5% of the total CO_2 emitted across the entire life cycle of the fuel. Most remaining CO_2 comes from emissions at the oil refinery, which contributes 9.8% of the total CO_2 emissions.

Foreign crude oil production and foreign crude oil transport represent the third largest sources of CO_2 emissions (2.22%). As we saw with the energy numbers, transport of foreign crude generates roughly four times the amount of CO_2 emitted by domestic crude transport.

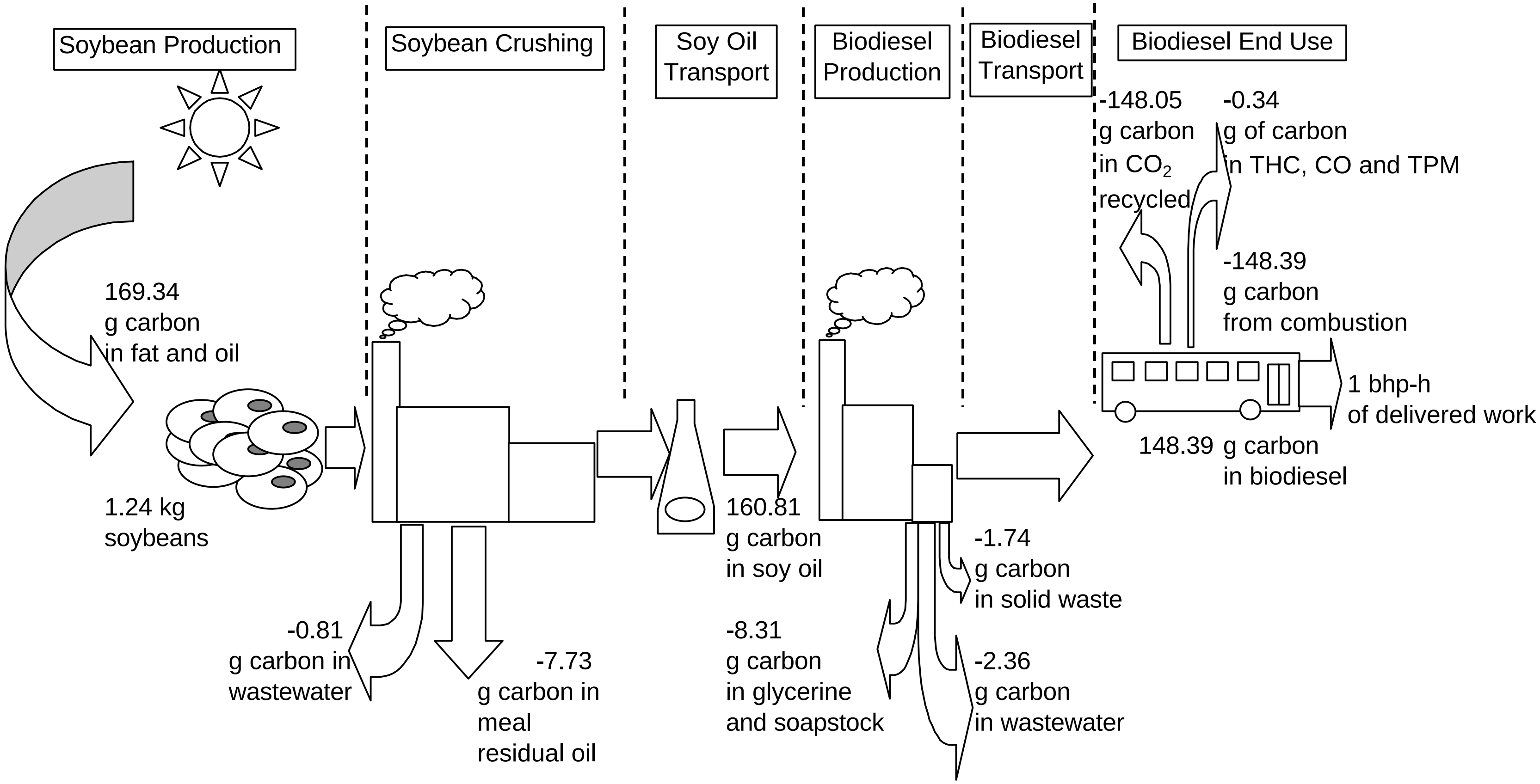
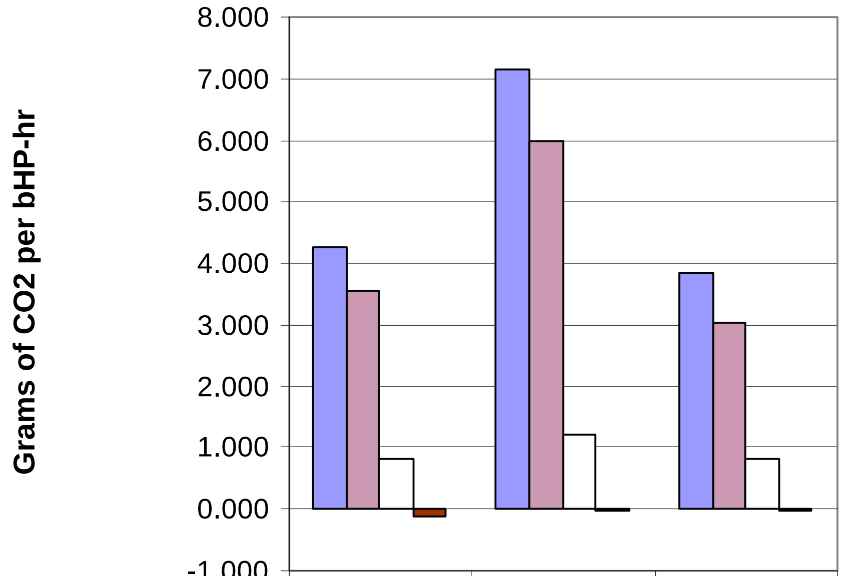


Figure 97: Biomass Carbon Balance for Biodiesel Life Cycle[102]

[102] All numbers presented as carbon equivalent. To calculate actual CO_2 emissions, multiply carbon equivalent numbers by 3.67 (the ratio of the molecular weight of CO_2 divided by the molecular weight of carbon).

Foreign oil production generates 68% higher emissions of CO_2 than domestic crude oil production. This is contrary to what might be expected based on the energy consumption numbers presented in the previous section. Domestic crude oil production uses 68% more energy than foreign crude oil production because of the greater reliance on more energy intensive advanced oil recovery technologies used in the United States. The increased CO_2 emissions resulting from the higher energy consumption of advanced oil recovery are offset by the practice of CO_2 reinjection, which effectively sequesters carbon.[103]

A second factor leads to higher CO_2 emissions in foreign oil production: the flaring of natural gas at the well head. Figure 98 demonstrates this point. Conventional crude oil extraction for foreign production generates 50% more CO_2 than does its domestic counterpart. This is true for both onshore and offshore production. The key difference appears to be the fact that foreign oil producers, on average, flare four times as much natural gas as domestic producers because there are fewer market opportunities for this gas. To test the effect of this practice, we ran the LCI model with an assumption of no flaring of natural gas in foreign operations. As Figure 98 shows, this scenario leads to CO_2 emissions from foreign oil production that are almost the same as from domestic oil production.



	Domestic	Foreign (Flare)	Foreign (No Flare)
Total	4.260	7.157	3.827
Conventional Onshore	3.557	5.993	3.039
Conventional Offshore	0.821	1.195	0.820
Advanced Onshore	-0.118	-0.032	-0.032

Figure 98: Comparison of CO_2 Emissions for Domestic and Foreign Crude Production

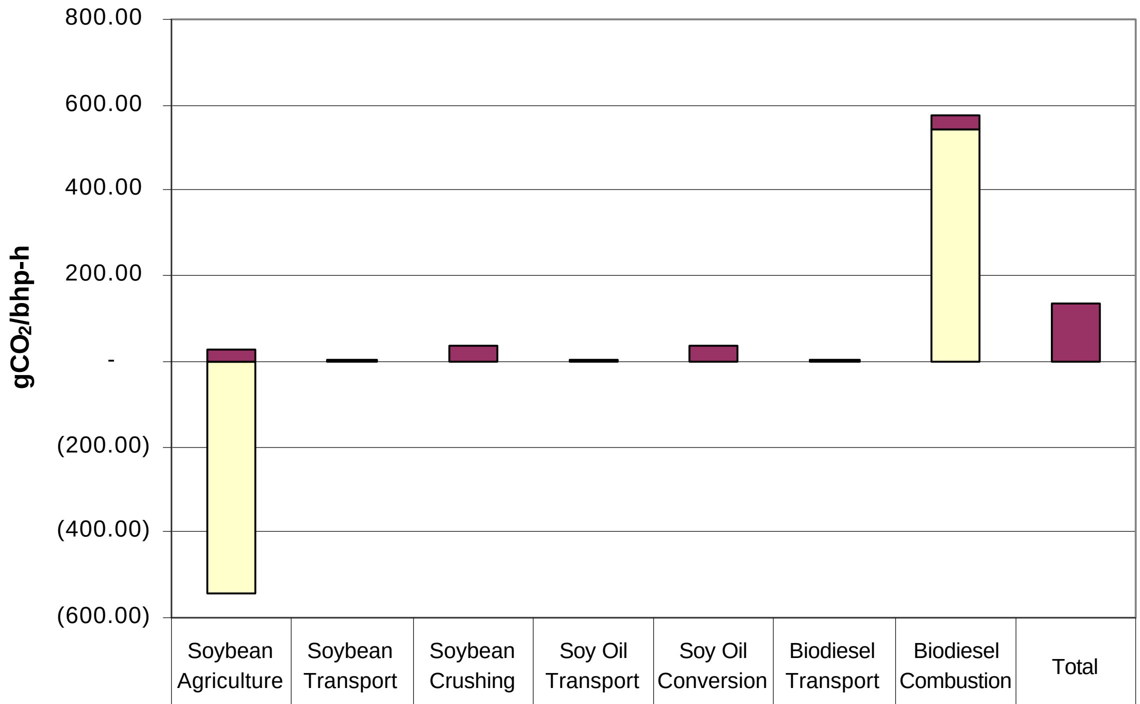
As with the energy efficiency results, we can see that there are significant implications of our CO_2 results for projections of foreign oil dependence. Foreign oil production introduces two penalties for CO_2

the review process. They suggested the idea of allowing for sequestration of carbon in advanced oil recovery based on estimates which they provided. Their comments indicate that 0.75 metric tons of CO_2 are injected in the well per metric ton of oil recovered, and that half of this CO_2 remains sequestered in the oil reservoir.

emissions: 1) CO_2 emissions due to well head flaring practices and CO_2 emissions from the transport of oil. Thus, the CO_2 emissions from petroleum diesel can be expected to increase as our reliance on foreign oil increases.

9.1.2.3 Biodiesel Life Cycle Emissions of CO_2

Figure 99 shows results of the LCI model for CO_2 emissions in the biodiesel life cycle. The biomass carbon mass balance described in section 9.1.2.1 was used to account for the carbon taken up in the production of soybeans and subsequently released in the combustion of biodiesel. Of the 169 grams of carbon taken up by the soybean plants in the agriculture stage, we take credit for only 148.05 grams of carbon (see Figure 97). This is equivalent to 543.34 grams of CO_2 removed from the atmosphere for every brake horsepower-hour of delivered biodiesel engine work. The remaining uptake of CO_2 is associated with by-products and waste streams in the soybean crushing and conversion stages of the life cycle for biodiesel. We did not feel it was appropriate to take credit for this carbon.



	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soy Oil Transport	Soy Oil Conversion	Biodiesel Transport	Biodiesel Combustion	Total
Fossil CO2	28.6588	1.7749	34.7595	3.81335	34.5227	2.2946	30.6235	136.44735
Biomass CO2	(543.34)	0	0	0	0	0	543.34	0

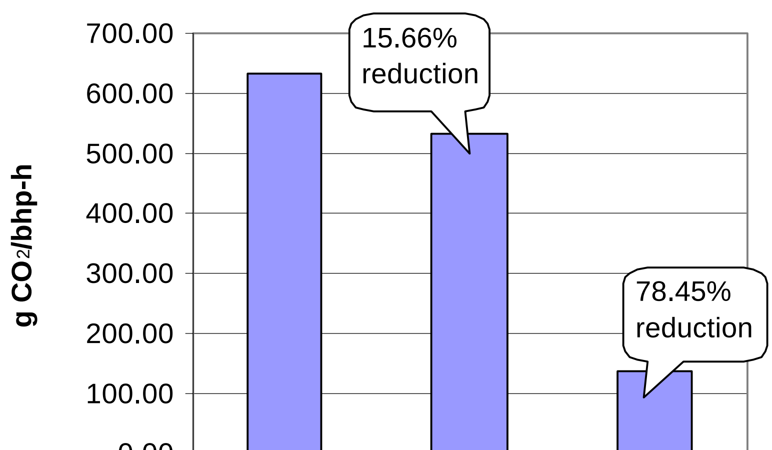
Figure 99: CO_2 Emissions for Biodiesel Life Cycle

As with the petroleum diesel life cycle, most of the CO_2 emissions are from the diesel engine tailpipe; 85% of the emissions occur at this point. The remaining CO_2 comes almost equally from soybean agriculture, soybean crushing, and conversion of soy oil to biodiesel.

9.1.2.4 The Effect of Biodiesel on CO_2 Emissions from Urban Buses

At the tailpipe, biodiesel emits almost 10% more CO_2 than petroleum diesel, most of which is renewable[104]. Biodiesel generates 573.96 gCO_2/bhp-h, compared with 548.02 gCO_2/bhp-h for petroleum diesel (see combustion estimates in Figure 96 and Figure 99). The higher CO_2 levels result from more complete combustion and the concomitant reductions in other carbon-containing tailpipe emissions. As Figure 100 shows, the overall life cycle emissions of CO_2 from 100% biodiesel are 78.45% lower than those of petroleum diesel. The reduction is a direct result of carbon recycling in soybean plants.

B20, the most commonly used form of biodiesel in the United States today, provides a 15.66% reduction in net CO_2 emissions compared to petroleum diesel. When biodiesel is blended with diesel fuel, reductions in CO_2 emissions are proportional to the amount of biodiesel. Figure 101 plots results for LCI runs conducted for a range of biodiesel blends from zero to 100%. Our LCI model indicates that CO_2 emission reductions vary linearly from the maximum of 79% for pure biodiesel to zero for the case of normal petroleum diesel.



	Petroleum Diesel	B20	B100
Net CO2	633.28	534.10	136.45

Figure 100: Comparison of Net CO_2 Life Cycle Emissions for Petroleum Diesel and Biodiesel Blends (g CO_2/bhp-h)

[104] The methanol component of biodiesel is fossil based.

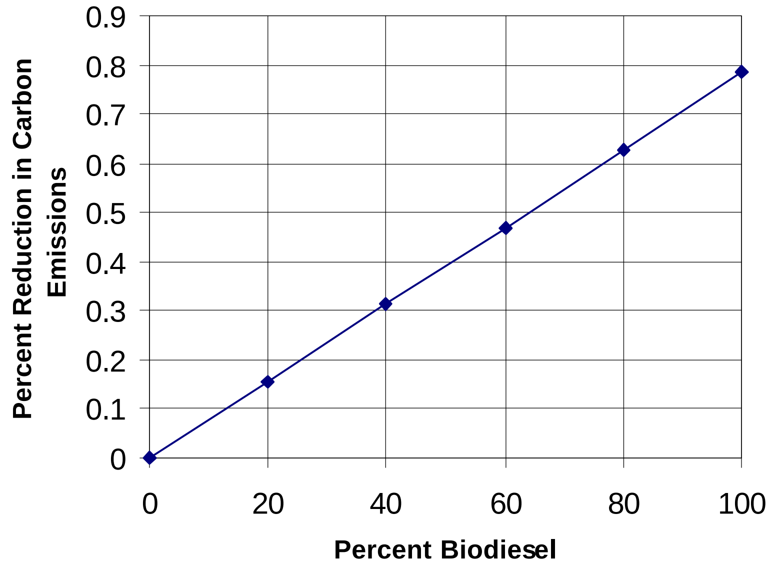


Figure 101: Effect of Biodiesel Blend Level on CO_2 Emissions

9.1.3 Life Cycle Consumption of Primary Resources

Primary resources consist of raw materials that are extracted from the environment. Because these resources are finite, it is important to understand the kinds of demands that are placed on these resources by each fuel. LCIs provide a way to quantify the total impact of these fuels on natural resources. The raw materials included the LCI model are:

- Primary energy resources (coal, oil, natural gas and uranium)
- Phosphate rock
- Potash
- Perlite (silicon oxide ore)
- Limestone
- Sodium chloride
- Water.

9.1.3.1 Life Cycle Consumption of Primary Resources for Petroleum Diesel

Table 127 summarizes the raw material inventory for key steps in the life cycle of petroleum diesel. Analysis of raw material consumption summarized in this table is provided in this section.

As the primary energy feedstock for diesel production, petroleum consumption is, by definition, almost exclusively reflected in crude oil extraction. Foreign and domestic crude production are 98.2% of the total oil use. A small amount of petroleum consumption is associated with refining, where crude oil is used directly as an energy source as well as a feedstock for diesel production. A small consumption of crude oil is also associated with diesel fuel used in transport steps.

Table 127: LCI Inventory of Raw Material Consumption for Petroleum Diesel (kg/bhp-h)

Raw Material	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Oil Transport	Foreign Crude Oil Transport	Crude Oil Refining	Diesel Fuel Transport	Total
Coal	0.00119	0.00104	0.000334	0.000372	0.002544	0.000405	0.00589
Limestone	0.00023	0.00020	6.36E-05	7.09E-05	0.00048	7.73E-05	0.00112
Natural Gas	0.00596	0.00311	5.19E-05	0.000188	0.00679	9.27E-05	0.01620
Oil	0.09331	0.09231	0.000196	0.001793	0.000734	0.000598	0.18894
Perlite	0	0	4.21E-08	4.05E-07	4.24E-05	1.33E-07	0.00004
Phosphate Rock	0	0	0	0	0	0	0
Potash	0	0	0	0	0	0	0
Sodium Chloride	0	0	0	0	0	0	0
Uranium	2.86E-08	2.50E-08	8.00E-09	8.91E-09	6.03E-08	9.71E-09	1.41E-07
Water Used	0.02025	0.00549	3.58E-05	0.000258	0.000167	9.33E-05	0.02629

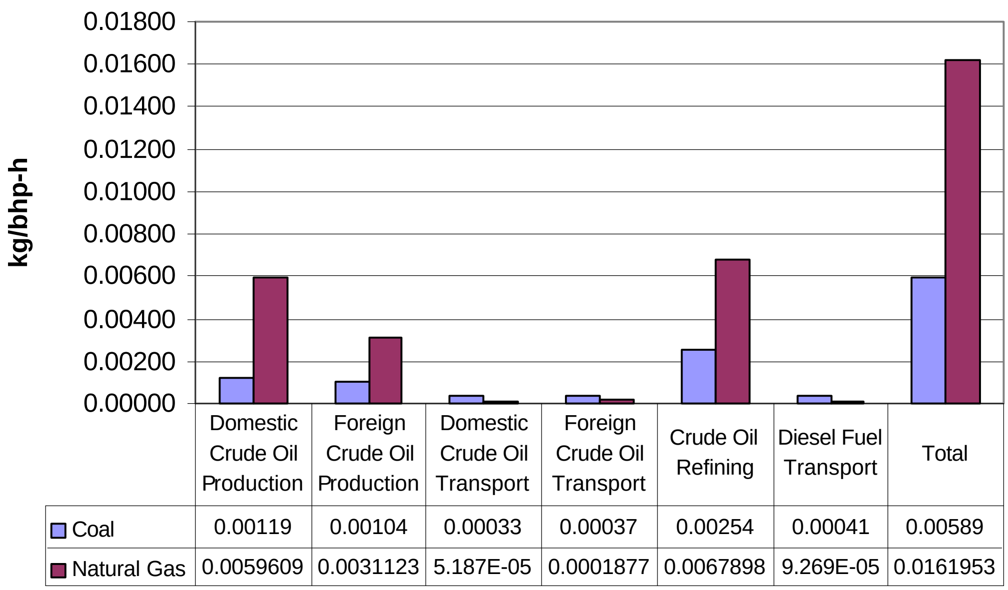


Figure 102: Life Cycle Consumption of Coal and Natural Gas for Petroleum Diesel

Figure 102 summarizes coal and natural gas consumption for petroleum diesel. Refining and extraction account for 98% of the natural gas consumption. These two parts of the life cycle almost split the demand for natural gas (56% for extraction and 42% for refining). Natural gas is used directly in these steps as a source of process energy. There is also indirect consumption of natural gas associated with electricity purchased off the grid. Domestic crude production uses twice as much natural gas as foreign crude production, reflecting its greater reliance on energy-intensive advanced recovery schemes. The distribution of coal consumption tracks with electricity demand. Again, crude oil extraction and refining consume the larger amount of coal, in total representing 81% of the life cycle use of coal. Refining accounts for 43% of the coal use; extraction accounts for 38%[105].

Figure 103 summarizes uranium consumption. Both uranium and coal use are indicators of electricity demand in this model. The distribution of uranium use shown here is identical to the distribution of coal shown in Figure 102. Refining uses 38% of the total uranium demand; extraction accounts for 43%.[106]

Figure 104 shows limestone consumption for petroleum diesel. Limestone is consumed as part of electricity production, where it is used in flue gas desulfurization. The distribution of its use tracks identically with coal, uranium, and electricity.

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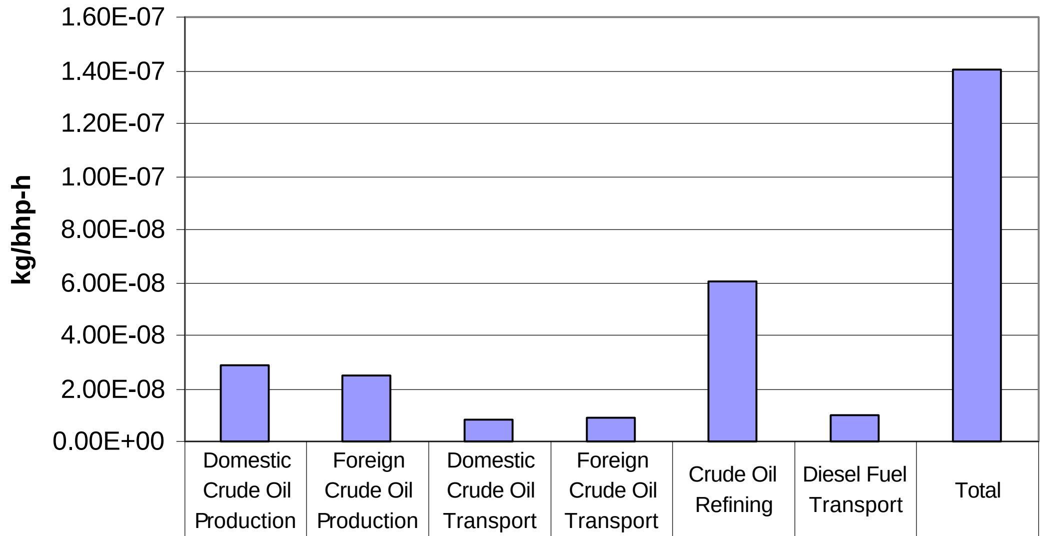

	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Oil Transport	Foreign Crude Oil Transport	Crude Oil Refining	Diesel Fuel Transport	Total
Uranium	2.8591E-08	2.5038E-08	7.9993E-09	8.9098E-09	6.0284E-08	9.7125E-09	1.4053E-07

Figure 103: Life Cycle Consumption of Uranium for Petroleum Diesel

Figure 105 shows that 98% of the demand for water is in crude production. Water use is four times higher for domestic crude production than for foreign crude production because of a higher reliance on advanced recovery processes in the United States. A very small amount of water is required for offshore conventional oil recovery. None is required for onshore conventional recovery.

Table 127 shows consumption of perlite, a silicon oxide mineral. Perlite is used for catalyst production in the oil refining step. Thus, it shows up primarily in the refinery, and secondarily as an indirect consumption associated with diesel fuel used in transport steps.

[105] The consumption of coal is affected by our simplifying assumption that the mix of primary energy sources for electricity generation is the same for foreign oil production as it is for U.S. oil production.

[106] The same caution applies for uranium consumption as was discussed for coal.

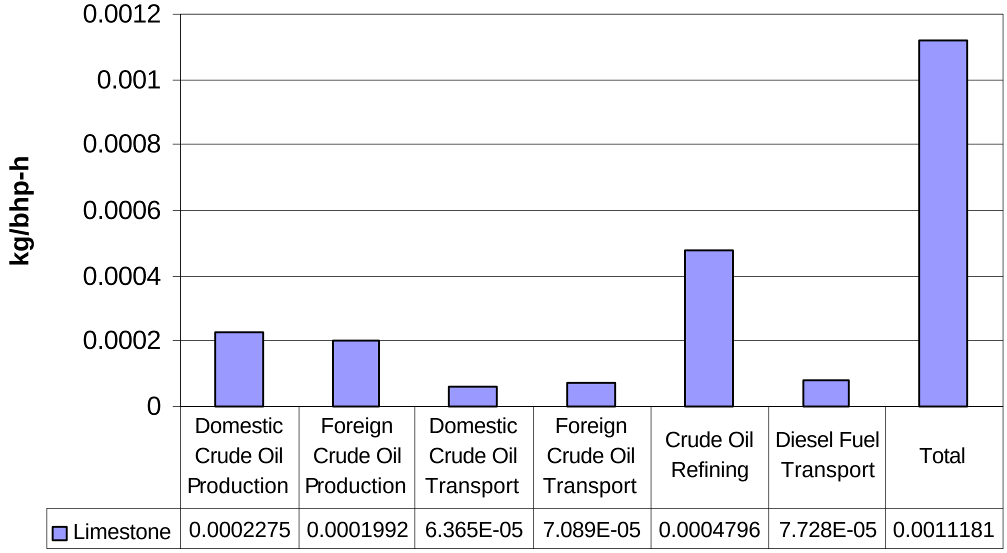

Figure 104: Life Cycle Consumption of Limestone for Petroleum Diesel

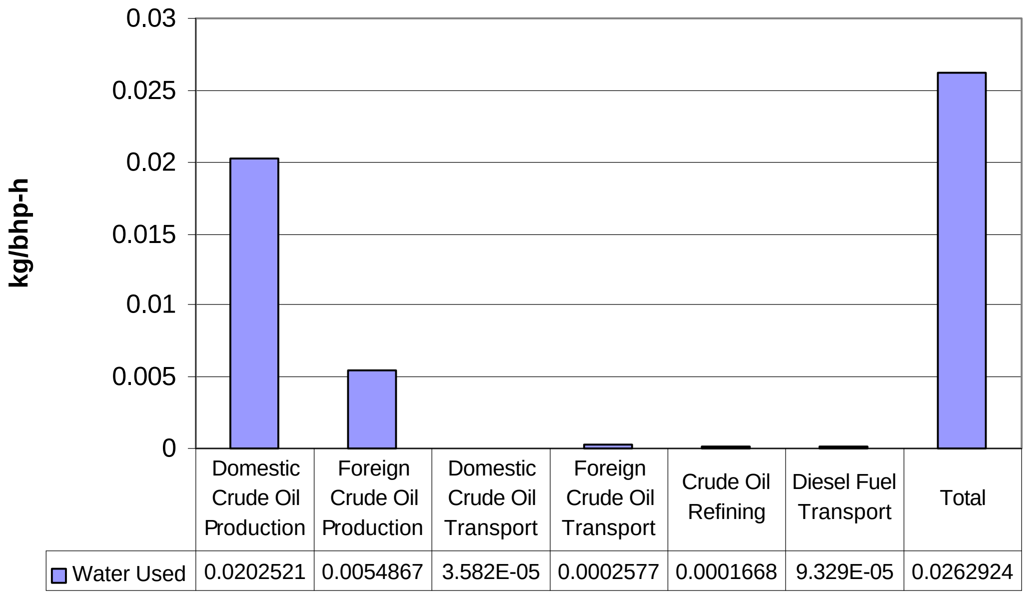

Figure 105: Life Cycle Consumption of Water for Petroleum Diesel

9.1.3.2 Life Cycle Consumption of Primary Resources for Biodiesel

Table 128 summarizes the resource demands across the life cycle for biodiesel. Analysis of the LCI shown in this table follows immediately in this section.

Coal and oil consumption for biodiesel are shown in Figure 106. As with the petroleum diesel life cycle, coal consumption tracks electricity usage. The coal and oil estimates for soybean crushing and soy oil conversion are both related to electricity. Petroleum oil consumption in the other parts of the life cycle reflect the use of diesel and gasoline. The use of tractors, trucks and other farm equipment makes agriculture the largest consumer of petroleum oil. Agriculture represents 67.6% of the petroleum oil used in the biodiesel life cycle.

Table 128: Life Cycle Consumption of Primary Resources for Biodiesel

Raw Material	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Total
Coal	0.001328	0.000017	0.003221	0.000035	0.002405	0.000022	0.00703
Limestone	0.000172	0.000003	0.000614	0.000007	0.000340	0.000004	0.00114
Natural Gas	0.002599	0.000046	0.008729	0.000097	0.019219	0.000059	0.03075
Oil	0.006826	0.000533	0.000519	0.001133	0.000413	0.000689	0.01011
Perlite	1.330E-06	1.211E-07	0.000E+00	2.575E-07	0.000E+00	1.566E-07	1.87E-06
Phosphate Rock	0.009397	0	0	0	0	0	0.00940
Potash	0.004417	0	0	0	0	0	0.00442
Sodium Chloride	0	0	0	0	0.00350	0	0.00350
Uranium	7.293E-08	3.97E-10	7.721E-08	8.44E-10	3.542E-08	5.15E-10	1.87E-07
Water Used	86.2493	7.41E-05	0.0007109	0.000158	0.113338	9.58E-05	86.364

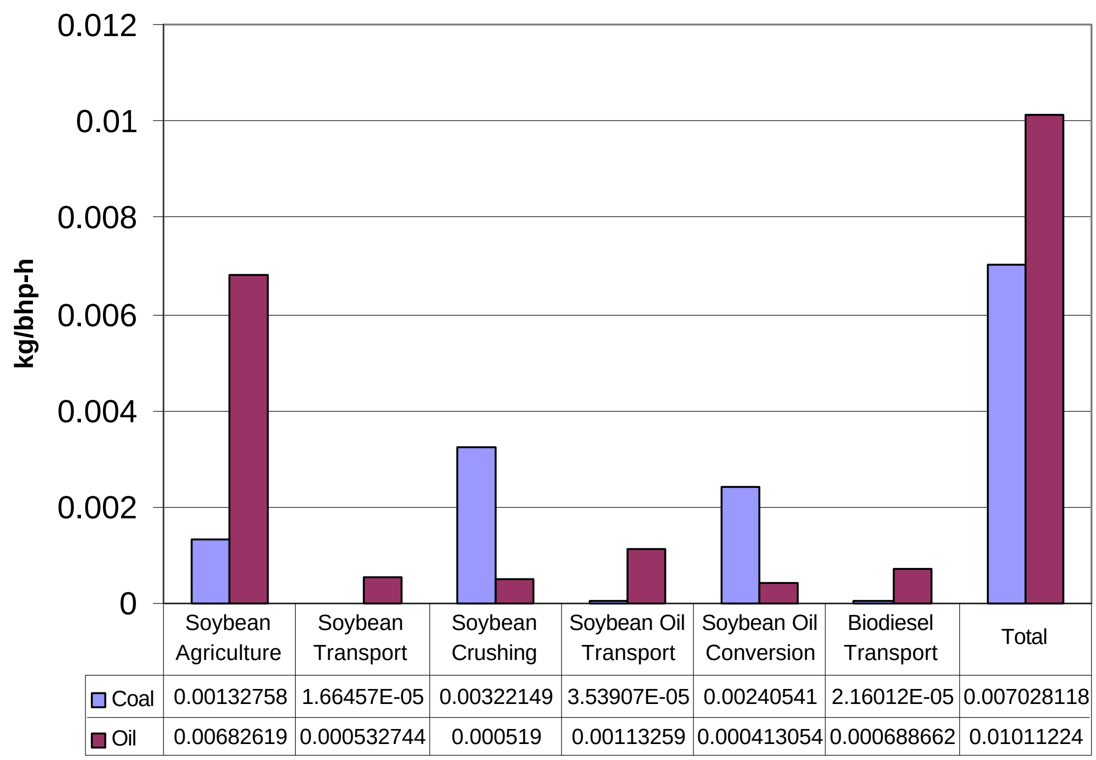

Figure 106: Life Cycle Consumption of Coal and Oil for Biodiesel

Figure 107 shows the amounts of natural gas used in the key steps in the life cycle of biodiesel. Use of natural gas includes the production of process energy used directly in each step, as well as natural gas used to produce electricity and methanol. The combination of soy oil conversion and soybean crushing represents the greatest requirement for use of natural gas, consuming 91% of the total life cycle input of natural gas. The conversion step alone accounts for almost two-thirds of the natural gas used in the life cycle. The use of methanol as a feedstock in conversion of soy oil to biodiesel makes the conversion step the highest consumer of natural gas on a life cycle basis[107].

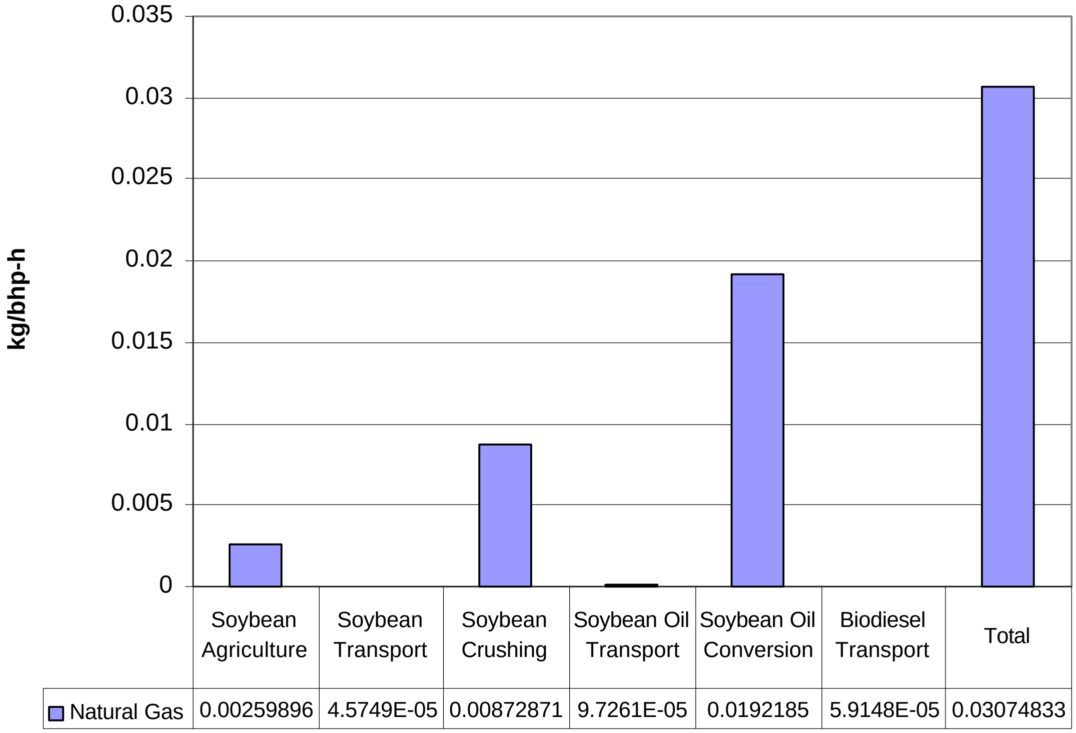

Figure 107: Life Cycle Consumption of Natural Gas for Biodiesel

Uranium consumption is shown in Figure 108. Because uranium is used to produce, the pattern of uranium use across the life cycle should track with coal consumption. The model shows almost twice the level of uranium consumption expected for farming. The unusually high uranium consumption can be traced back to the use of a data source for the production of agrochemicals. This data source is based on a plant located in France, where the electricity supply is predominantly nuclear. The electricity inputs were integrated into the Ecobalance data for this facility, and were not readily separated. The uranium consumption estimates for farming are artifacts of this problem with the data. Figure 109 shows the limestone consumption for each stage of biodiesel. It is in agreement with the distribution of consumption shown for coal in Figure 102.

A number of primary resources listed in Table 128 are associated with specific steps in the life cycle. Water is the largest of these. Its consumption for biodiesel is dominated by the use of water for agriculture. Farming accounts for 99.87% of the water consumed in the life cycle. The phosphate rock

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[107] On the basis of natural gas used directly in each stage, the soybean crushing and conversion steps use similar amounts of natural gas. In the life cycle calculation, however, natural used to make the methanol is an indirect consumption associated with the conversion step.

and potash are also exclusively used in farming. Sodium chloride is an indirect input to soy oil conversion via HCl acid production.

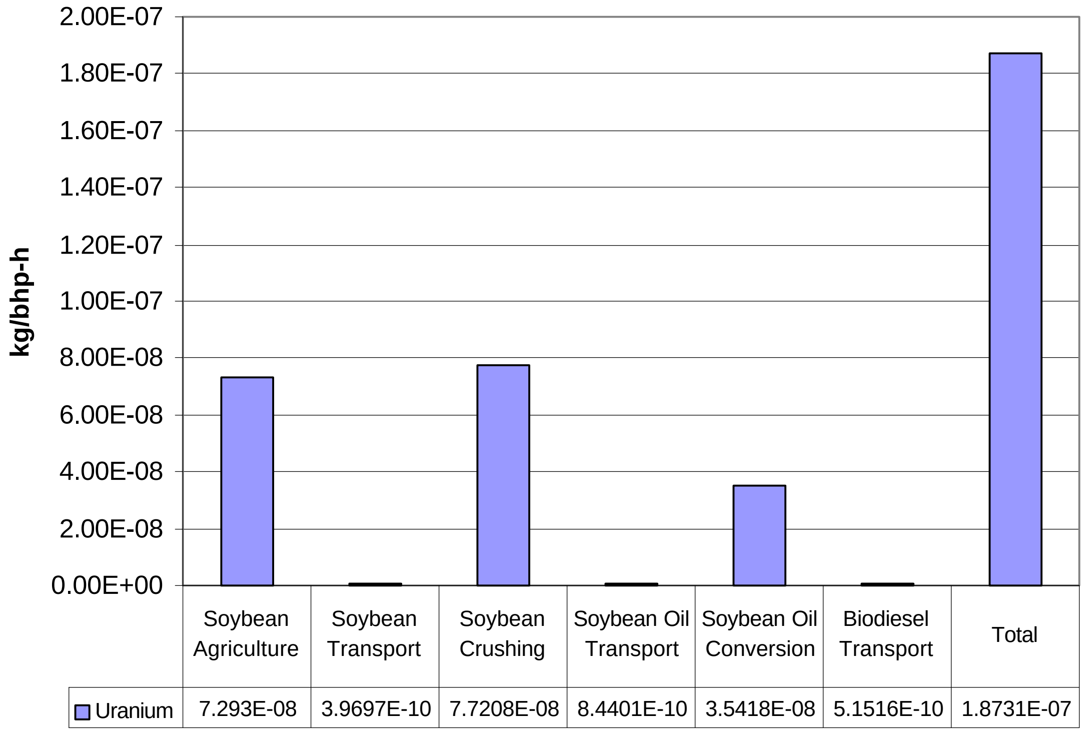
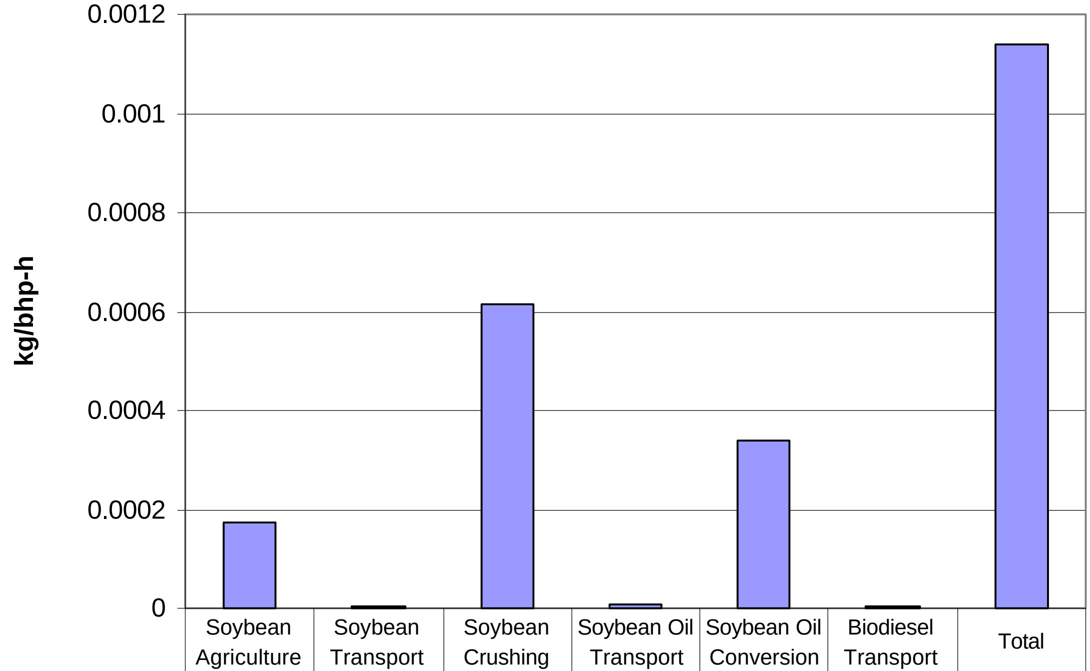


Figure 108: Life Cycle Consumption of Uranium for Biodiesel

9.1.3.3 The Effect of Biodiesel on Primary Resource Consumption

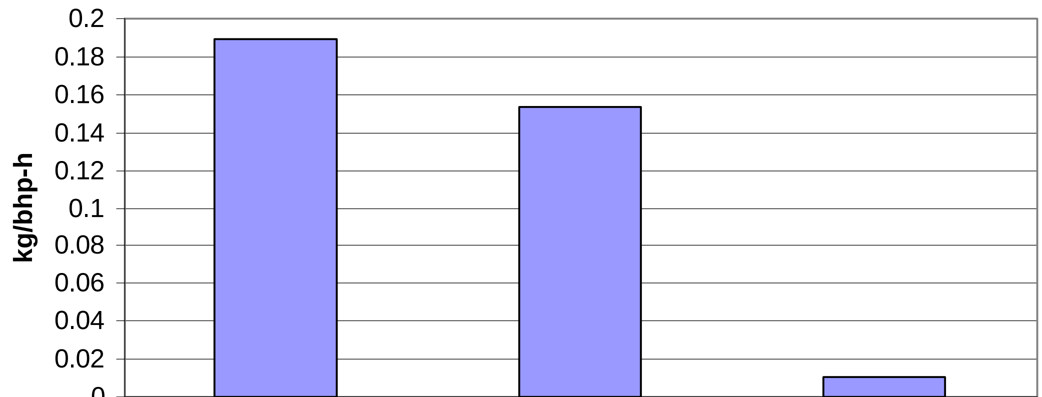
Figure 110 compares petroleum oil consumption for petroleum diesel, B20, and B100. The use of B100 as a substitute for petroleum diesel effects a 95% reduction in life cycle consumption of petroleum. The 20% blend of biodiesel provides a proportionate reduction of 19%.

Consumption of coal and natural gas is a different story (see Figure 111). The use of B100 increases coal consumption by 18.6%. This reflects the higher overall use of electricity in the biodiesel life cycle, relative to petroleum diesel. Electricity consumption in the soybean crushing stage is the dominant factor for biodiesel because of the mechanical processing and solids handling equipment involved. Natural gas use increases by 89.5% for B100 versus petroleum diesel. Two factors contribute to this increase: 1) the assumed use of natural gas for the supply of steam and process heat in soybean crushing and soy oil conversion, and 2) the use of natural gas to produce methanol used on the conversion step.



	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Total
Limestone	0.0001718	3.1585E-06	0.00061429	6.7153E-06	0.00034041	4.0988E-06	0.00114047

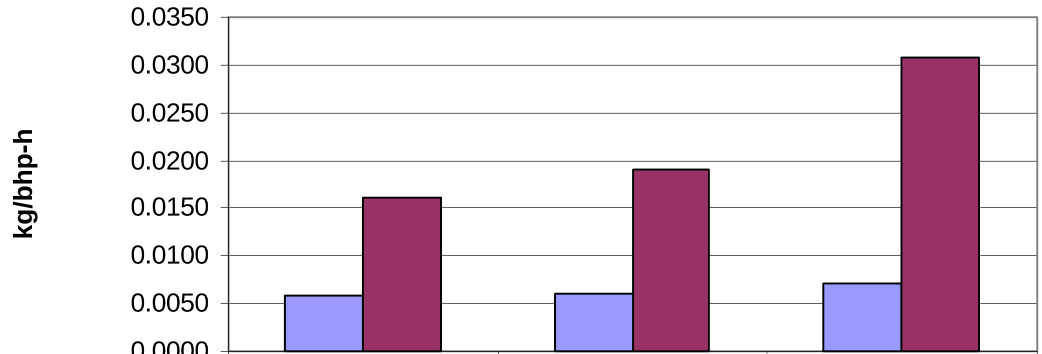
Figure 109: Life Cycle Consumption of Limestone for Biodiesel



	Petroleum Diesel	B20	B100
Oil	0.188939	0.153173	0.0101122

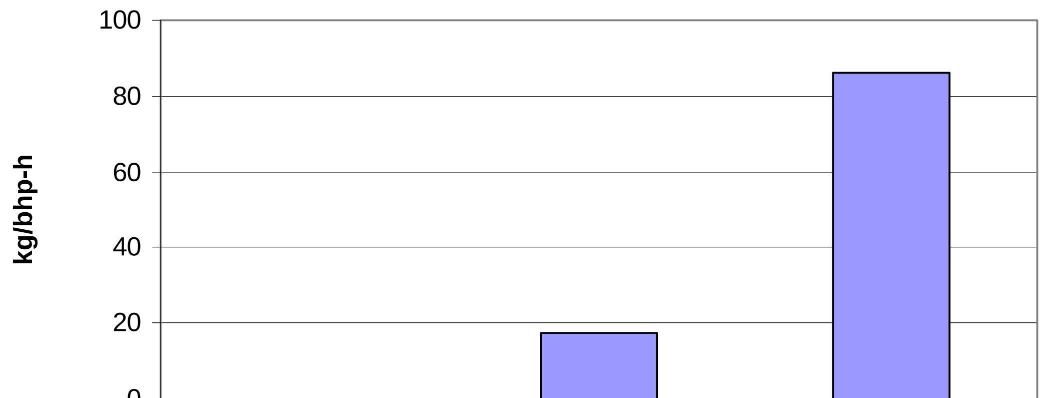
Figure 110: Petroleum Consumption for Petroleum Diesel, B20, and B100

Water consumption is higher for biodiesel, than for petroleum diesel. Water use for petroleum diesel is not even visible on a plot scaled to show biodiesel use (see Figure 112). That is because the biodiesel life cycle uses water at a rate that is three orders of magnitude higher than that of petroleum diesel. The impact of this water use is not clear. For instance, when water use is compared to total wastewater generated, it appears that the biodiesel life cycle generates far less wastewater. Although water designated as waste is produced in crude oil production, it can also be used to increase oil recovery by well reinjection. In the biodiesel life cycle it is consumed during agriculture, and is generally recycled into the environment for other uses. We offer no simple way to compare water use between the two life cycles because no simple equivalency exists in its use and final disposition.



	Petroleum Diesel	B20	B100
Coal	0.0059	0.0061	0.0070
Natural Gas	0.0162	0.0191	0.0307

Figure 111: Coal and Natural Gas Consumption for Petroleum Diesel, B20, and B100



	Petroleum Diesel	B20	B100
Water	0.0262924	17.2938	86.3636

Figure 112: Water Use for Petroleum Diesel, B20, and B100

9.1.4 Life Cycle Emissions of Regulated and Nonregulated Air Pollutants

Regulated air pollutants include the following:

- CO
- NO_x
- PM10
- NMHC

The emissions of these air pollutants are regulated at the tailpipe for diesel engines. SO_x does not have specific tailpipe limits, but it is controlled through sulfur content of the fuel. Other air emissions included in this study are CH_4, benzene, formaldehyde, N_2O, HCl, HF, and NH_3. N_2O is associated with agricultural field emissions. HCl and HF are associated with coal combustion in electric power stations. NH_3 release occurs primarily in fertilizer production.

In this section, we discuss only those pollutants for which the most comprehensive and consistent data are available. These include the regulated air pollutants listed above. PM and HC are reported in different forms, depending on the data sources available. Benzene and formaldehyde emissions are not consistently reported. In some cases, we have combined pollutants into categories. HC data are reported as THC, defined as:

$$THC = \left(CH_4 + Benzene + formaldehyde + HC_{unspecified} + HC_{noCH4}\right)$$

where:

THC = total hydrocarbons

CH_4 = methane

$HC_{unspecified}$ = unspecified hydrocarbons

HC_{noCH4} = hydrocarbons excluding methane

Likewise, particulates are combined as a single category according to the following formula:

$$TPM = \left(PM10 + PM_{unspecified}\right)$$

where:

TPM = total particulate matter

PM10 = particulate matter less than 10 micron

$PM_{unspecified}$ = unspecified particulate matter

9.1.4.1 Life Cycle Air Emissions from Petroleum Diesel Life Cycle

Table 129 presents a summary of the air emissions LCI for petroleum diesel. The steps of the life cycle included in these results are:

- Foreign and domestic crude oil extraction
- Transport of crude oil to the refinery (for both foreign and domestic oil)
- Production of diesel fuel from crude oil at a domestic oil refinery
- Transport of the diesel fuel to bus fleet operators
- Diesel fuel use.

Analysis of the inventory for specific pollutants or groups of pollutants shown in Table 129 is presented in this section.

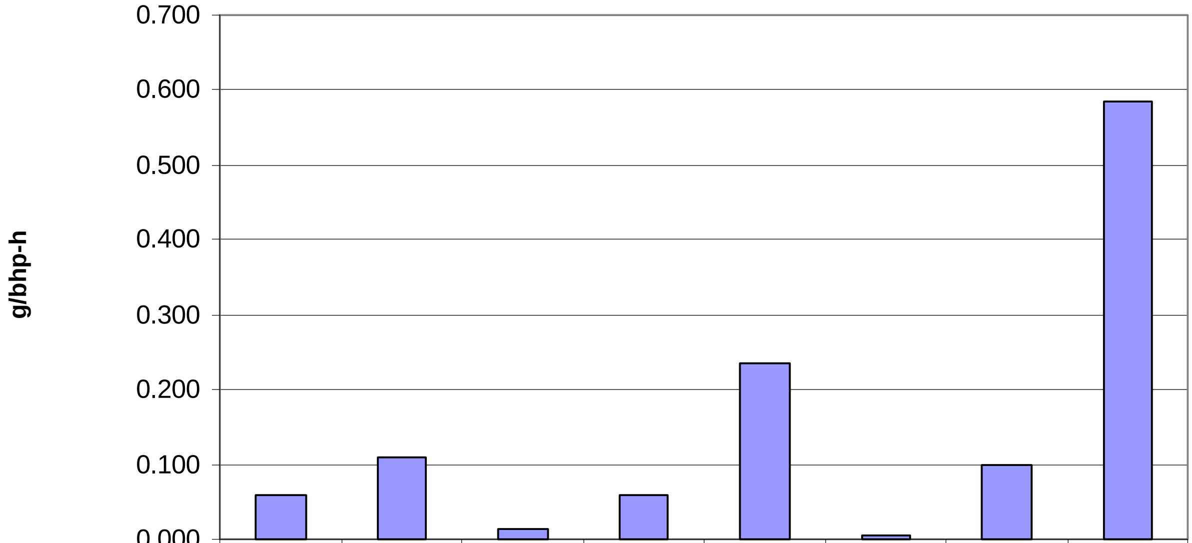
THC emissions from the life cycle for petroleum diesel are summarized in Figure 113. We found that CO_2 emissions from the petroleum life cycle were dominated by emissions at the tailpipe, but this was not true for THC. The largest contributor of THC is the oil refinery, which emits 40.4% of the total life cycle flow. Domestic and foreign crude production represent the next largest contribution, at 29%. Tailpipe emissions account for 17% of the total. Transport of foreign crude oil is also a significant contributor, accounting for 10% of the THC released in the life cycle.

Table 129: LCI of Air Emissions for Petroleum Diesel (g/bhp-h)[108]

Air Pollutant	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
NH_3	4.39E-09	3.84E-09	1.85E-09	6.69E-09	1.08E-08	3.92E-09	0.00E+00	3.15E-08
Benzene	2.14E-05	2.03E-05	4.15E-08	4.00E-07	1.45E-07	1.31E-07	0.00E+00	4.24E-05
CO	0.006091	0.011088	0.001064	0.001546	0.043144	0.006875	1.200000	1.269810
Formaldehyde	0.000277	0.000281	0.000001	0.000005	0.000002	0.000002	0.000000	0.000568
NMHC	0.013648	0.015506	0.000103	0.000306	0.000470	0.001433	0.100000	0.131467
Hydrocarbons (unspecified)[109]	9.76E-05	8.54E-05	1.02E-02	5.53E-02	1.82E-01	1.19E-03	0.00E+00	2.49E-01
Hydrogen Chloride	0.000644	0.000564	0.000180	0.000201	0.001357	0.000219	0.000000	0.003164
Hydrogen Fluoride (HF)	8.05E-05	7.05E-05	2.25E-05	2.51E-05	1.70E-04	2.73E-05	0.00E+00	3.96E-04
CH_4	0.045281	0.093621	0.002656	0.004278	0.053414	0.003589	0.000000	0.202839
NO_x	0.024000	0.015720	0.006651	0.010242	0.129891	0.022055	4.800000	5.008558
N_2O	0.004049	0.001149	0.000034	0.000082	0.001255	0.000216	0.000000	0.006784
PM10	0.000194	0.000066	0.000159	0.000006	0.001459	0.002210	0.080000	0.084094
Particulates (unspecified)	0.016796	0.014704	0.004956	0.008848	0.079114	0.005864	0.000000	0.130281
SO_x	0.128553	0.083197	0.011121	0.080880	0.440475	0.009708	0.172402	0.926335

[108] Note that THC (not listed in the table) is the sum of benzene, formaldehyde, hydrocarbons (unspecified), NMHC (Non Methane Hydrocarbons), and CH_4. Similarly, data we report in other parts of this study for TPM (total particulate matter) represent the sum of PM10 and Particulates (unspecified). This latter category represents data in which the type of particulates measured was not specified.

[109] Unspecified hydrocarbons are *not* the sum of NMHC and CH_4. This is because the unspecified category of emissions is ambiguous. We do not know if original data sources were referring to total hydrocarbons or NMHC. This ambiguity is a common problem in life cycle analysis because of the need to use data collected across a wide range of sources.



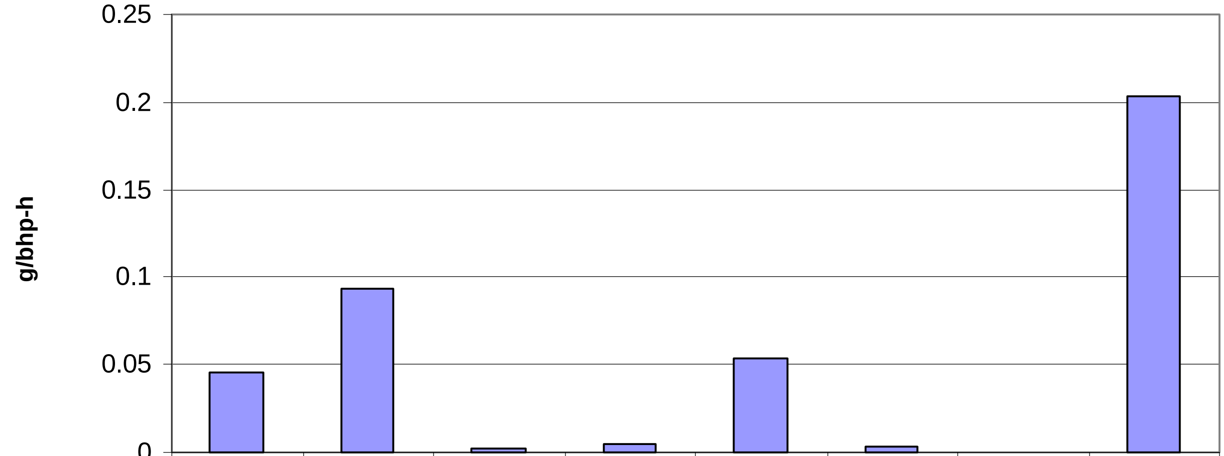
	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
Total Hydrocarbons	0.059325	0.109514	0.012950	0.059934	0.236034	0.006211	0.100000	0.583968

Figure 113: THC Emissions from Petroleum Diesel Life Cycle

The THC emissions that occur before the fuel's end-use contain a significant amount of CH_4, which comprises 42% of the THC emissions that occur in the diesel fuel production and distribution steps. Sources of CH_4 in the petroleum diesel life cycle are shown in Figure 114. Life cycle CH_4 releases are credited to oil extraction and oil refining activities. CH_4 emissions in foreign crude oil extraction account for 85.5% of the THC released during this step. Domestic oil production is similar, with CH_4 making up 76% of its THC emissions. The rather high percentage of CH_4 in the THC emissions of crude oil extraction reflects the practice of natural gas venting, which is done to a greater extent in foreign oil production than it is in domestic oil production. There are two major sources of CH_4 emissions for the oil refinery: the direct use of natural gas and electricity. Both sources involve indirect emissions of CH_4 are associated with the production of natural gas. In total, CH_4 represents 34% of the THC released throughout the life cycle.

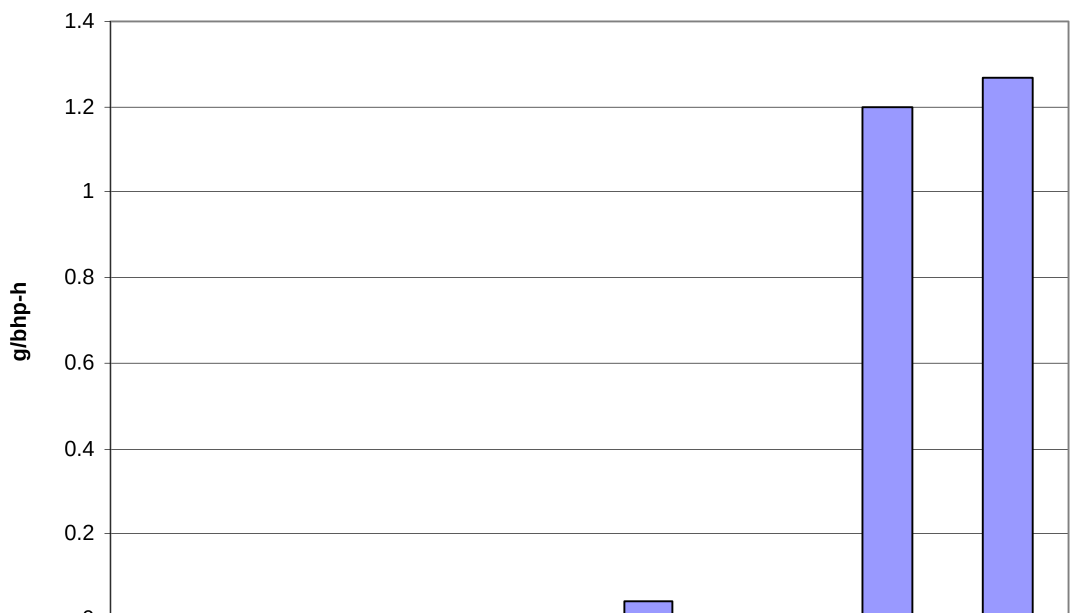
CO emissions for the petroleum diesel life cycle are shown in Figure 115. Emissions from the end-use of the fuel overwhelm the contributions of CO from any other part of the life cycle. CO from the combustion of diesel in the bus represents 94.5% of the total life cycle emissions.

Figure 116 shows the CO emissions for all steps but combustion. This expanded scale allows visual inspection of the relative contributions of these steps to the remaining 5.5% of CO emissions. The relative size of the contributions from these steps is similar to what has been shown for THC. Refining is the next largest contributor after combustion, representing two-thirds of the non-end-use CO. Total CO emitted from foreign and domestic crude oil extraction is about half the level of refinery emissions.



	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
Methane (CH4)	0.0452807	0.0936212	0.0026561	0.0042778	0.0534141	0.00358927	0	0.20283917

Figure 114: CH_4 Emissions from Petroleum Diesel Life Cycle



	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
CO	0.0060914	0.0110883	0.0010643	0.0015464	0.0431441	0.0068755	1.2	1.26981

Figure 115: CO Emissions for Petroleum Diesel Life Cycle

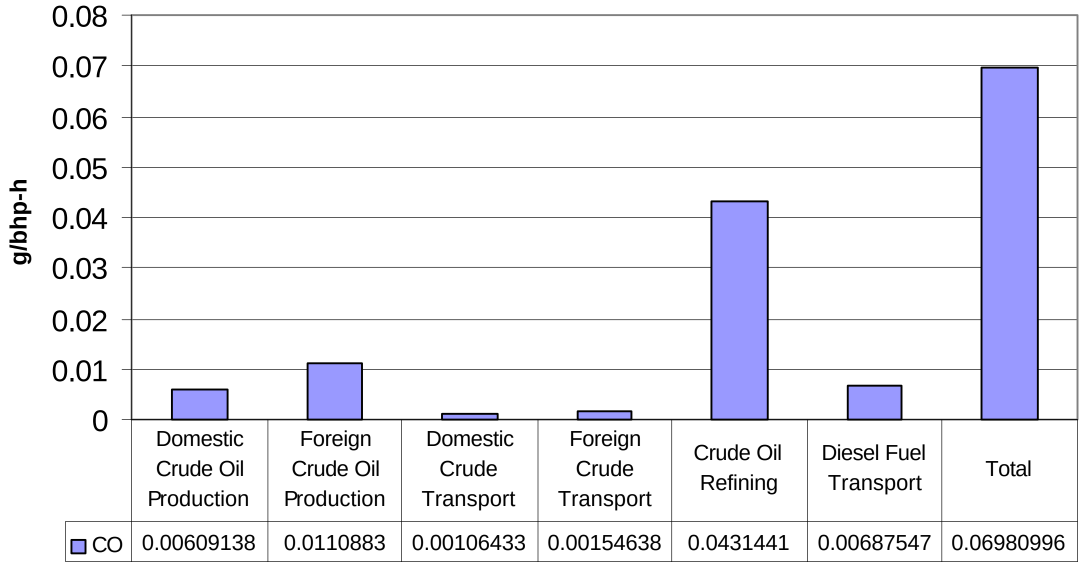
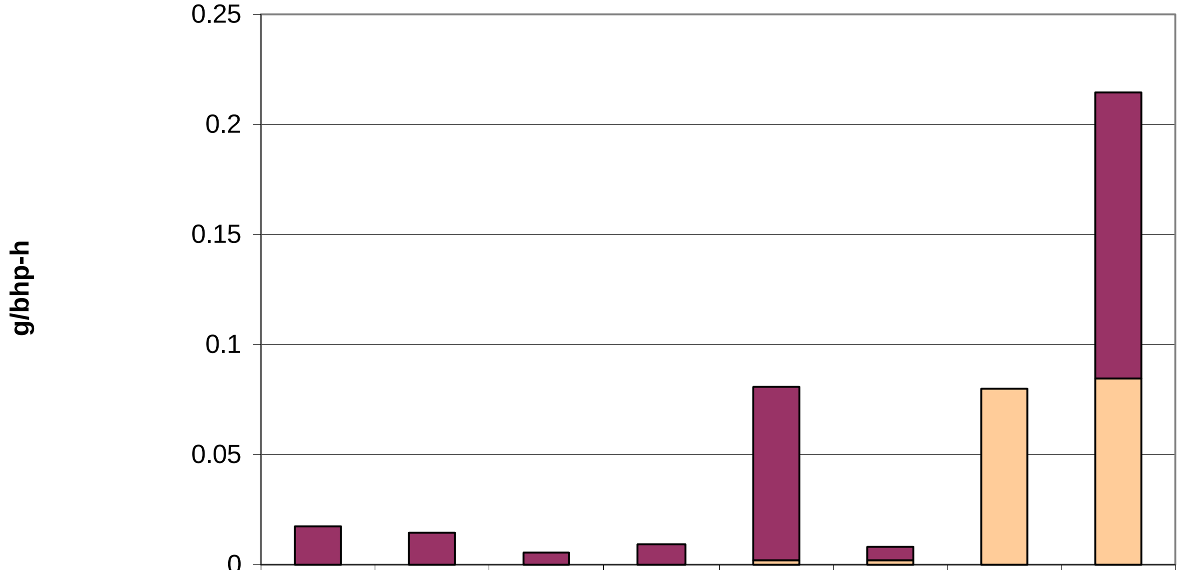


Figure 116: CO Emissions from the Petroleum Life Cycle (Excluding End-Use Combustion of the Fuel)

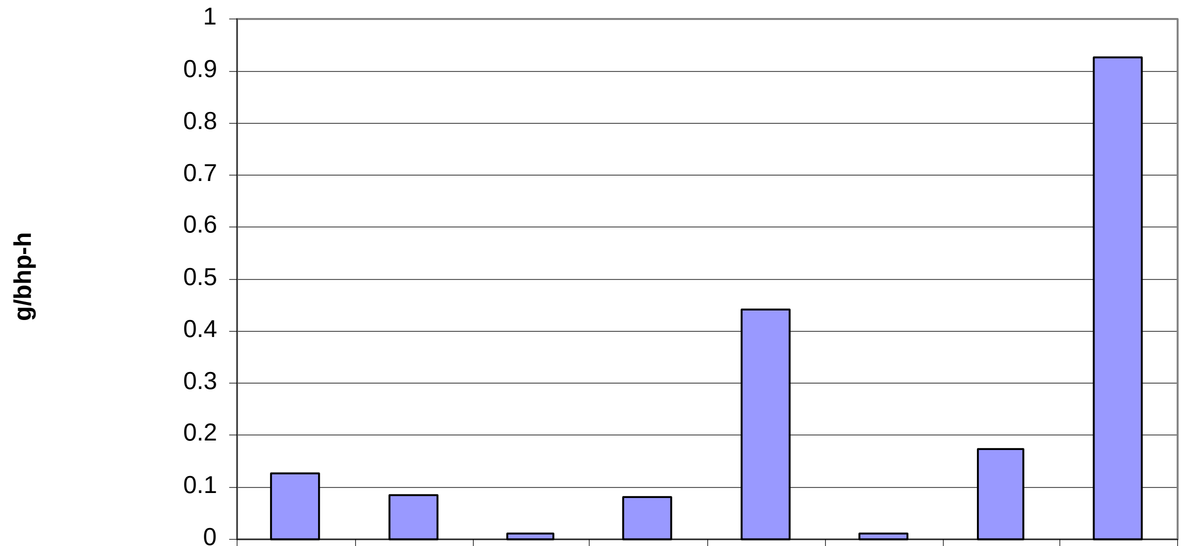
TPM emissions for the petroleum diesel life cycle are summarized in Figure 117. Both unspecified PM and PM10 are shown cumulatively for each step of the life cycle. Some care has to be taken in interpreting these results because of the differences in reporting among the various data sources. Most of the sources did not indicate what type (or size range) of particulates was measured. In the case of the diesel fuel emissions, the TPM includes only PM10, and thus does not reflect emissions of coarser particulates. The engine tailpipe and the oil refinery are the two dominant sources of TPM (37% and 38% of the TPM emissions for the life cycle, respectively). Foreign and domestic crude oil production together contributes 15% of the life cycle TPM emissions.

A comparison of the TPM emissions and SO_x emissions for the petroleum diesel life cycle reveals that these emissions seem to track each other very closely. The relative contributions for each of these pollutants are similar, especially for the fuel production and distribution parts of the life cycle. This close tracking of SO_x and PM emissions is not surprising because sulfates are major contributors to the formation of particulates. The largest contribution of SO_x emissions comes from the oil refinery, which accounts for 48% of the total. Crude oil production contributes another 23%. The distribution of SO_x emissions in the production and distribution stages closely mirrors that of the process energy requirements for petroleum diesel shown in Figure 88. Diesel fuel combustion accounts for only 19% of the total SO_x emissions.



	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
Particulates (unspecified)	0.0167957	0.0147043	0.0049555	0.0088476	0.0791143	0.0058635	0	0.130281
Particulates (PM10)	0.0001935	6.595E-05	0.0001593	5.971E-06	0.0014593	0.0022096	0.08	0.0840937

Figure 117: TPM Emissions from Petroleum Diesel Life Cycle



	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
Sulfur Oxides (SOx)	0.128553	0.0831973	0.0111208	0.0808795	0.440475	0.0097077	0.172402	0.9263353

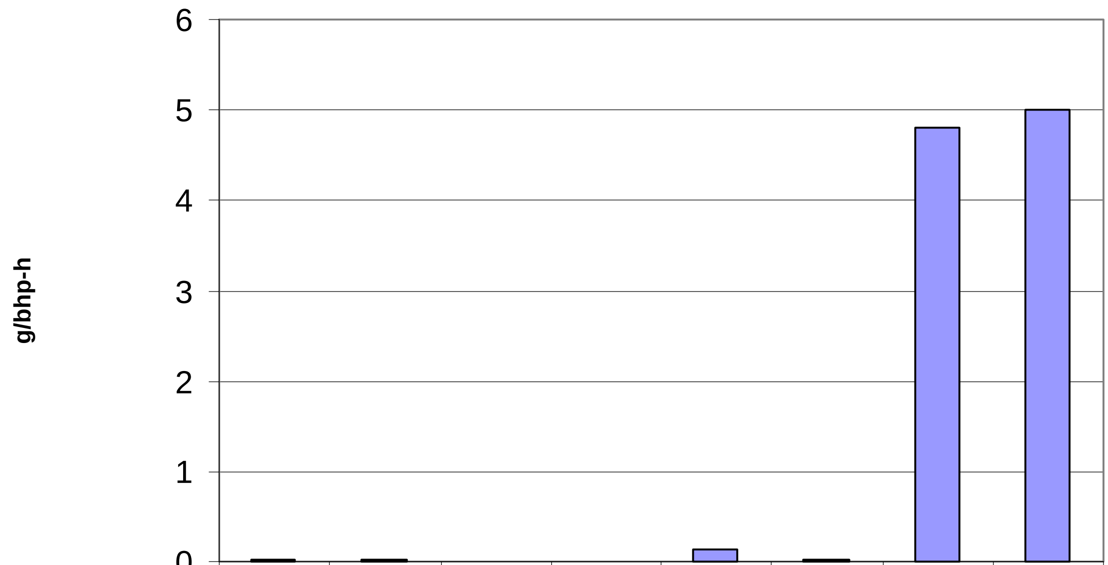
Figure 118: SO_x Emissions from Petroleum Diesel Life Cycle

NO_x emissions for the petroleum diesel life cycle are reported in Figure 119 and Figure 120. As with the CO emissions, NO_x emissions are overwhelmed by the impact of the fuel's end-use. NO_x emissions from the tailpipe of the bus are 96% of the total. Oil refining makes up the bulk of the remaining 4% of NO_x emissions.

In order to better show the relative distribution of NO_x emissions for the fuel production and distribution steps, the emissions are shown in an expanded scale without diesel fuel combustion in Figure 120. The distribution of emissions is similar to that of CO. Oil refining is the dominant source of emissions, accounting for 62% of the non-end-use combustion emissions of NO_x. The importance of NO_x emissions from diesel fuel combustion in diesel engines again increases the impact of diesel fuel transport. This same effect was observed with CO emissions (Figure 116).

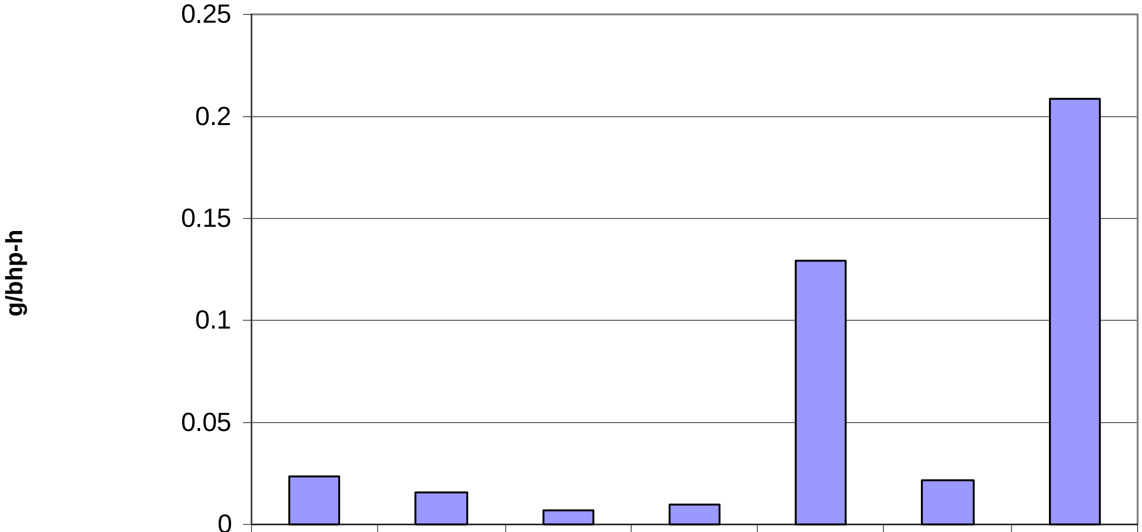
HCl and HF emissions for the petroleum diesel life cycle are presented in Figure 121 and Figure 122. The relative contributions of HCl and HF from each step in the life cycle track each other exactly. These emissions result from the combustion of coal used in electric power generation. These emissions are indicators of electricity consumption in each step of the life cycle. Most (81%) of the emissions occurs in crude oil refining and crude oil production, split almost equally between the two.

No discussion is presented on the emissions of N_2O, benzene, formaldehyde, and NH_3 because few consistent data were available on these pollutants across the life cycle of petroleum diesel.



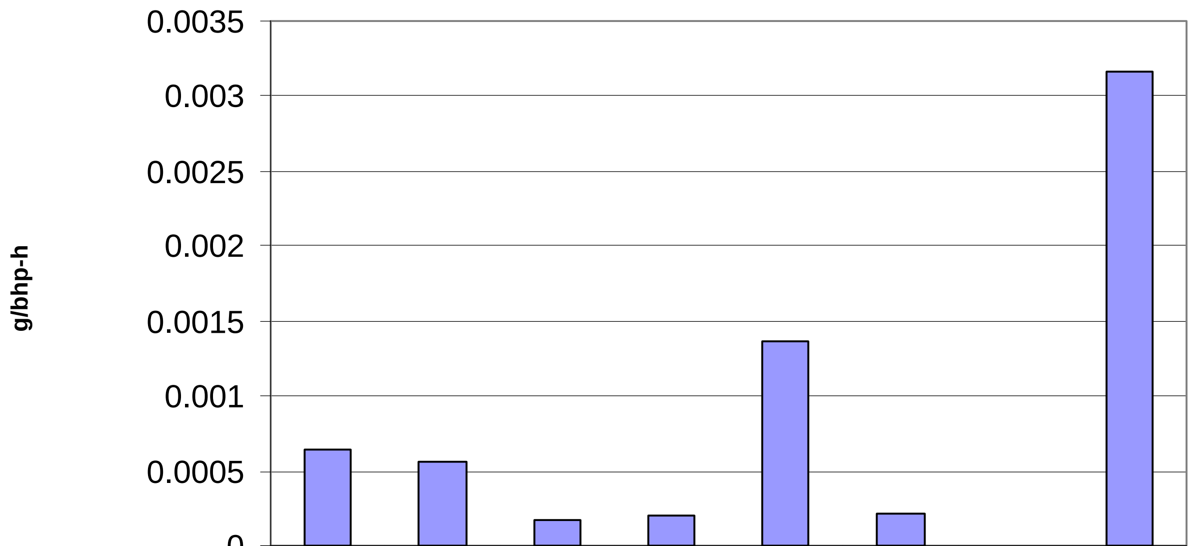
	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
Nitrogen Oxides (NOx)	0.024	0.0157198	0.0066505	0.0102417	0.129891	0.022055	4.8	5.008558

Figure 119: NO_x Emissions from Petroleum Diesel Life Cycle (Reported as NO_2)



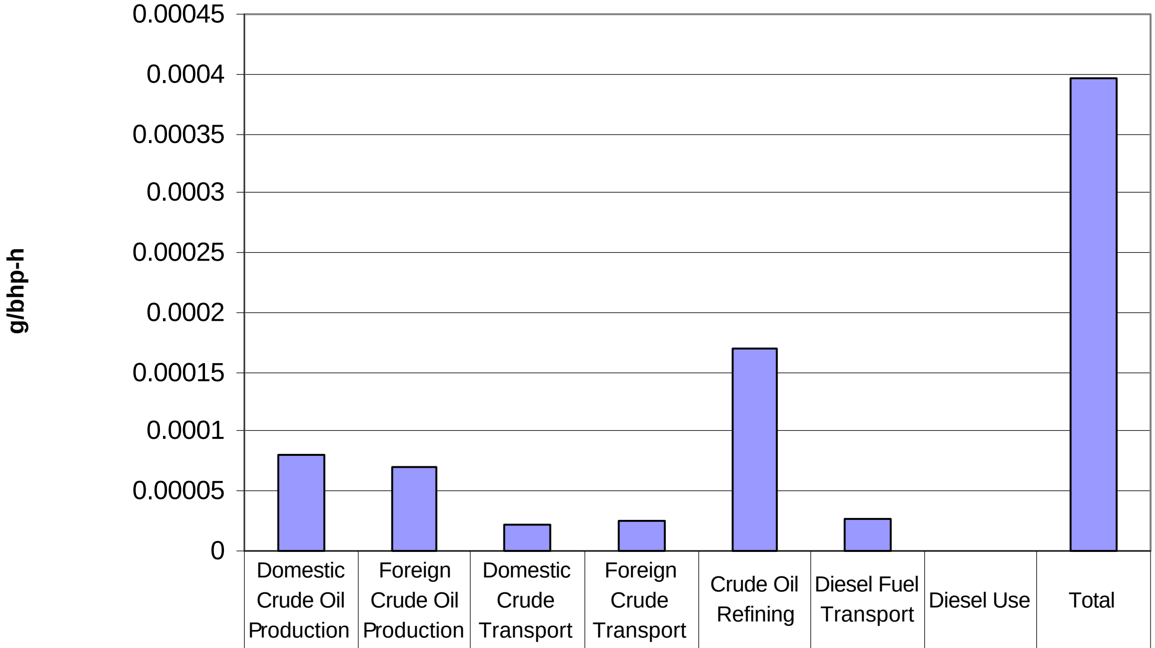
	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Total
Nitrogen Oxides (NOx)	0.024	0.0157198	0.00665054	0.0102417	0.129891	0.022055	0.20855804

Figure 120: NO_x Emissions from Petroleum Diesel Life Cycle Excluding End-use Combustion (Reported as NO_2)



	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
Hydrogen Chloride (HCl)	0.0006437	0.0005638	0.0001801	0.0002006	0.0013574	0.0002187	0	0.0031643

Figure 121: Life Cycle Emissions of HCl for Petroleum Diesel



	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Diesel Use	Total
Hydrogen Fluoride (HF)	8.047E-05	7.047E-05	2.251E-05	2.508E-05	0.0001697	2.734E-05	0	0.0003955

Figure 122: Life Cycle Emissions of HF for Petroleum Diesel

9.1.4.2 Life Cycle Emissions of Air Pollutants for Biodiesel

Table 130 provides a summary of all of the life cycle air emissions inventories for biodiesel. The basic steps included are:

- Soybean agriculture
- Transport of beans to soybean processor (crushing facility)
- Soy oil recovery (at the crusher)
- Transport of soy oil to a biodiesel facility
- Conversion of soy oil at a biodiesel facility
- Transport of biodiesel
- Use of biodiesel in an urban bus.

The results presented in Table 130 are for B100. Blends of biodiesel and petroleum diesel such as B20 will have emissions that lie between those of diesel and biodiesel, in proportion to the percentage of biodiesel included. Overall emissions for the B20 blend are discussed in the next section on comparisons of emissions for petroleum diesel and biodiesel blends. As with the petroleum life cycle discussion, results are analyzed for those pollutants or groups of pollutants for which a consistent and comprehensive set of data is available.

Table 130: LCI Air Emissions for Biodiesel (g/bhp-h)[110]

Air Pollutant	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Biodiesel Use	Total
NH_3	0.0734632	2.2735E-09	8.02E-06	4.83E-09	5.4472E-09	2.94E-09	0	0.073471
Benzene	1.313E-06	1.195E-07	0	2.54E-07	0	1.54E-07	0	1.84E-06
CO	0.136856	0.00602014	0.01054	0.012727	0.0125584	0.007782	0.64524	0.831723
Formaldehyde	1.78E-05	1.60E-06	5.20E-13	3.40E-06	2.38E-13	2.07E-06	0	2.48E-05
NMHC)	0.0539448	0.00129623	0.323816	0.00019	0.00031698	0.001676	0.06327	0.44451
Hydrocarbons (unspecified) [111]	0.11591	0.00070209	0.000263	0.00442	0.0296103	0.000908	0	0.151813
HCl	0.000282	8.9382E-06	0.001738	1.9E-05	0.00153278	1.16E-05	0	0.003593
HF	1.23E-05	1.12E-06	2.17E-04	2.38E-06	9.97E-05	1.45E-06	0	0.000334
CH_4	0.0283374	0.00063603	0.064765	0.001371	0.101683	0.000823	0	0.197616
NO_x	0.201205	0.0166995	0.065193	0.062899	0.0829794	0.021588	5.22672	5.677283
N_2O	0.0013084	0.00017635	0.000315	4.07E-05	0.00022874	0.000228	0	0.002297
PM10	0.0137127	0.00201252	0.000592	0.001541	0.00056848	0.002602	0.025544	0.046572
Particulates (unspecified)	0.0154781	0.00037925	0.045433	0.000806	0.0357402	0.000491	0	0.098329
SO_x	0.0939614	0.00261499	0.248258	0.005551	0.498182	0.003382	0	0.851949

Figure 123 presents THC emissions for the life cycle of biodiesel. Combustion of biodiesel accounts for only 8% of the THC emissions. The soybean crushing operation contributes 49% of the THC emissions. Soybean agriculture contributes 25% of the total life cycle emissions of THC. The next largest contributor to THC emissions is the soy oil conversion step, representing 17% of the total. Transportation of beans, soy oil and biodiesel contribute very little to the overall life cycle emissions of THC (totaling around 1.5%).

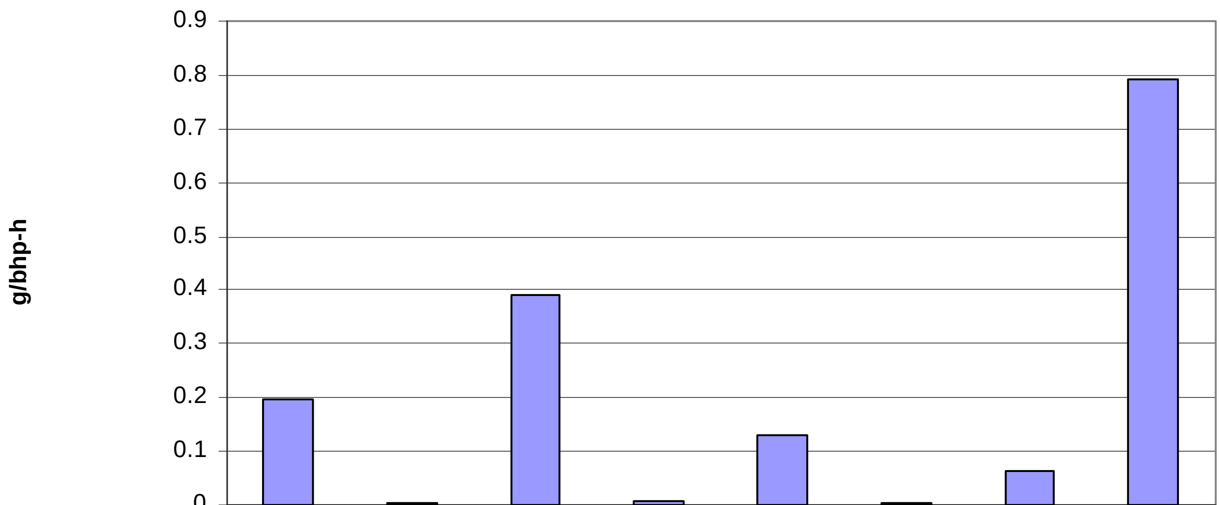
Though we would expect THC emissions to track energy consumption through the life cycle, this is not the case for soybean crushing. Even though energy consumption in the soybean crushing operation is less than that of biodiesel conversion (Figure 94), soybean crushing has emissions of THC that are more than

[110] Note that THC (not listed in the table) is the sum of benzene, formaldehyde, hydrocarbons (unspecified), NMHC (Non Methane Hydrocarbons), and CH_4. Similarly, data we report in other parts of this study for TPM (total particulate matter) represent the sum of PM10 and Particulates (unspecified). This latter category represents data in which the type of particulates measured was not specified.

[111] Unspecified hydrocarbons are *not* the sum of NMHC and CH_4. This is because the unspecified category of emissions is ambiguous. We do not know if original data sources were referring to total hydrocarbons or NMHC. This ambiguity is a common problem in life cycle analysis because of the need to use data collected across a wide range of sources.

double those of conversion. Figure 124 shows the sources of THC from the crushing operation. The steps shown indicate emissions associated with the production of steam, electricity, natural gas, and hexane, in addition to the actual crushing operation itself. The crushing operation is directly responsible for 85% of the THC emissions. Virtually all these emissions are attributable to the loss of hexane through vents and leaks in the crushing operation.

THC from soybean agriculture is predominantly from volatilization of applied chemicals during farming, which represent 54% of the THC (see Figure 125). The combustion products from gasoline and diesel equipment represent the next largest contributions to THC emissions from farming. Tractor and truck operations produce 21% of the THC emissions from the farm. The remaining 25% of farm emissions of THC come from indirect emissions associated with production of fertilizers and agrochemicals.

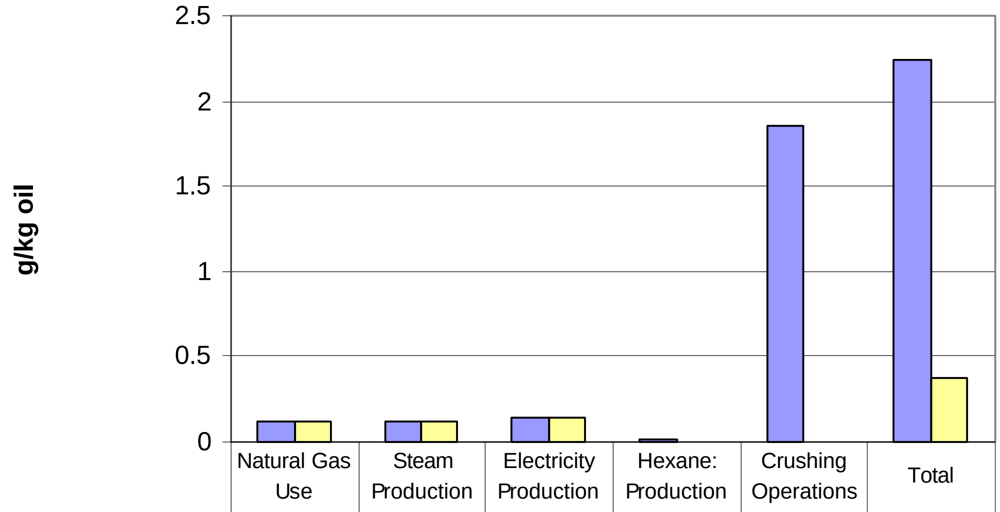


	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Biodiesel Use	Total
Total Hydrocarbons	0.19821259	0.00263619	0.38884461	0.00598538	0.13161028	0.00340834	0.06327	0.79396738

Figure 123: THC Emissions from Biodiesel Life Cycle

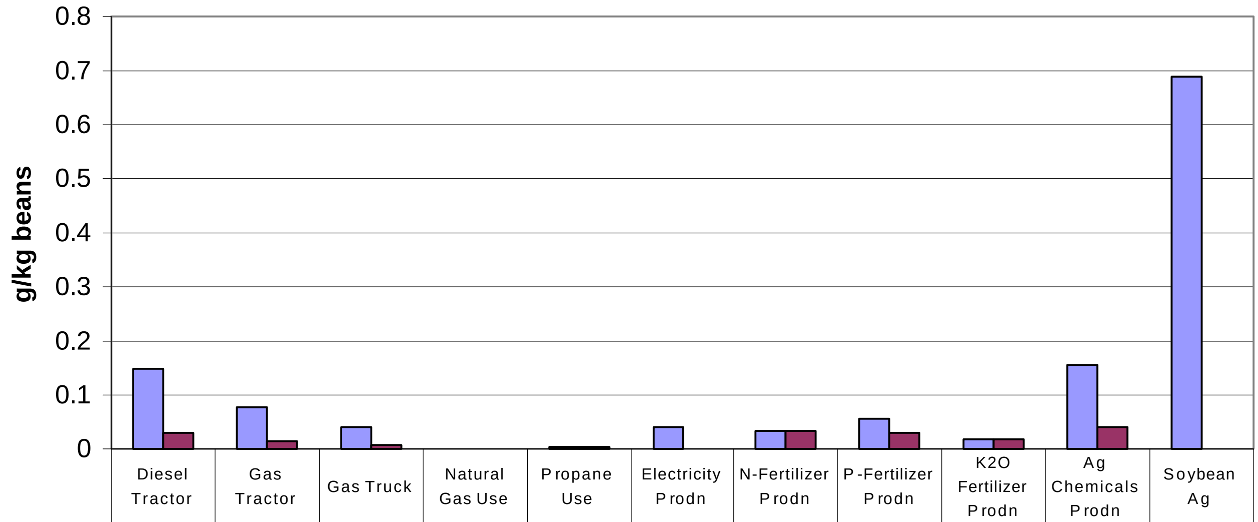
CH_4 emissions for the biodiesel life cycle are shown in Figure 126. CH_4 is 25% of the THC emissions from the life cycle for biodiesel, and makes up 27% of the THC emissions from the fuel production and distribution steps. The biodiesel conversion step is responsible for 51% of all of the CH_4 emissions. The reason for this large contribution can be seen in Figure 127. Almost all the THC from the conversion step are CH_4. This step introduces indirect emissions of CH_4 associated with the production of methanol, which is used as a co-reactant with soybean oil in the production of biodiesel. Methanol usage accounts for 64% of the CH_4 emissions from this step. Steam and electricity account for the rest (27% and 9%, respectively). The relatively large contribution from steam is because steam production is assumed to use natural gas as its primary energy source. The sources of CH_4 emissions for methanol and steam production are indirect emissions of natural gas associated with extracting and recovering of natural gas itself.

Figure 128 shows CO emissions from the biodiesel life cycle. As with petroleum diesel, biodiesel life cycle emissions of CO are dominated by end-use combustion of the fuel, which accounts for 77.6% of the total. As Figure 129 indicates, 73% of the remaining CO is generated in the soybean agriculture step, related to the operation of diesel- and gasoline-powered vehicles.



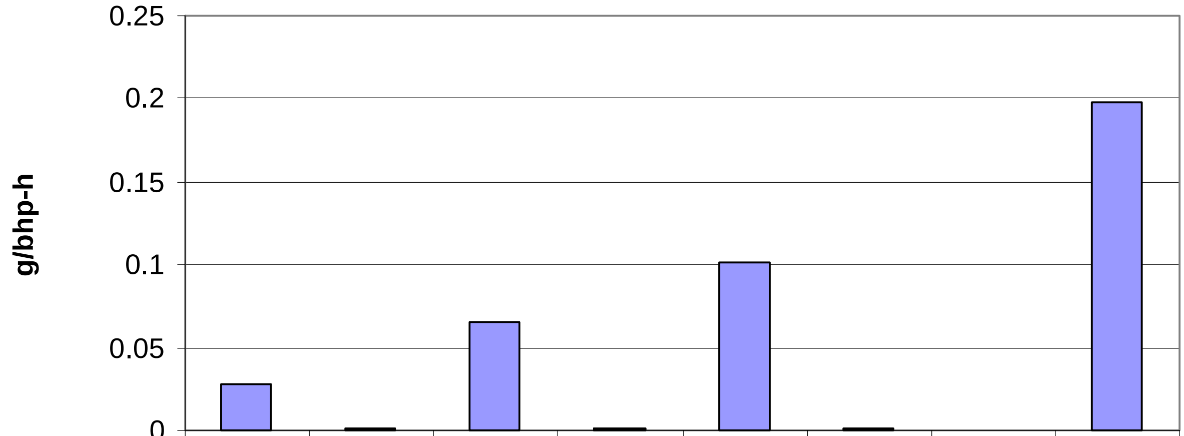
	Natural Gas Use	Steam Production	Electricity Production	Hexane: Production	Crushing Operations	Total
Total Hydrocarbons	0.11619974	0.12001802	0.1406515	0.0147413	1.84941	2.24102056
Methane	0.1154	0.119192	0.138668	9.7739E-08	0	0.3732601

Figure 124: Sources of THC and CH_4 in Soybean Crushing



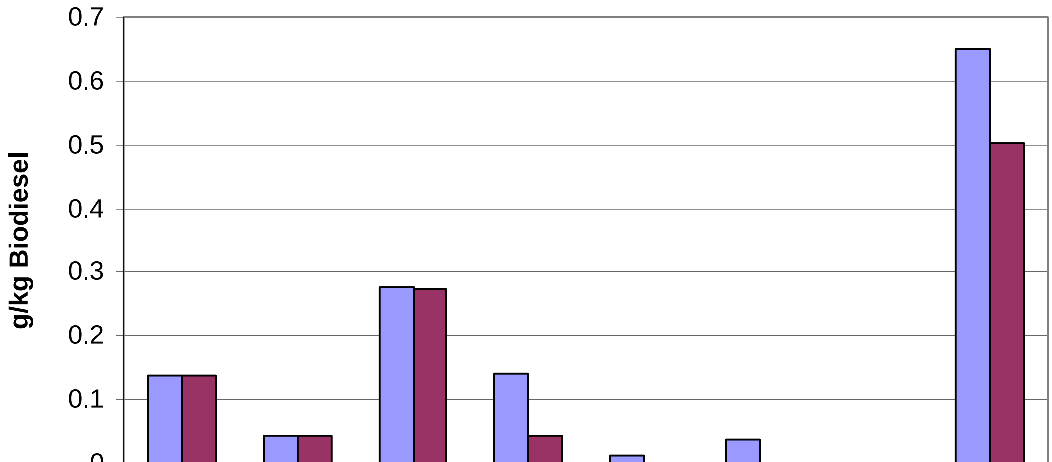
	Diesel Tractor	Gas Tractor	Gas Truck	Natural Gas Use	Propane Use	Electricity Prodn	N-Fertilizer Prodn	P-Fertilizer Prodn	K2O Fertilizer Prodn	Ag Chemicals Prodn	Soybean Ag
Total HC	0.14986311	0.07744463	0.04092051	8.4023E-05	0.004261	0.0405046	0.03242079	0.05727562	0.01698824	0.1557406	0.689277
CH4	0.0304545	0.0152945	0.00809988	3.6453E-05	0.00416533	0.0006385	0.0323383	0.0313895	0.0167681	0.0416346	0

Figure 125: Sources of THC and CH_4 in Soybean Agriculture



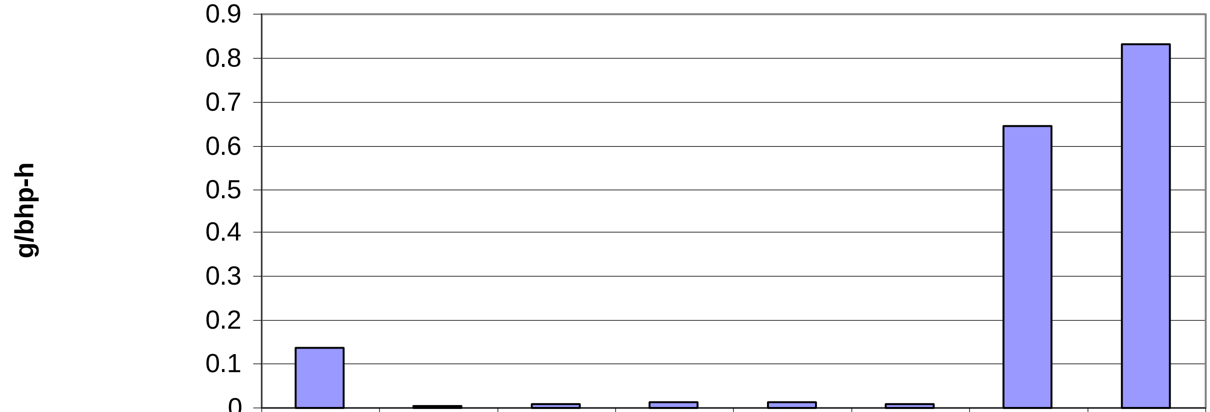
	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Biodiesel Use	Total
Methane (CH4)	0.0283374	0.00063603	0.0647652	0.00137128	0.101683	0.0008228	0	0.1976157

Figure 126: CH_4 Emissions from the Biodiesel Life Cycle



	Steam Production	Electricity Production : US	Methanol Production	Sodium Methoxide Production	Sodium Hydroxide Production	Hydrogen Chloride Production	Soybean Conversio n	Total
Total HC	0.1378628	0.0447179	0.2749598	0.1410302	0.0122119	0.0376176	0	0.6484002
CH4	0.136914	0.0440873	0.274471	0.0454863	0	0	0	0.5009586

Figure 127: Sources of CH_4 Emissions from the Biodiesel Production Step

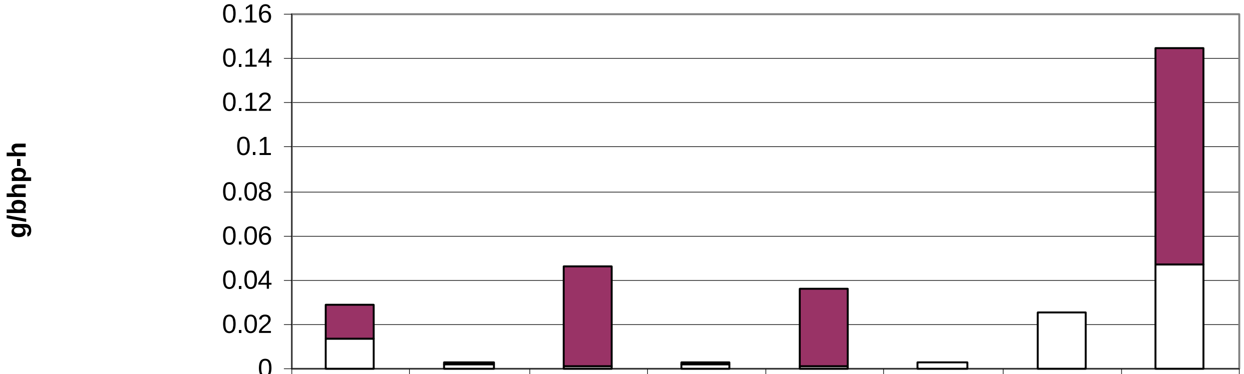


	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Biodiesel Use	Total
Carbon Monoxide (CO)	0.136856	0.0060201	0.0105397	0.012727	0.0125584	0.0077821	0.64524	0.8317233

Figure 128: CO Emissions from the Biodiesel Life Cycle

	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Total
Carbon Monoxide (CO)	0.136856	0.00602014	0.0105397	0.012727	0.0125584	0.00778207	0.18648331

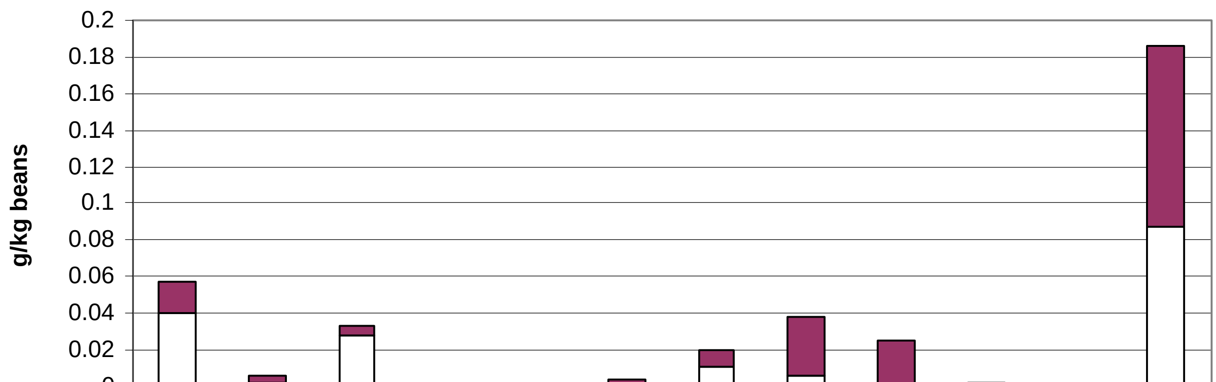
Figure 129: CO Emissions from the Biodiesel Life Cycle (Excluding End-use)



	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Biodiesel Use	Total
Particulates (unspecified)	0.0154781	0.0003793	0.0454334	0.0008063	0.0357402	0.0004914	0	0.0983287
Particulates (PM10)	0.0137127	0.0020125	0.0005918	0.0015413	0.0005685	0.0026015	0.025544	0.0465724

Figure 130: TPM Emissions from Biodiesel LCA

TPM emissions from the life cycle of biodiesel are shown in Figure 130. The bar graph shows cumulative levels for PM10 and unspecified particulates. Two-thirds of the TPM are in the unspecified category. PM10 from the end-use combustion of biodiesel represent only 18% of the total emissions. Soybean agriculture emissions are split half-and-half between PM10 and unspecified particulates. Figure 131 shows the distribution of TPM emissions from the farm. Half the particulates are from vehicle use and half are associated with the production of fertilizers used on the farm. Unspecified particulates from soybean crushing and soy oil conversion are a result of electricity and steam consumption. Of the two, electricity production introduces the bulk of the particulates. This is because steam production is modeled assuming only natural gas as the primary energy source; electricity from the grid is based on a national average mix of coal, oil, gas, nuclear, and hydroelectric sources.



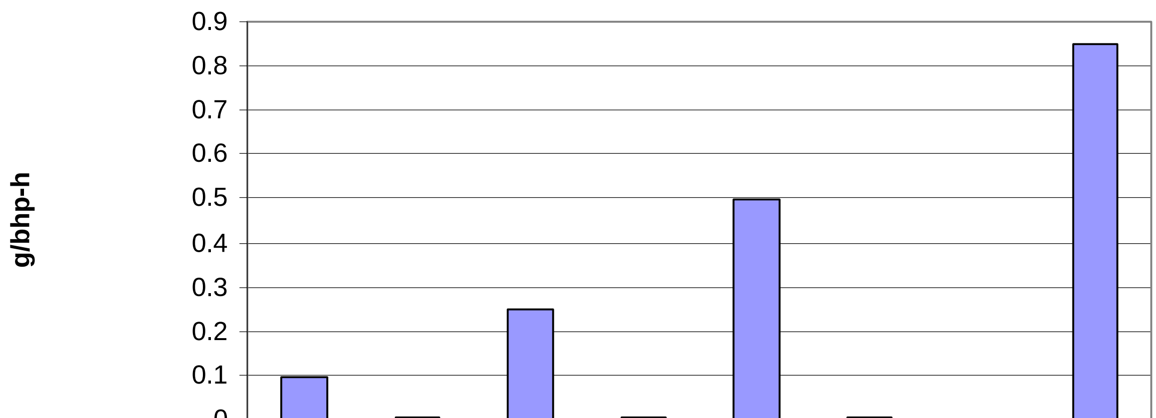
	Diesel Tractor	Gasoline Tractor	Gasoline Truck	Natural Gas Use	Propane Use	Electricity Use	N-Fertilizer Prodn	P-Fertilizer Prodn	K2O Fertilizer	Agrochem Prodn	Soybean Ag	Total
PM (Unspec)	0.017448	0.0045497	0.0045497	3.188E-09	1.533E-06	0.0036567	0.0091939	0.0318103	0.0255524	0.0020028	0	0.098765
PM10	0.0399735	0.0019474	0.0282214	9.873E-07	0.0001165	0	0.0111519	0.0060888	0	0	0	0.0875004

Figure 131: Sources of TPM in Soybean Agriculture

Figure 132 shows SO_x emissions from the life cycle for biodiesel. Soy oil conversion to biodiesel is responsible for 58% of the emissions. The large contribution of SO_x from this step is related to steam production and indirect emissions associated with methanol production. As indicated in Figure 133, the use of methanol accounts for 66% of the SO_x emissions from this step. The soybean crushing step generates SO_x through the consumption of steam, natural gas, and electricity (see Figure 134). Farming introduces SO_x primarily through consumption of diesel fuel in tractors and consumption of nitrogen fertilizer (see Figure 135).

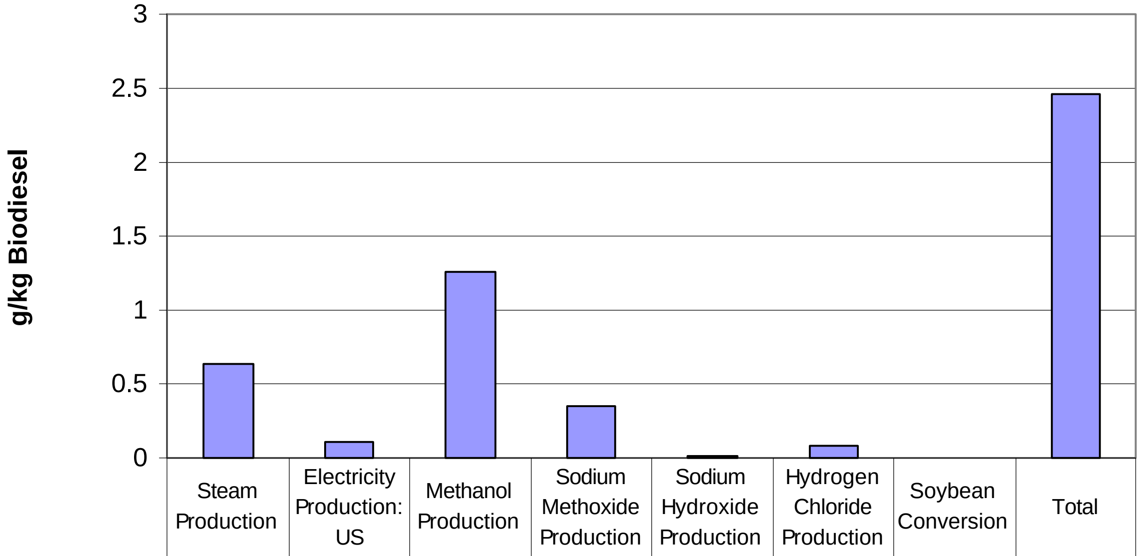
Figure 136 shows NO_x emissions for biodiesel. The life cycle emissions are dominated by emissions from end-use combustion of the fuel. This represents 92% of the total. The remaining emissions track energy consumption for each step, except the agriculture step. Emissions on the farm are disproportionately higher because of the contribution of NO_x from diesel tractor emissions.

Figure 137 and Figure 138 show emissions for HCl and HF, respectively. In the case of petroleum diesel, both of these emissions tracked precisely with electricity consumption. For biodiesel, this is not the case. HF emissions track very well with electricity. HCl emissions for soy oil conversion do not track electricity. As can be seen in Figure 139 and Figure 140, HCl emissions occur as part of sodium methoxide, sodium hydroxide, and HCl production. These emissions are not related to electricity, but are specific to the production processes for these raw materials.



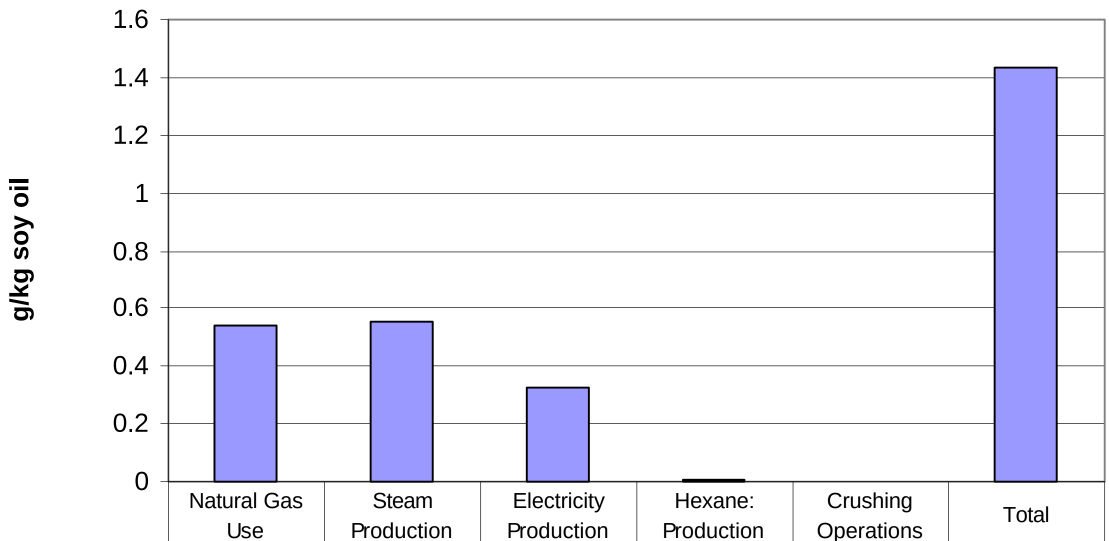
	Soybean Agricultur	Soybean Transport	Soybean Crushing	Soybean Oil	Soybean Oil	Biodiesel Transport	Biodiesel Use	Total
Sulfur Oxides (SOx)	0.0939614	0.002615	0.248258	0.0055511	0.498182	0.0033818	0	0.8519493

Figure 132: SO_x Emissions from Biodiesel Life Cycle (Reported as SO_2)



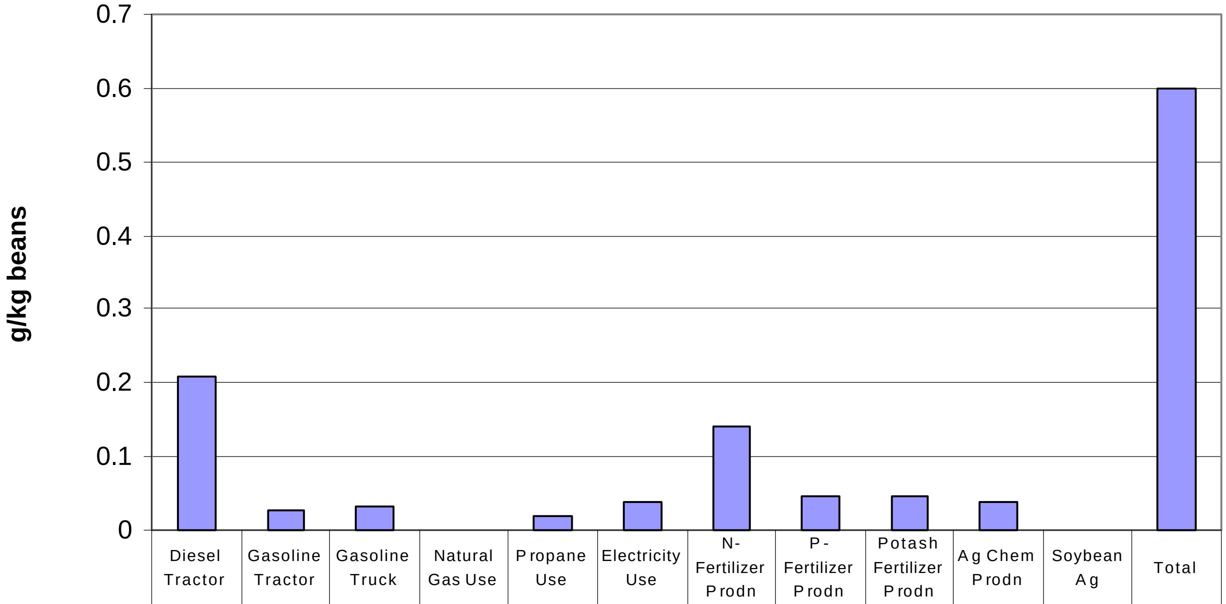
	Steam Production	Electricity Production: US	Methanol Production	Sodium Methoxide Production	Sodium Hydroxide Production	Hydrogen Chloride Production	Soybean Conversion	Total
Sulfur Oxides	0.638761	0.104258	1.26082	0.355926	0.0187876	0.0758267	0	2.4543793

Figure 133: Sources of SO_x Emissions from Soy Oil Conversion Step



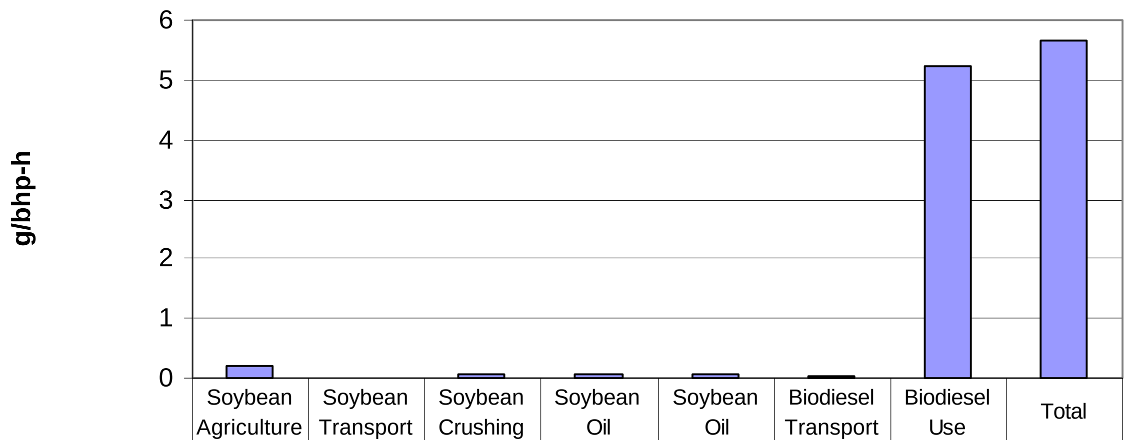
	Natural Gas Use	Steam Production	Electricity Production	Hexane: Production	Crushing Operations	Total
Sulfur Oxides	0.538386	0.556078	0.327924	0.0083909	0	1.4307789

Figure 134: Source of SO_x from Soybean Crushing



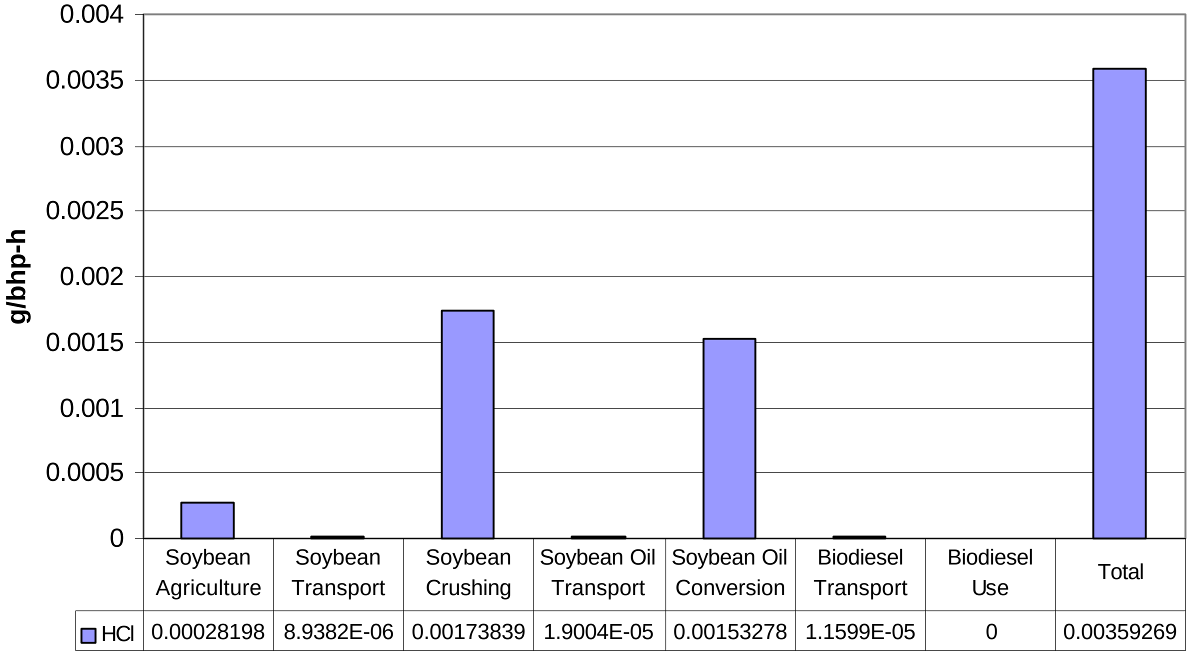
	Diesel Tractor	Gasoline Tractor	Gasoline Truck	Natural Gas Use	Propane Use	Electricity Use	N-Fertilizer Prodn	P-Fertilizer Prodn	Potash Fertilizer Prodn	Ag Chem Prodn	Soybean Ag	Total
Sulfur Oxides	0.210076	0.026763	0.031401	4.03E-05	0.0195	0.038261	0.140053	0.047131	0.047096	0.039243	0	0.599564

Figure 135: Sources of SO_x Emissions from Soybean Agriculture



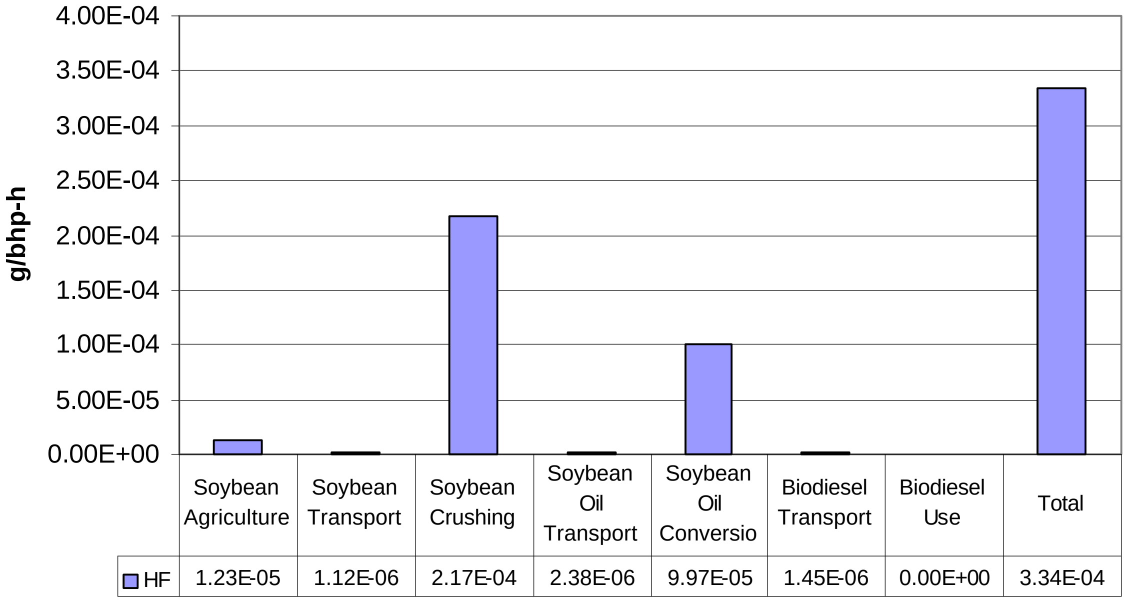
	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil	Soybean Oil	Biodiesel Transport	Biodiesel Use	Total
Nitrogen Oxides	0.201205	0.0166995	0.0651928	0.0628989	0.0829794	0.0215876	5.22672	5.6772832

Figure 136: NO_x Emissions from Biodiesel Life Cycle



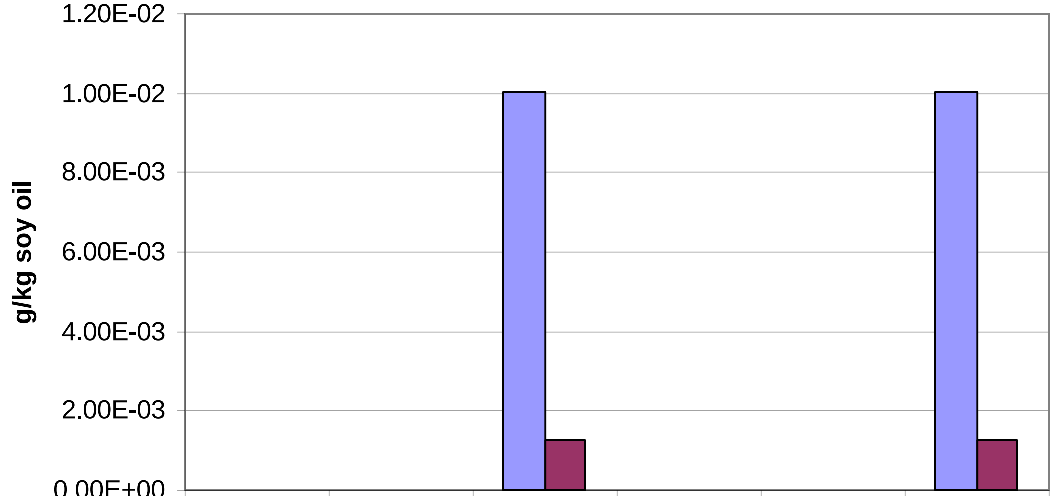
	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Biodiesel Use	Total
HCl	0.00028198	8.9382E-06	0.00173839	1.9004E-05	0.00153278	1.1599E-05	0	0.00359269

Figure 137: HCl Emissions from Biodiesel Life Cycle



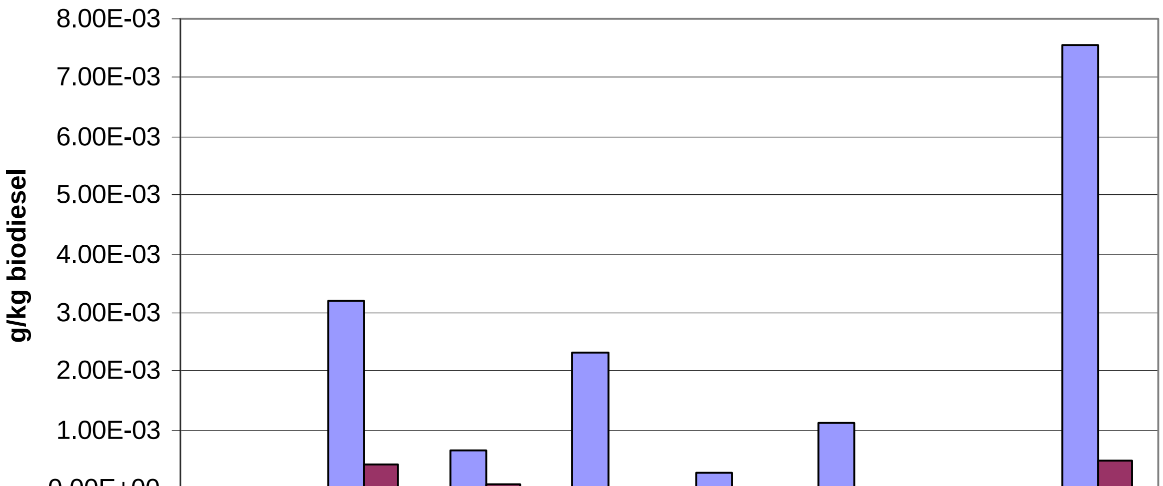
	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversio	Biodiesel Transport	Biodiesel Use	Total
HF	1.23E-05	1.12E-06	2.17E-04	2.38E-06	9.97E-05	1.45E-06	0.00E+00	3.34E-04

Figure 138: HF Emissions from Biodiesel Life Cycle



	Natural Gas Use	Steam Production	Electricity Production	Hexane: Production	Crushing Operations	Total
HCl	2.26E-08	2.34E-08	0.01002	0	0	0.01002
HF	2.83E-09	2.92E-09	0.00125	0	0	0.00125

Figure 139: Sources of HCl and HF in Soybean Crushing



	Steam Production	Electricity Production: US	Methanol Production	Sodium Methoxide Production	Sodium Hydroxide Production	Hydrogen Chloride Production	Soybean Conversion	Total
HCl	2.68E-08	0.00319	0.00064	0.00230	0.00028	0.00114	0	0.00755
HF	3.35E-09	0.00040	0.00008	1.28E-05	0	0	0	0.00049

Figure 140: Sources of HCl and HF in Soy Oil Conversion

9.1.4.3 Comparison of Life Cycle Air Emissions from Biodiesel and Petroleum Diesel

Table 131 summarizes the overall life cycle air emissions for petroleum diesel, B20, and B100. This section provides a discussion of the relative differences in emissions for these three fuels.

Table 131: Air Emissions for Petroleum Diesel, B20, and B100 (g/bhp-h)[112]

Pollutant	Petroleum Diesel	B20	B100
CH_4	0.202839	0.201795	0.197616
NO_x	0.006784	0.005887	0.002297
CO	1.26981	1.18219	0.831723
NMHC	0.131467	0.194075	0.44451
Hydrocarbons (unspecified)[113]	0.249053	0.229605	0.151814
Benzene	4.24E-05	3.43E-05	1.84E-06
Formaldehyde	0.000568	0.000459	2.48E-05
PM10	0.084094	0.076589	0.046572
Particulates (Unspecified)	0.130281	0.123891	0.098329
SO_x	0.926335	0.911458	0.851949
NO_x	5.00856	5.1423	5.67728
HCl	0.003164	0.00325	0.003593
HF	0.000396	0.000383	0.000334
NH_3	3.15E-08	0.014694	0.073471

Figure 141 displays THC emissions for these three systems. B100 increases THC emissions by 36%. The effect of blending is linear. Thus, increases in HCs for B20 are around 7%. The THC include CH_4. Figure 142 shows that CH_4 emissions for B100 and B20 actually drop slightly (2.56% and 0.5%, respectively). All the CH_4 savings occur in the fuel production and distribution steps. The largest contributor to CH_4 emissions in the biodiesel life cycle is the production of methanol required in the transesterification. Thus, another opportunity for reducing emissions is to substitute current methanol technology with a renewable process that does not start with natural gas as a feedstock. Likewise, substituting ethanol for methanol would reduce this source of CH_4 emissions. The effect of using ethanol or renewable methanol is not clear, however. A better understanding of life cycle flows for these alcohols

[112] Note that THC (not listed in the table) is the sum of benzene, formaldehyde, hydrocarbons (unspecified), NMHC (Non Methane Hydrocarbons), and CH_4. Similarly, data we report in other parts of this study for TPM (total particulate matter) represent the sum of PM10 and Particulates (unspecified). This latter category represents data in which the type of particulates measured was not specified.

[113] Unspecified hydrocarbons are *not* the sum of NMHC and CH_4. This is because the unspecified category of emissions is ambiguous. We do not know if original data sources were referring to total hydrocarbons or NMHC. This ambiguity is a common problem in life cycle analysis because of the need to use data collected across a wide range of sources.

is needed. Furthermore, ethanol has other effects on the conversion technology for biodiesel that would have to be assessed.

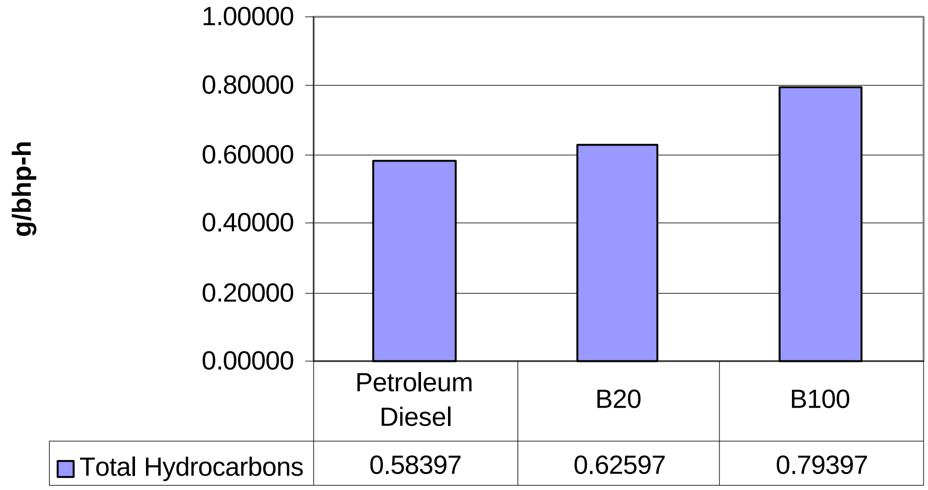


Figure 141: Life Cycle Emissions of THC for Petroleum Diesel, B20, and B100

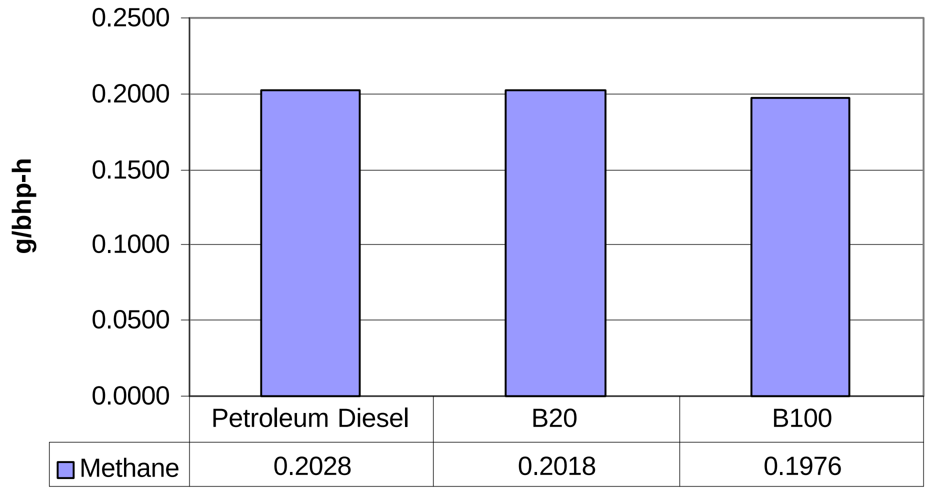


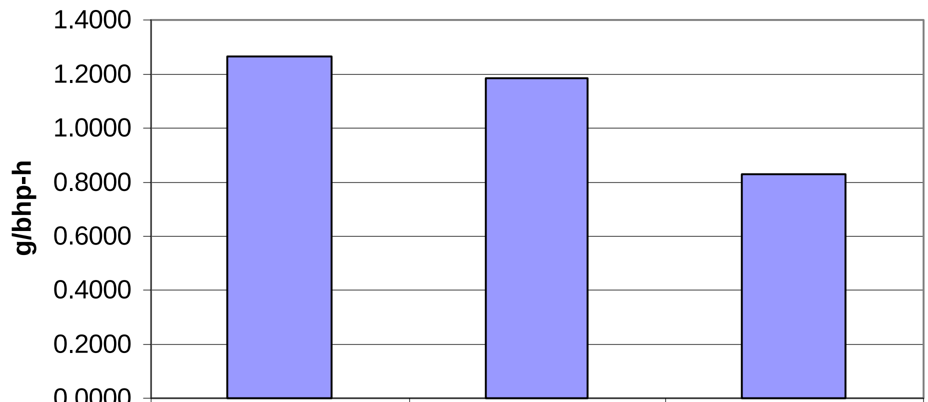
Figure 142: Life Cycle Emissions of CH_4 for Petroleum Diesel, B20, and B100

CO emissions for petroleum diesel, B20, and B100 show dramatic differences in life cycle emissions (see Figure 143). B100 has 34.5% lower emissions of CO on a life cycle basis. Because tailpipe emissions dominate both petroleum and biodiesel life cycles, the reductions in CO that occur at the end-use step are key factors in establishing life cycle emissions.

Interpreting the results of the TPM emissions inventories is complicated by the nature of the data collected. As indicated in the previous two sections, TPM data have been reported as PM10 (particulate matter of 10 microns or less) and unspecified particulates. The most prudent way to compare these inventories is on the basis of TPM, which is the sum of both these types of PM. All three measures of TPM are shown in Figure 144. TPM drop 32.41% for B100 compared to petroleum diesel. Reductions in

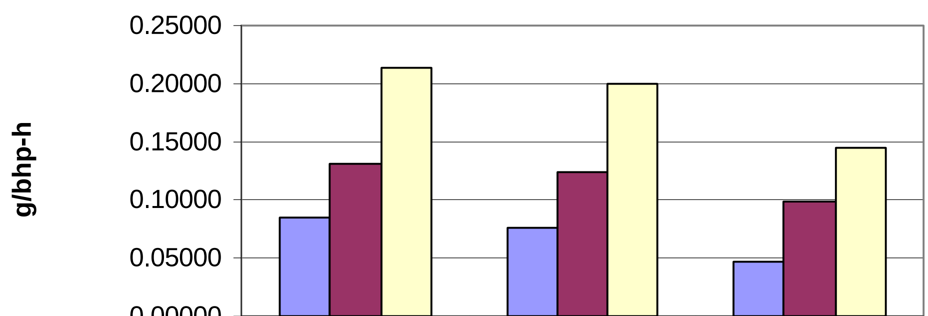
PM10 look better. B100 provides a 44.6% reduction in PM10, though this result is ambiguous because of the lack of consistent data on PM10 throughout the life cycles of both petroleum diesel and biodiesel.

Figure 145 compares SO_x emissions for petroleum diesel and biodiesel blends. Even though biodiesel completely eliminates SO_x emissions from the tailpipe, its impact on life cycle emissions is not that great. B100 reduces SO_x emissions by 8.03% compared to petroleum diesel. There are two reasons for this. First, the relative contribution of SO_x emissions from the tailpipe in the petroleum life cycle is small (see Figure 118). Second, SO_x emissions in the fuel production and distribution steps for all these fuels very much depend on process energy consumption. Biodiesel and petroleum diesel have very similar process energy demands; thus, they exhibit relatively similar levels of SO_x emissions.



	Petroleum Diesel	B20	B100
CO	1.2698	1.1822	0.8317

Figure 143: Life Cycle Emissions of CO for Petroleum Diesel, B20, and B100



	Petroleum Diesel	B20	B100
PM10	0.08409	0.07659	0.04657
PM (Unspec)	0.13028	0.12389	0.09833
Total PM	0.21437	0.20048	0.14490

Figure 144: Life Cycle Particulate Matter Emissions for Petroleum Diesel, B20, and B100

NO_x emissions for all three fuels are presented in Figure 146. As discussed previously, biodiesel increases NO_x emissions in diesel engines[114] unless adjustments are made to the engine, such as retarding of engine timing. Research is already underway to understand what causes NO_x to increase when biodiesel is used and to develop changes to the fuel to eliminate this problem. The results of this study underscore the importance of this kind of research for biodiesel. Our engine combustion model predicts a 8.89% increase in NO_x at the tailpipe when B100 is used, but the life cycle emissions for this fuel increase by 13.35%. The increased level of NO_x emissions for the life cycle versus the tailpipe emissions is caused by diesel fuel use in the agriculture step. Blending biodiesel with petroleum diesel mitigates NO_x emissions. B20 has life cycle emissions of NO_x that are 2.67% higher than petroleum diesel.

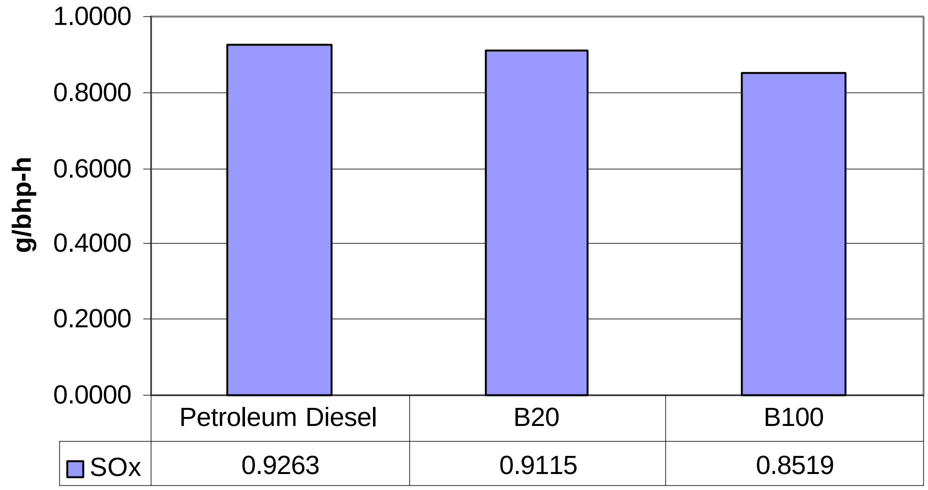


Figure 145: Life Cycle SO_x Emissions for Petroleum Diesel, B20, and B100

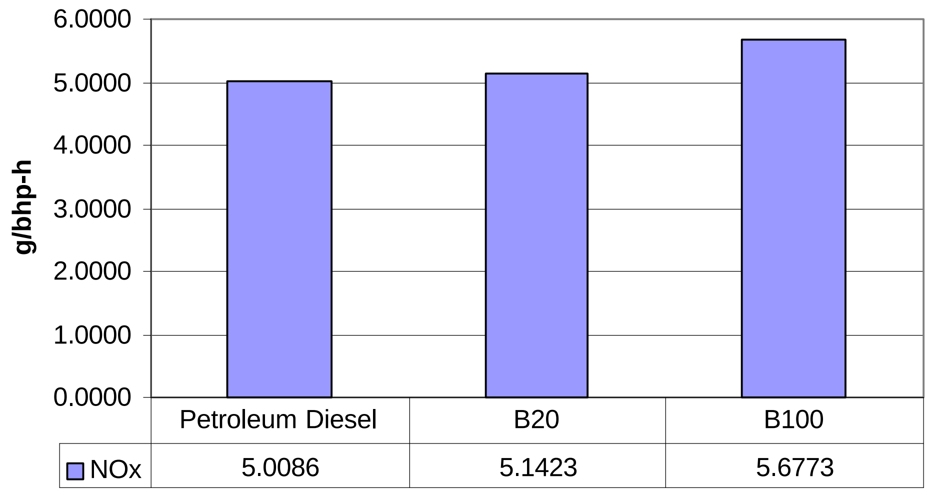


Figure 146: Life Cycle NO_x Emissions for Petroleum Diesel, B20, and B100

[114] This affect appears to be smaller based on testing with newer engines. If most new engines demonstrate the same trend , life cycle NOx emissions for biodiesel may approach those of petroleum diesel.

Figure 147 shows life cycle emissions of HF for petroleum diesel, B20, and B100. Biodiesel reduces HF emissions; by 15.5% for B100 and 3.1% for B20. HF emissions correlate strongly with electricity consumption. The reduced emissions result from a reduction in electricity usage compared to petroleum diesel.

Figure 148 shows HCl emissions for petroleum diesel and the two biodiesel fuels. Biodiesel has 13.54% higher emissions of HCl on a life cycle basis than petroleum diesel. In the case of petroleum, HCl emissions correlated with electricity consumption, but biodiesel's emissions did not. The use of sodium methoxide, sodium hydroxide, and HCl increases emissions for biodiesel above those normally associated with power generation.

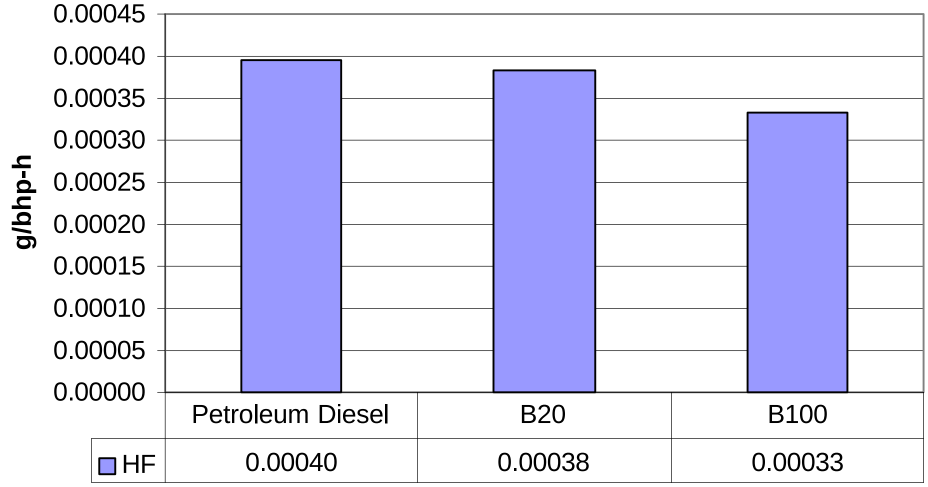


Figure 147: Life Cycle HF Emissions for Petroleum Diesel, B20, and B100

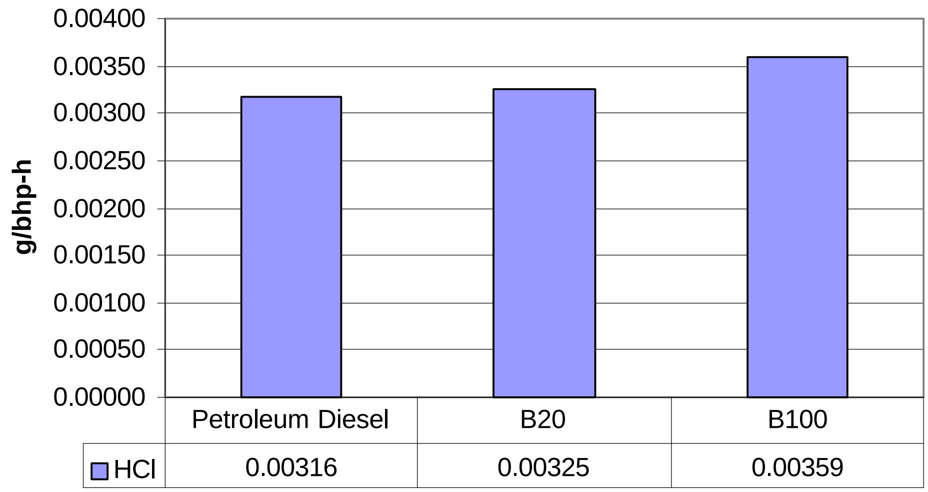


Figure 148: Life Cycle HCl Emissions for Petroleum Diesel, B20, and B100

9.1.4.4 Potential Effects of Biodiesel as a Diesel Substitute on Life Cycle Air Emissions

One way to summarize the comparison of biodiesel and petroleum diesel life cycle air emissions is to consider the relative change in life cycle emissions for each of the two biodiesel fuels, B20 and B100, using petroleum diesel as a baseline. These changes are shown in Table 132, Figure 149, and Figure 150.

The plots in Figure 149 and Figure 150 demonstrate that all the trends for life cycle emissions predicted by the LCI model are linear functions of biodiesel blend rate. This should be the case, because the emissions were modeled independently for each fuel, and no interacting effects associated with blending of the fuels was assumed. The most important assumption in this regard is for air emissions. The engine emission tests analyzed for this study support the assumption of linearity (see section 6.1.3 on tailpipe emissions for biodiesel and diesel fuel).

Table 132: Relative Change in Life Cycle Air Emissions for Fuels Containing 20% and 100% Biodiesel

Pollutant	B20	B100
CO	-6.90%	-34.50%
PM	-6.48%	-32.41%
HF	-3.10%	-15.51%
SOx	-1.61%	-8.03%
CH_4	-0.51%	-2.57%
NOx	2.67%	13.35%
HCl	2.71%	13.54%
HC	7.19%	35.96%

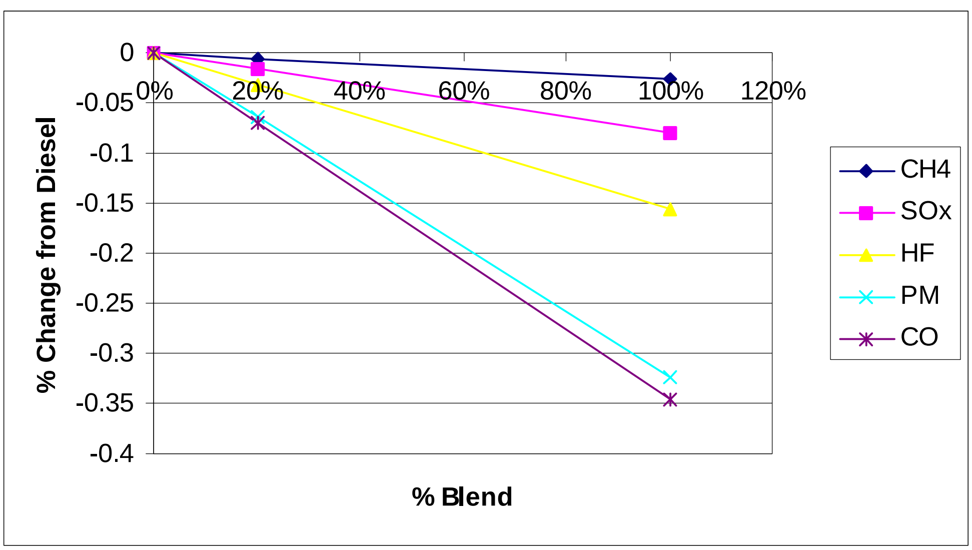


Figure 149: Effect of Biodiesel Blend on Life Cycle Air Emissions of CH_4, SO_x, HF, PM10, and CO

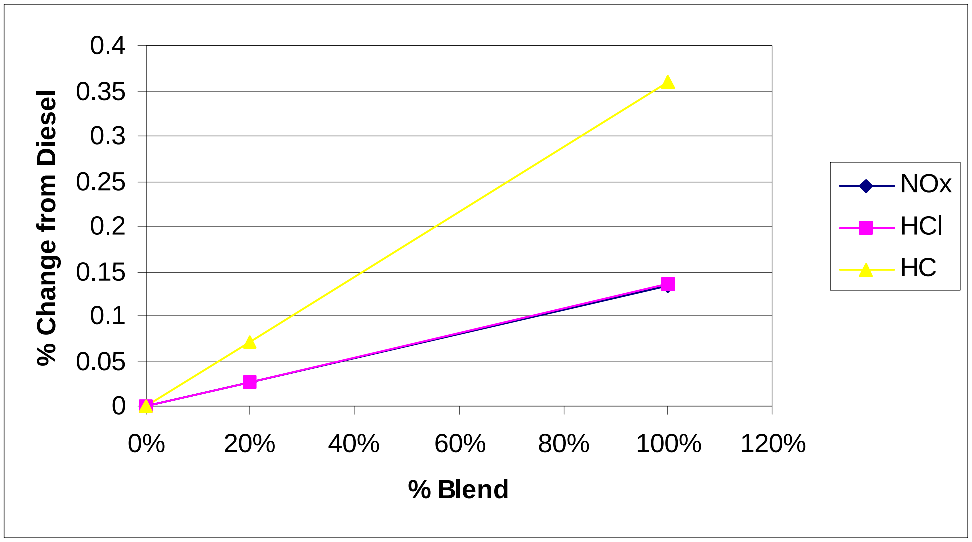


Figure 150: Effect of Biodiesel Blend Level on Air Emissions of NO_x, NMHC and HCl

The largest difference in air emissions for the two life cycles is for CO. Reductions in CO reach 34.5% when using B100. In terms of total emissions from diesel fuels, CO is also the second largest of all the air emissions on a mass basis. CO is a major target of EPA air quality standards because of its inherent health-related impacts in urban areas. It also plays a role in smog formation. Biodiesel could, therefore, be an effective tool for mitigating CO in EPA's designated CO non-attainment areas[115].

The next largest difference in air emissions for the two life cycles is for TPM. B100 exhibits life cycle emissions of TPM that are 32.41% lower than those of petroleum diesel. This improvement is a direct result of reductions in PM10 at the tailpipe of the bus. PM10 emitted from mobile sources is also a major EPA target because of its role in respiratory disease. Urban areas represent the greatest risk in terms of numbers of people exposed and level of PM10 present. Use of biodiesel in urban buses is potentially a viable option for controlling the emissions of PM10.[116]

On a life cycle basis, B100 increases life cycle THC emissions substantially, compared to petroleum diesel. The major cause of this increase is the release of hexane at the soybean crushing facility. It is important to keep in mind that tailpipe emissions of THC are lower for biodiesel-fueled buses than those for petroleum diesel-fueled buses. Where localized effects such as ground level ozone formation are concerned, biodiesel may prove to be beneficial because of its ability to reduce THC emissions that may contribute to smog in urban areas. Our results point out the need for research and development on soybean processing to look for ways to reduce or eliminate the emissions of hexane.

Life cycle emissions of CH_4 emissions are slightly lower for biodiesel, compared to petroleum diesel. All these emissions occur in the fuel production and utilization steps. As indicated in Figure 149 and Table 132, B100 has life cycle emissions of CH_4 that are 2.56% lower than those of petroleum diesel. CH_4 has

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[115] These are urban areas in the U.S. identified as not currently meeting National Ambient Air Quality Standards for levels of CO.

[116] Among the options under consideration by EPA are regulations that would control levels of PM2.5, as opposed to PM10. PM2.5 includes particles of 2.5 microns or less in diameter. That is, EPA is focusing its attention on the very smallest particles in ambient air. Data collected in this study focus on PM10. While our results bode well for lowering levels of PM10, no information is available on the effect of biodiesel on this new class of smaller particles.

long been recognized as a greenhouse gas, with much greater greenhouse gas potential than CO_2. Thus, even though the relative reductions of CH_4 are small, the benefits of biodiesel's impact on greenhouse gas effects could be substantial[117].

Perhaps the next most critical pollutant from the perspective of human health and environmental quality is NO_x. The triumvirate of CO, THC, and NO_x is the key to controlling smog in urban areas. The relative importance of each of these precursors is not at all clear, because they interact in a complex set of chemical reactions catalyzed by sunlight.[118] When biodiesel is used as a substitute for petroleum diesel, it effectively reduces tailpipe emissions of two of the three smog precursors (CO and THC). However, it increases NOx emissions. B100 exhibits 13.35% higher emissions of NO_x than petroleum diesel on a life cycle basis, mostly due to increases of NO_x that occur at the tailpipe. It is almost an aphorism in the engine industry that PM10 and NO_x emissions are two sides of a technology trade-off. Biodiesel seems to fit this observation. Dealing with this trade-off involves a combination of fuel research and engine technology research. With these two degrees of freedom, solutions are potentially achievable that meet the tougher future standards for NO_x without sacrificing the other benefits of this fuel.

Life cycle emissions of SO_x are reduced by only 8% when B100 is used as a diesel fuel substitute. This is a relatively low reduction given that biodiesel completely eliminates SO_x at the tailpipe. The amount of SO_x in the emissions from a diesel engine is a function of sulfur content in the fuel. With this in mind, EPA regulates sulfur content in diesel fuel, rather than regulating the tailpipe emissions. The latest requirements for diesel fuel include 0.05 wt% sulfur for on-highway fuel. Biodiesel can eliminate SO_x emissions because it is sulfur-free.

HCl and HF are emitted in very low levels as a part of the life cycles of both petroleum diesel. Both occur as a result of coal combustion in electric power generation. HF levels drop with biodiesel in proportion to the amount of electricity consumed over the life cycle of the fuel. This amounts to 15.51% reductions for B100. HCl emissions, on the other hand, increase with biodiesel blend. Biodiesel has additional sources of HCl associated with the production and use of inorganic acids and bases used in the conversion step. B100 increases emissions of HCl by 13.54%.

9.1.4.5 Tailpipe Emissions for Petroleum Diesel and Biodiesel

Unlike CO_2 emissions, the air pollutants from diesel engines that are regulated by EPA tend to have more localized effects. Effects of CO, THC, NO_x, and TPM (particularly PM10) are acutely important in localized urban areas. Therefore, it is important to understand emission levels at the engine tailpipe as well as on a life cycle basis. Furthermore, as the previous discussion illustrates, life cycle emissions of the regulated air pollutants are substantially different from what is seen at the tailpipe. With these points in mind, we present in this section a discussion centered on a comparison of the tailpipe emissions from biodiesel and petroleum diesel. We contrast life cycle and tailpipe emissions for each pollutant, with some indication of the relative importance of one versus the other. The tailpipe emissions presented here are based entirely on the extensive review of engine performance and engine emissions data for petroleum diesel and biodiesel, as presented in the section on urban bus operations.

Table 133 summarizes typical diesel exhaust emissions for 1994 bus engines. These emissions were used as a baseline for modeling diesel engine emissions for petroleum diesel and biodiesel. The emissions of

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[117] While methane is a more potent greenhouse gas, its half-life in the atmosphere is less than that of carbon dioxide. These complications in understanding the impact of each pollutant illustrate why we have avoided making quantitative judgements about the life cycle impacts of biodiesel. We leave it to others to evaluate the comparative inventories of biodiesel and diesel in terms of their positive and negative impacts.

[118] For an excellent discussion of the complexities of urban air pollution, see Seinfeld, John H., "Urban Air Pollution: State of the Science" in *Science, Vol 243,* pp 745-752.

NMHC, PM10, CO and NO_x are actually monitored by EPA on a normalized basis of 1 bhp-h of delivered work (the same functional basis used in the LCI for this study). The SO_x emission shown in this table is based on diesel engine performance for current low-sulfur diesel as designated for on-highway use.

Table 133: Baseline Diesel Engine Emissions for Low-Sulfur Petroleum Diesel[119]

Air Pollutant	g/bhp-h
CO	1.1
NMHC (Hydrocarbons except methane)	0.1
PM10)	0.08
SO_x	0.17
NO_x	4.8

In this study, bus engines were assumed to be calibrated to the 1994 engine emissions listed in Table 133. Changes in performance for the engines when operated on biodiesel were predicted using generalized correlations of engine emissions data to predict relative changes for a given engine. The results of the LCI model should only be used to evaluate comparative performance of diesel engines operating petroleum diesel and biodiesel. Emission results presented here should not be used to judge absolute performance of engines operating on these fuels against EPA regulations, because they do not reflect emission levels of specific engines.

Tailpipe emissions for these regulated pollutants are shown in Figure 151 and Figure 152 for petroleum diesel, B20, and B100. Biodiesel's greatest impacts are, in order of importance, on SO_x, PM10, NMHC, and CO emissions.

SO_x emissions are completely eliminated when neat biodiesel is used because biodiesel is sulfur free. By contrast, the life cycle reductions of SO_x for B100 are only 8%. B20 provides a 20% reduction in sulfur. B100 and B20 reduce tailpipe emissions of PM10 by 68% and 13.6%, respectively. NMHC is reduced by 36.70% when B100 is used, and by 7.3% when B20 is used. CO emissions from the tailpipe drop by 46.23% and 9.3%, respectively, when B100 and B20 are used. Biodiesel's effects on CO, NMHC, and PM10 are due to the fact that this fuel contains molecular oxygen, and thus improves overall combustion.

Biodiesel actually causes an increase in NO_x emissions. B100 has tailpipe emissions that are 8.89% higher than those of petroleum diesel. At the lower level of biodiesel in B20, this effect is reduced to about 2%. Changes in engine timing can effect a trade-off between TPM and NO_x emissions on current engines. Smaller changes in NO_x emissions for B100 and B20 have been observed in current research programs on new engine models, but it is still to early to predict whether all or just a few future engines will display this characteristic.

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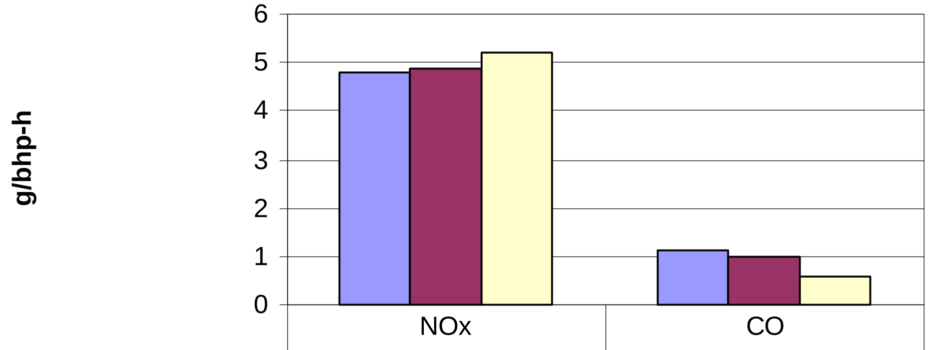
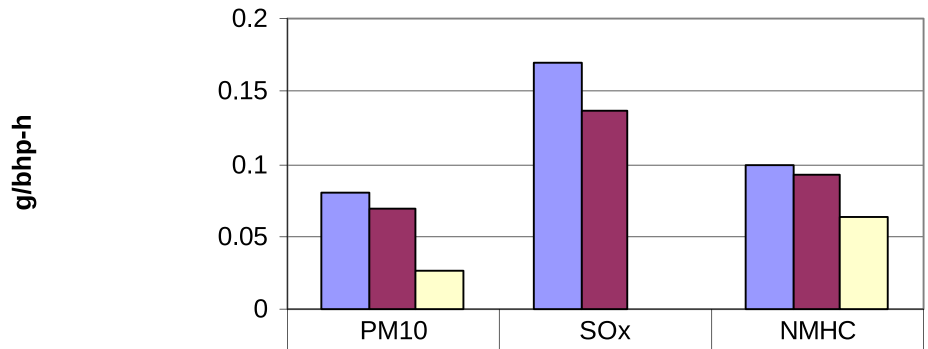
[119] CO, NO_x, NMHC and PM10 emissions are based on 1994 calibration data from the U.S. Environmental Protection Agency's report *1994 Summary Report: Diesel Heavy Duty Engines*. August 24, 1994. Downloaded from the EPA Office of Mobile Sources website at www.epa.gov/omswww/gopher. SO_x is based on emissions from engines using .05 wt% sulfur diesel fuel.



	NOx	CO
Petroleum Diesel	4.8	1.1
B20	4.885344	0.998294
B100	5.22672	0.59147

Figure 151: Tailpipe Emissions of CO and NO_x for Petroleum Diesel and Biodiesel



	PM10	SOx	NMHC
Petroleum Diesel	0.08	0.17	0.1
B20	0.0691088	0.136	0.092654
B100	0.025544	0	0.06327

Figure 152: Tailpipe Emissions of PM10, NMHC and SO_x for Petroleum Diesel and Biodiesel

Not only does biodiesel reduce the total level of particulates emitted at the tailpipe of a diesel engine, but it also changes the character of the particulates emitted. As discussed in the section on urban bus operations, PM10 consists of a soot fraction and a VOF. The soot, which is carbon produced by pyrolysis reactions during combustion, drops dramatically as biodiesel is added to the fuel blend. Figure 153 shows the emissions of soot for petroleum diesel, B20, and B100. Biodiesel has a greater impact on soot. B100 emits 83.6% less soot than petroleum diesel. B20 reduces soot by 22%. Although the environmental impacts of reducing soot versus TPM are not clear[120], there is an aesthetic benefit associated with

[120] Mauderly, in a recent paper from Lovelace Laboratories, a leading research firm in health effects of diesel and biodiesel particulate matter, provides a theory and data that claim soot leads to cancerous growths in mice populations. The effect on human populations is under debate.

significantly less visible smoke observed from the tailpipe. For urban bus operators, this translates to improved public relations.

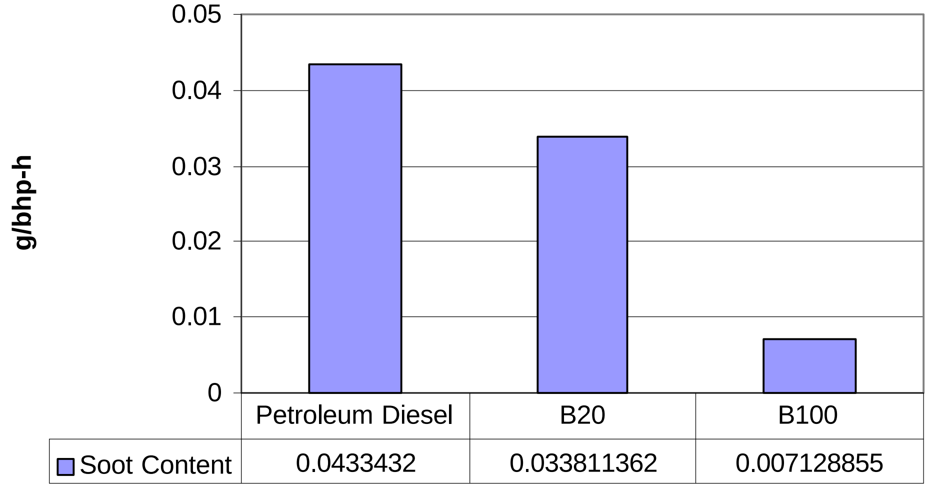
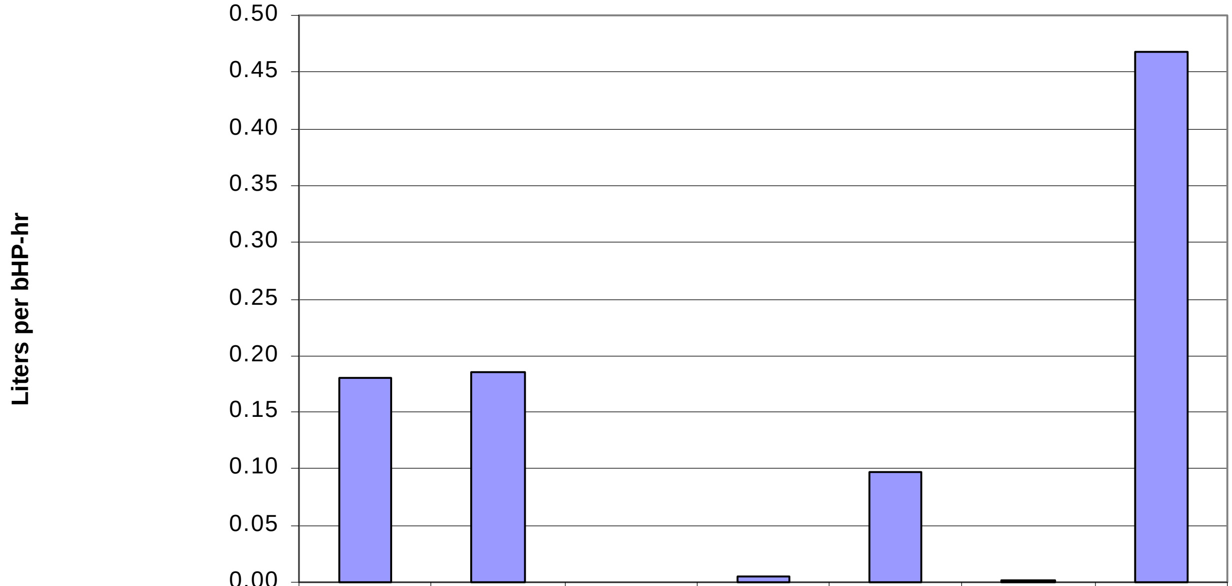


Figure 153: Effect of Biodiesel on Tailpipe Emissions of Soot

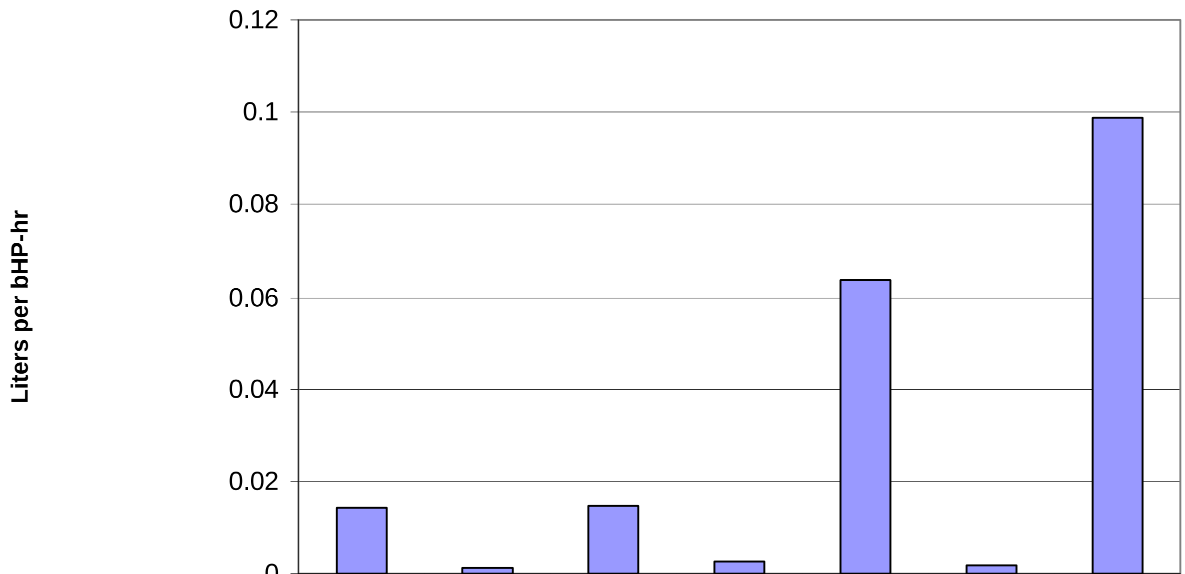
9.1.5 Life Cycle Emissions of Water Effluents

We tracked a number of waterborne effluents through the life cycles for petroleum diesel and biodiesel such as BOD and COD. Specific data are presented for each part of the life cycles in the previous sections. However, relatively few data were consistently available. Therefore, the comparisons of the two life cycles are limited to total flow of wastewater. Figure 154 summarizes wastewater flows associated with petroleum diesel. Foreign and domestic crude oil extraction account for 78% of the total wastewater flow. Only about 12% is associated with the refinery. Figure 155 shows the distribution of wastewater flows for the biodiesel life cycle. Two-thirds of the total wastewater flows in the life cycle for biodiesel come from the soy oil conversion process. This step in the life cycle generates relatively dilute wastewater containing oil and soap from the processing of the soybean oil. A comparison of total wastewater flows from the life cycles for petroleum diesel and biodiesel is shown in Figure 13. Petroleum diesel generates roughly five times as much wastewater flow as biodiesel.



	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Total
Water (chemically polluted)	0.179857	0.184834	0.000483816	0.00444363	0.0975913	0.00148017	0.468689916

Figure 154: Wastewater Flows for Petroleum Diesel Life Cycle



	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soy Oil Transport	Soy Oil Conversion	Biodiesel Transport	Total
Water (chemically polluted)	0.0145117	0.00133698	0.0147419	0.00280892	0.0638697	0.00170794	0.09897714

Figure 155: Wastewater Flows for Biodiesel Life Cycle

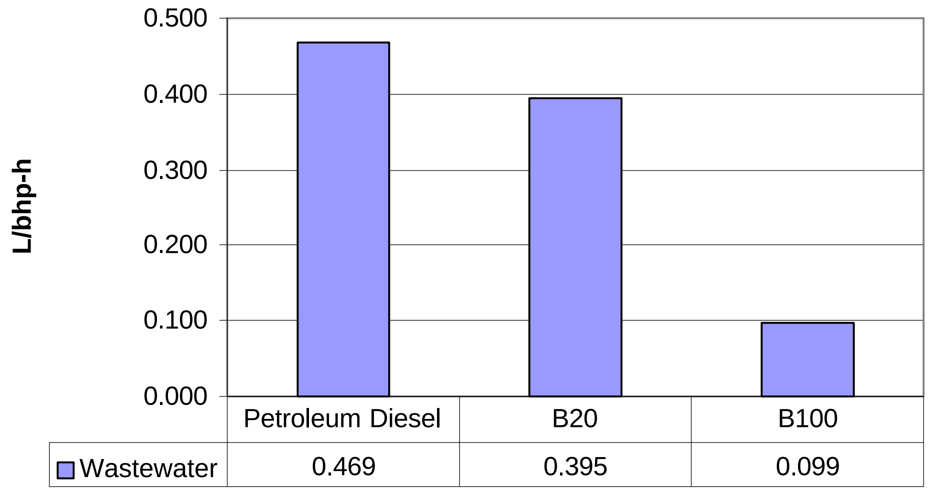
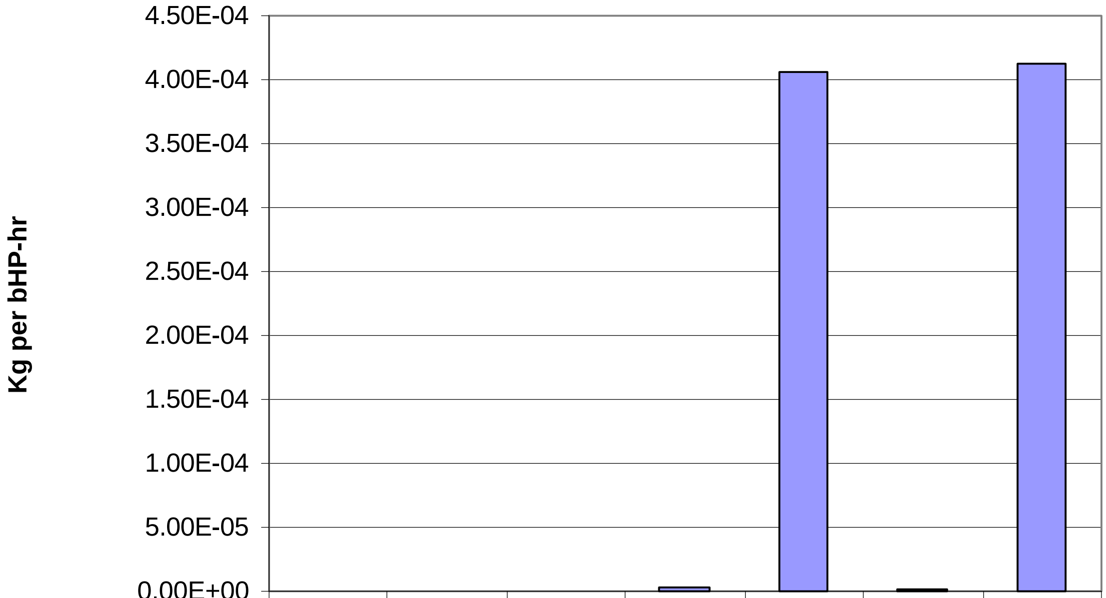


Figure 156: Comparison of Life Cycle Wastewater Flows for Petroleum Diesel and Biodiesel Life Cycles

9.1.6 Life Cycle Flows of Solid Waste

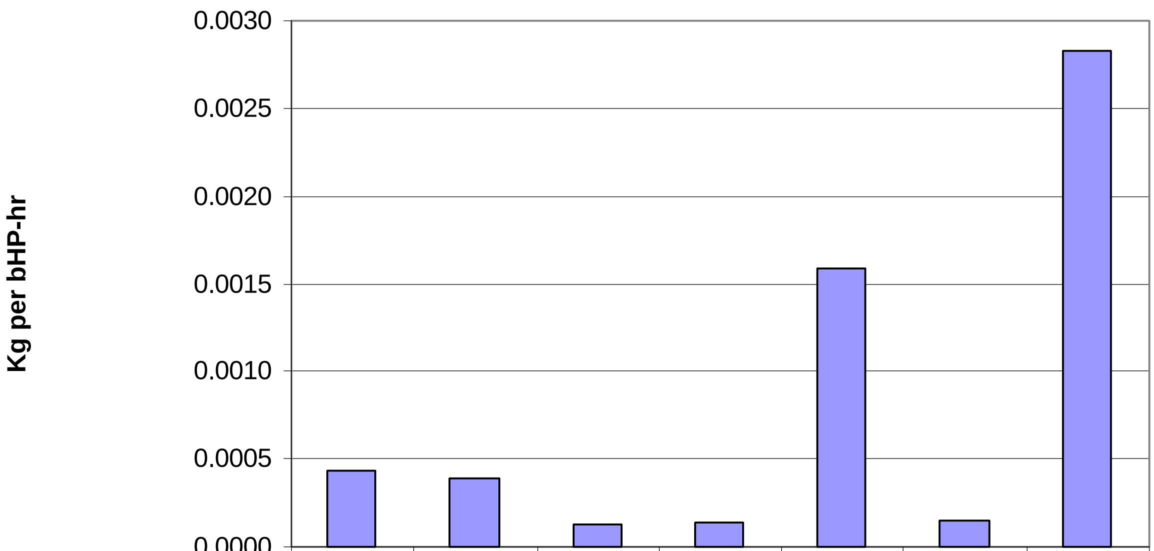
Solid waste from the two life cycles is classified as hazardous or nonhazardous. Figure 157 shows the life cycle contributions to solid waste for petroleum diesel. Hazardous waste is derived almost entirely from the crude oil refining process. The minor levels of solid waste that show up in foreign crude transport and diesel fuel transport are indirect flows of solid waste attributable to diesel fuel consumption in the transportation process. Total hazardous waste generation amounts to 0.41 g/bhp-h of engine work. Nonhazardous waste flows are shown in Figure 158. Just over half of the non-hazardous waste is generated in the crude oil refining step. Another one-third is generated in the foreign and domestic crude oil extraction steps. Total nonhazardous waste generation is 2.8 g/bhp-h.

Figure 159 presents data on hazardous waste generation from the biodiesel life cycle. Hazardous waste amounts to only 0.018 g/bhp-h of engine work. Surprisingly, the most significant source of this hazardous waste is farming. Soybean agriculture produces 70% of the hazardous waste from the entire life cycle. An inspection of the sources of hazardous waste from farming (as shown in Figure 161) reveals that these flows are indirect charges against agriculture for hazardous waste flows associated with the production of diesel and gasoline used on the farm. Likewise, the remaining hazardous waste in the life cycle for biodiesel stems from fuel use for transport of materials. Nonhazardous solid waste from the biodiesel life cycle is summarized in Figure 160. Biodiesel generates 6.1 grams of nonhazardous waste per brake horsepower-hour of engine work. Figure 162 and Figure 163 compare hazardous and nonhazardous solid waste generation for petroleum diesel and biodiesel. B100 reduces hazardous waste by 96% compared to petroleum diesel. Nonhazardous waste, on the other hand, is twice as high for B100. Given the more severe impact of hazardous versus nonhazardous waste disposal, this is a reasonable trade-off.



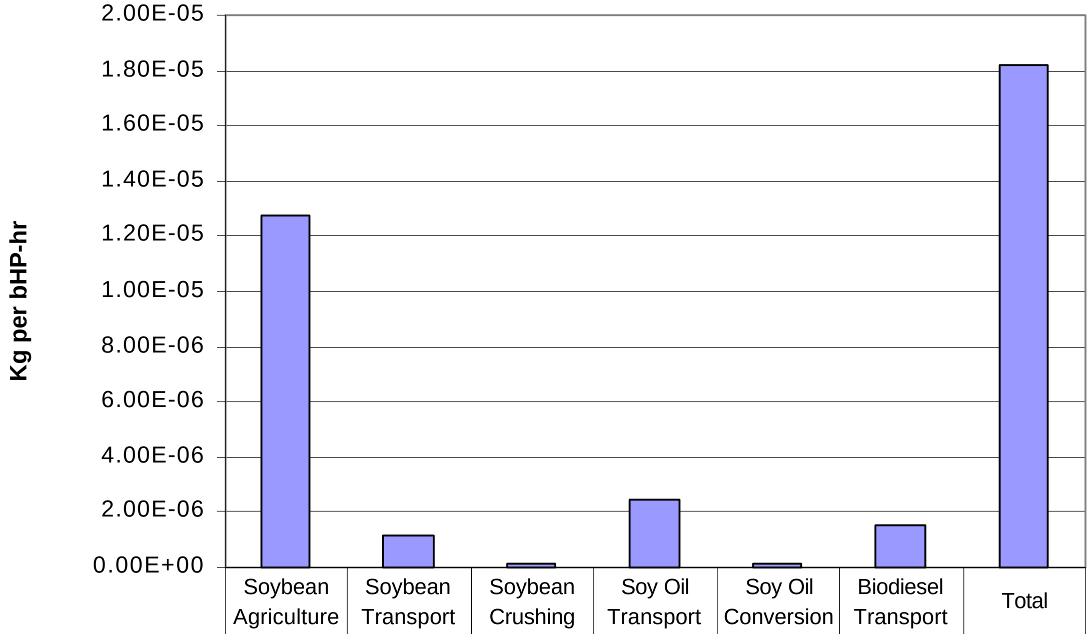
	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Total
Waste (hazardous)	5.02E-08	4.39E-08	4.18E-07	3.90E-06	0.0004068	1.29E-06	0.0004125

Figure 157: Life Cycle Emissions of Solid Hazardous Waste for Petroleum Diesel



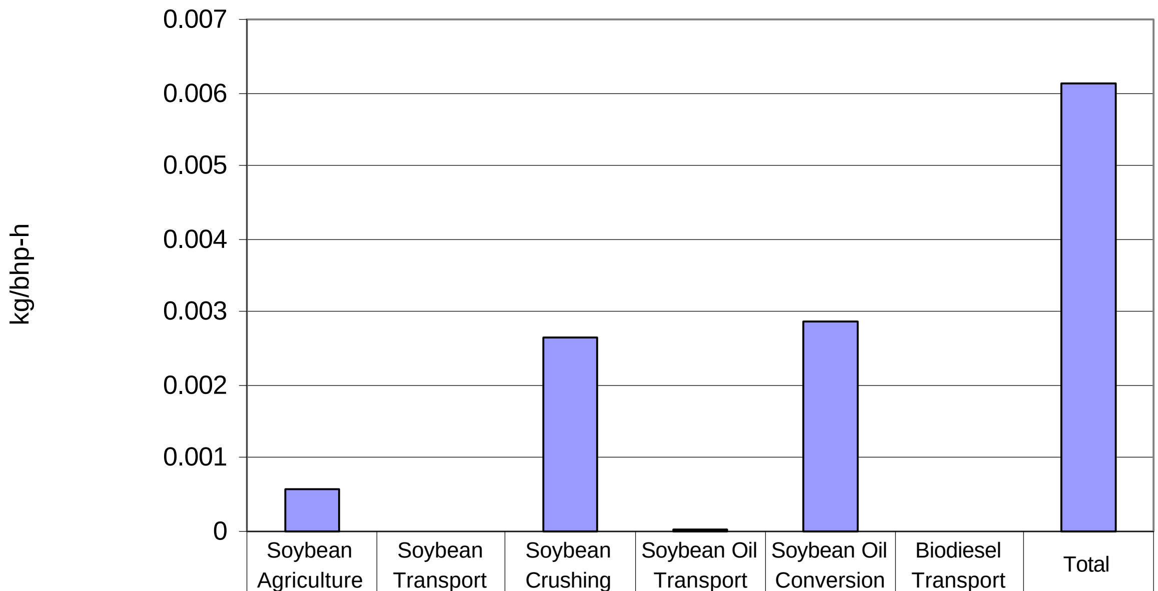
	Domestic Crude Oil Production	Foreign Crude Oil Production	Domestic Crude Transport	Foreign Crude Transport	Crude Oil Refining	Diesel Fuel Transport	Total
Waste (non-hazardous)	0.0004373	0.00038301	0.00012282	0.00014245	0.00158823	0.00015042	0.00282423

Figure 158: Life Cycle Flows of Nonhazardous Waste for Petroleum Diesel



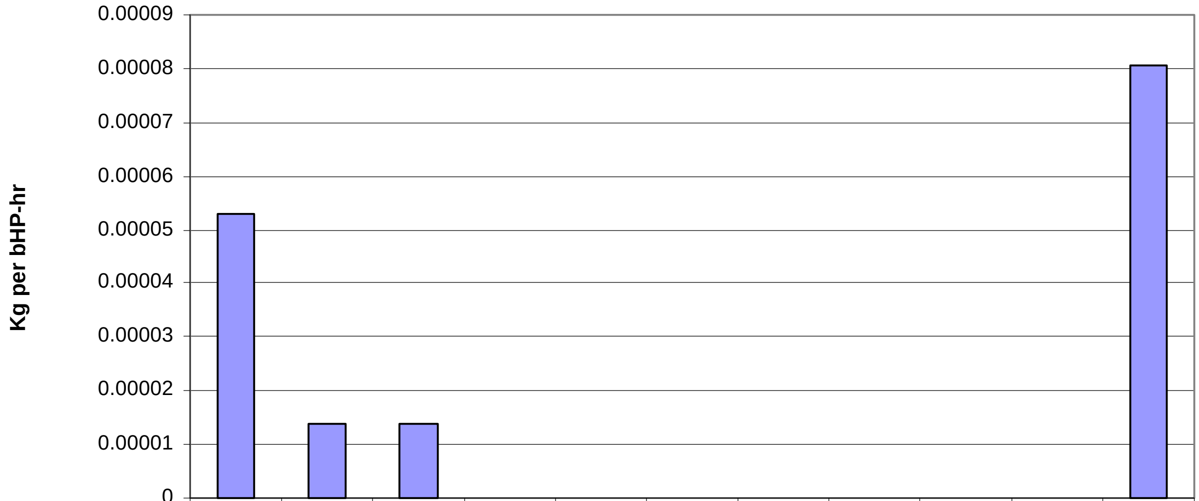
	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soy Oil Transport	Soy Oil Conversion	Biodiesel Transport	Total
Waste (hazardous)	1.28E-05	1.18E-06	1.35E-07	2.47E-06	1.55E-07	1.50E-06	1.8215E-05

Figure 159: Life Cycle Flows of Hazardous Solid Waste for Biodiesel



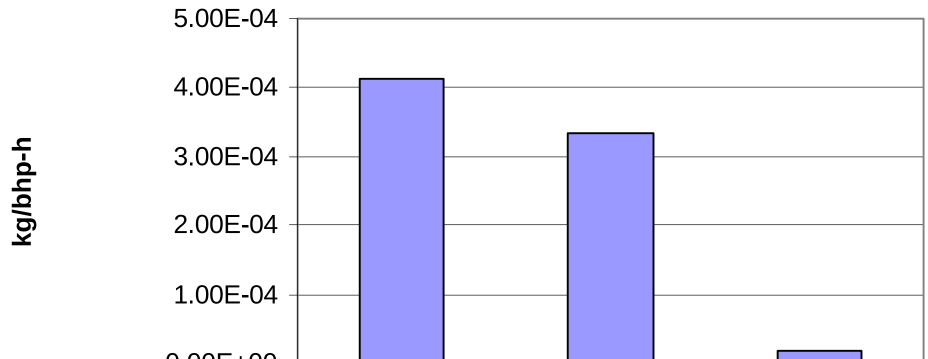
	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil Transport	Soybean Oil Conversion	Biodiesel Transport	Total
Nonhazardous Waste	0.00057695	7.974E-06	0.00264791	1.6953E-05	0.00286706	1.0338E-05	0.00612718

Figure 160: Life Cycle Flows of Nonhazardous Solid Waste for Biodiesel



	Diesel Tractor	Gasoline Tractor	Gasoline Truck	Natural Gas Use	Propane Use	Electricity Use	N-Fertilizer	P-Fertilizer	Potash	Agrochem	Total
Waste (hazardous)	5.294E-05	1.38E-05	1.38E-05	6.811E-15	3.275E-12	0	0	0	0	0	8.054E-05

Figure 161: Sources of Hazardous Waste in Soybean Agriculture



	Petroleum Diesel	B20	B100
Hazardous Waste	4.13E-04	3.34E-04	1.82E-05

Figure 162: Hazardous Waste Generation for Petroleum Diesel, B20, and B100 Life Cycles

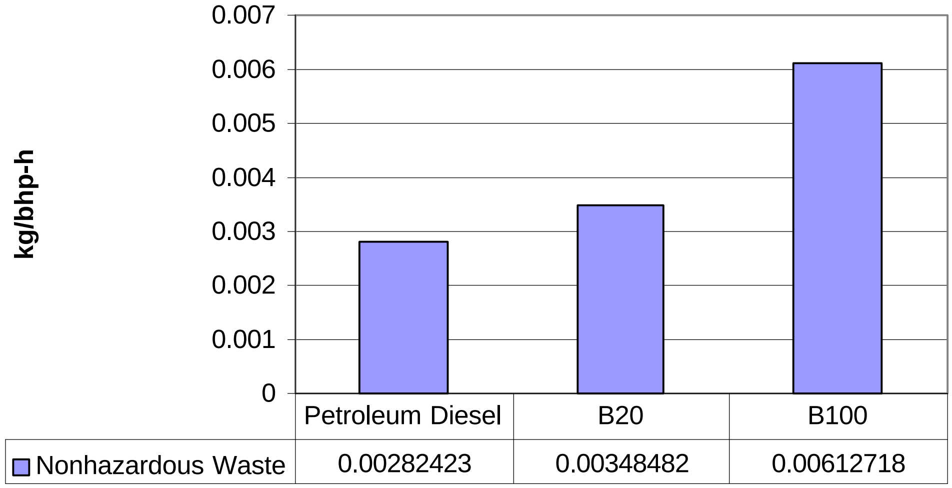


Figure 163: Nonhazardous Waste Generation for Petroleum Diesel, B20, and B100 Life Cycles

9.2 Sensitivity Studies

The purpose of conducting sensitivity studies on the life cycle of biodiesel is to establish the potential range for improvement in the fuel, and to establish the range of possible error associated with the assumptions made in the model. The LCI assumes a "current" time frame—that is, we are looking at existing agriculture, conversion technology, and engine technology within a short-term horizon. This sets realistic limitations on the bounds of the assumptions used in the model. In each step in the life cycle, we have considered where the potential for near-term improvements is.

In agriculture, there is certainly the possibility of genetic engineering designed to improve the per acre yield of oil in soybeans. The potential for such improvements is probably outside the time frame of this study, especially because any such changes in the soybean will be carefully considered against the risk of reducing meal productivity. Meal is the primary product from soybeans, and any alterations that switch the product mix from beans toward oil may not be desirable to the economics of the crop. In looking at the range of potential improvements in agriculture, we therefore limited ourselves to the range of possible efficiencies in soybean farming today in the United States. We chose to study the effect of producing and selling biodiesel in an optimal soybean-growing region. We selected a scenario in which Chicago is the target market for fuel sales to urban bus operators. This puts the marketplace close to one of the most efficient soybean-growing regions in the United States

Soybean crushing operations are based on well-established technology. Our model for soybean crushing is based on detailed operating information on a current soybean processor. Our results compare well with other published data on material and energy balances for this type facility. We did not consider any scenarios for improving the soybean crushing process. Future efforts in evaluating the life cycle of biodiesel production should look at this part of the life cycle. Alternatives to current hexane-based technology exist. These alternatives, as well as strategies for controlling hexane emissions from existing plants, should be explored since hexane emissions represent the bulk of the life cycle THC emissions.

Biodiesel conversion technology is also quite old. The commercial facility used in the LCI model is more than 40 years old. The technology developments for transesterification of soybean oil date back to the early part of this century. At first glance, it would appear that there is little potential variation for this part of the biodiesel life cycle. This turns out not to be the case. The recent interest in transesterification technology for biodiesel production has spurred a great deal of technology development in the past 15 years. Much of this activity has occurred in Europe, where new biodiesel production facilities have come on line in great numbers[121]. Therefore, we decided that this area warranted further evaluation because if the industry expands, we assume investors and developers will choose to use the most efficient technologies available compared to the older technology currently in place in the United States.

Like biodiesel production technology, diesel engine technology has gone through rapid change in the past decade, driven for the most part by the demand for improved emissions. We nevertheless chose not to evaluate this area. A great deal of new information is soon to be available on the performance of new engines designed to meet stricter standards for PM10 and NO_x. Rather than try to predict where this technology is going, and what its impact on biodiesel might be, we simply state here that new engines are being tested that may solve the problem of increased NO_x emissions, as identified in this study.

9.2.1 The Effect of an Enhanced Location for Biodiesel Production and Use

As indicated in the previous section, we studied the effect of placing biodiesel production and use in an ideal location, in lieu of the assumed national average conditions used in the base case inventory. To that end, we chose to model biodiesel production and use in the Chicago area. This location provides a good outlet for biodiesel sales for the urban bus end-use we modeled. More importantly, it allows us to consider near-term access to some of the best soybean farmland in the United States. This scenario reduces the distances required to move beans, oil, and biodiesel, and allows us to take advantage of high-yield soybean agriculture.

Basic changes to the model are shown in Table 134. The reduced distance for shipping of soybean oil is based on an evaluation of the location of crushing facilities to potential market locations. The results of the model with these assumptions is presented for B100, with the understanding that the improvements or worsening in life cycle emissions relative to petroleum diesel are proportional to the blend level.

Table 134: Model Parameters for the Chicago Area Biodiesel Scenario

Model Parameter	Baseline Scenario	Chicago Area Scenario
Soybean Agriculture	Yields and inputs based on national average (14 key soybean-producing states)	Yields and inputs based on production of soybeans from Illinois and Iowa. 50% of soybean supply is taken from each state.
Transport distances	National average distance for soy oil of 571 miles	Reduced distance of travel of 248 miles.

Changes in resource demands for this scenario are summarized in Table 135. Highlights of these results are presented immediately following this table. Placing biodiesel production and use in the Chicago area has positive benefits on energy consumption (see Figure 16). Impacts on natural gas and coal consumption are minor (2% and 4% savings, respectively). Petroleum consumption, on the other hand, drops by 24% from the national average base case. This leads to a slight increase in life cycle energy efficiency from the base case value of 81.5% to 82.7%. Biodiesel's fossil energy ratio increases from 3.216 to 3.430. The energy savings occur primarily on the farm. Figure 165 shows that process energy requirements for farming drops by 24%. Energy savings of 57% are also realized in the soy oil transport step; but this impact is smaller because of the relatively small contribution to energy demand made by this step. Water use drops dramatically in the Chicago area scenario. Biodiesel consumes 31% less water in this scenario.

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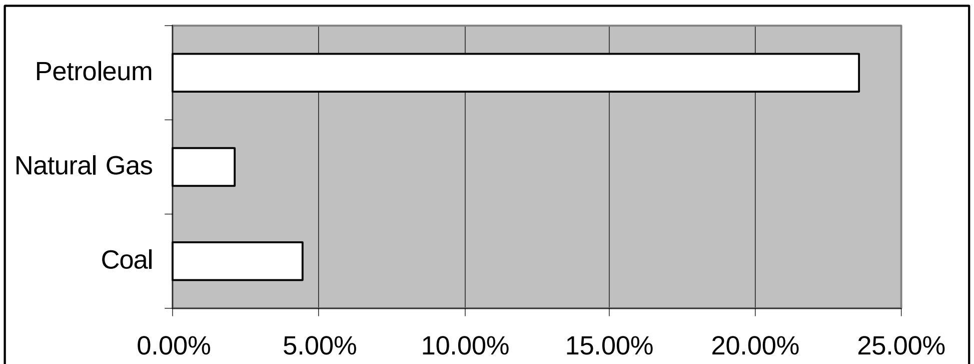
[121] As early as 1993, capacity in Europe for biodiesel production had reached levels of 376,000 metric tons per year (*Chemical Engineering*, February 1993.

Table 135: Chicago Scenario Life Cycle Resource Demands for Biodiesel (kg/bhp-h)

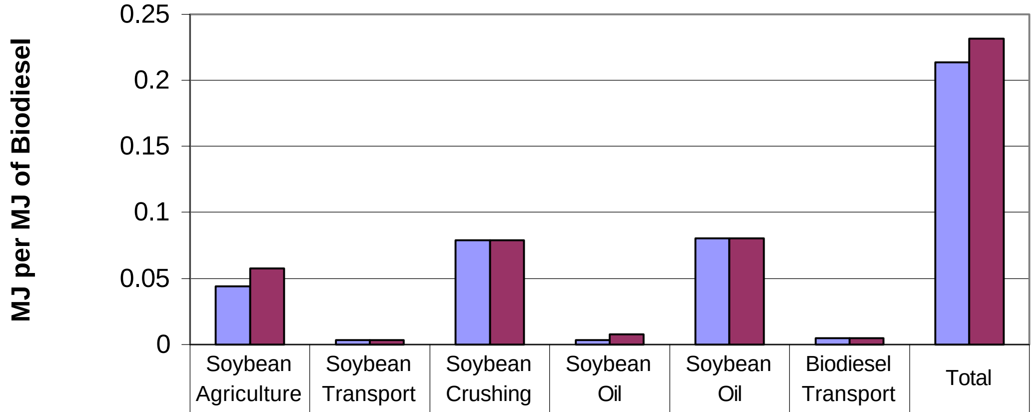
Primary Resources	Petroleum Diesel	Biodiesel Base Case	Biodiesel Chicago
Coal (in ground)	0.00589	0.007028	0.006716
Limestone ($CaCO_3$, in ground)	0.00112	0.001140	0.001139
Natural Gas (in ground)	0.01620	0.030748	0.030095
Oil (in ground)	0.18894	0.010112	0.007733
Perlite (SiO_2, ore)	4.30E-05	1.87E-06	1.34E-06
Phosphate Rock (in ground)	0	0.009397	0.011447
Potash (K_2O, in ground)	0	0.004417	0.004931
Sodium Chloride (NaCl)	0	0.003499	0.003499
Uranium (U, ore)	1.41E-07	1.87E-07	1.78E-07
Water Used (total)	0.02629	86.3636	59.8778



	Coal	Natural Gas	Petroleum
%	4.45%	2.13%	23.53%

Figure 164: The Effect of an Ideal Location for Biodiesel on Life Cycle Consumption of Primary Energy Resources

Air emissions for the Chicago area scenario are summarized in Table 136. The percent reductions of key pollutants are tabulated in Figure 166. The largest saving is for ammonia, which drops by 42%. The drop of 10% in PM10 emissions is consistent with the reductions in petroleum consumption associated with diesel fuel use on the farm. The Chicago scenario provides additional savings of 7% in CO_2 emissions. All other emissions savings are less than 4%.



	Soybean Agriculture	Soybean Transport	Soybean Crushing	Soybean Oil	Soybean Oil	Biodiesel Transport	Total
Chicago	0.043849	0.00338895	0.07937191	0.00312948	0.08007733	0.00438132	0.21419799
Base Case	0.057347	0.00338895	0.07937191	0.00720475	0.08007733	0.00438132	0.23177125

Figure 165: Sources of Energy Savings in the Chicago Area Biodiesel Scenario

Table 136: Life Cycle Air Emissons for Chicago Area Biodiesel Scenario

Air Pollutant	Petroleum Diesel	Biodiesel Base Case	Biodiesel Chicago	% Change from Biodiesel Baseline
Ammonia (NH_3)	3.15E-08	0.07347	0.04243	-42%
Benzene	4.24E-05	1.84E-06	1.32E-06	-28%
Carbon Dioxide (CO_2)	633.275	136.447	126.892	-7%
Carbon Monoxide (CO)	1.2698	0.831723	0.7883	-5%
Formaldehyde	0.000568	2.48E-05	1.79E-05	-28%
Hydrocarbons (except CH_4)	0.1315	0.44451	0.4306	-3%
Hydrocarbons (unspecified)	0.249053	0.15181	0.13698	-10%
Hydrogen Chloride (HCl)	0.003164	0.00359	0.00359	0%
Hydrogen Fluoride (HF)	0.0003955	0.000334	0.000329	-1%
Methane (CH_4)	0.2028	0.197616	0.19265	-3%
Nitrogen Oxides (NO_x as NO_2)	5.00856	5.67728	5.58294	-2%
Particulates (PM10)	0.0841	0.04657	0.0421258	-10%
Particulates (unspecified)	0.1303	0.09833	0.0970565	-1%
Sulfur Oxides (SO_x as SO_2)	0.9263	0.851949	0.821351	-4%

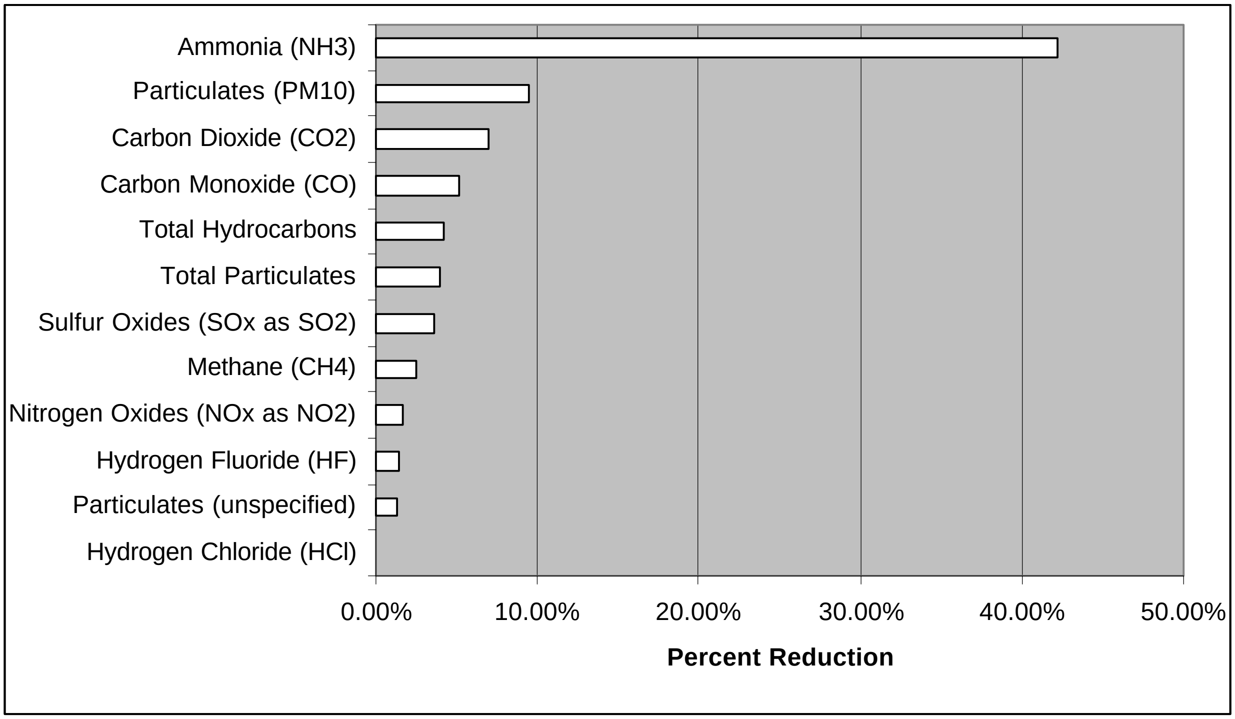


Figure 166 : Reductions in Life Cycle Air Emissions for the Chicago Area Biodiesel Scenario

Wastewater and solid waste emissions for the Chicago area scenario are presented in Table 137. Reductions in life cycle waste emissions are shown in Figure 167. Hazardous waste emissions are reduced dramatically. The 28% reduction corresponds to reductions in diesel fuel use in the farming of soybeans. Wastewater and nonhazardous solid waste reductions are 5.79% and 2.72% respectively.

Table 137: Life Cycle Water and Solid Emissions for the Chicago Area Biodiesel Scenario

Emission	Petroleum Diesel	Biodiesel Baseline	Biodiesel Chicago	% Change from Biodiesel Baseline
Solid Waste (hazardous)	0.000412523	1.82E-05	1.32E-05	27.70%
Solid Waste (nonhazardous)	0.00282423	0.00612718	0.00596055	2.72%
Wastewater	0.46869	0.0989614	0.0932325	5.79%

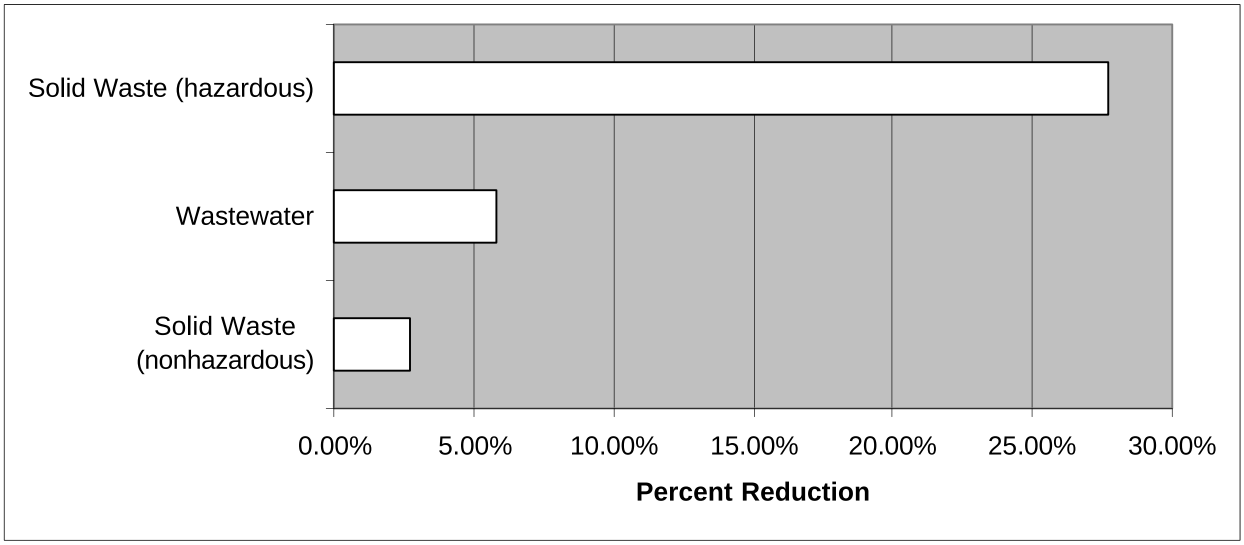


Figure 167: Water and Solid Waste Emissions Reductions for the Chicago Area Biodiesel Scenario

9.2.2 The Effect of Energy Requirements for Conversion of Soybean Oil to Biodiesel

A range of energy inputs for the conversion of soybean oil to biodiesel were used in the LCI model to test the effects of these modeling assumptions on the overall LCI of biodiesel. A survey of commercial technology for biodiesel reveals that there is high degree of variation on reported steam and electricity requirements for the transesterification process. High and low estimates for both steam and electricity used in the model are indicated in Table 138.

Table 138: Range of Energy Inputs for Soybean Oil Conversion Tested in LCI Model

Energy Use	Low Value	Baseline Scenario	High Value
Steam (kcal/metric ton of biodiesel produced)	95,022.7	329,793.5	617,922.2
Electricity (kWh/metric ton of biodiesel produced	9.0	28.9	40.0

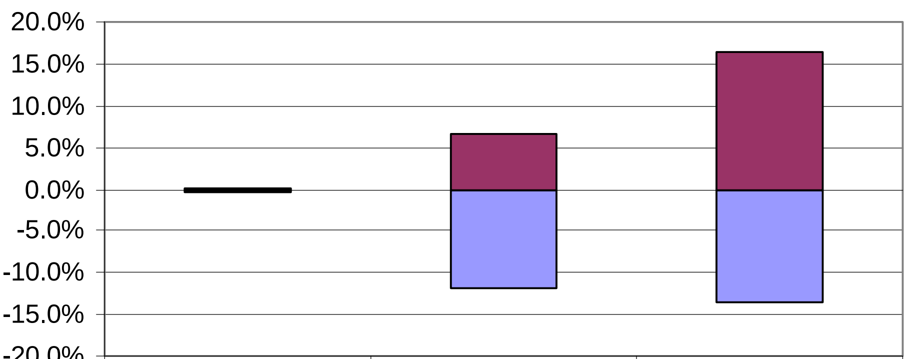
Steam requirements vary 3.5-fold from the lowest to the highest value. Electricity varies 4.4-fold. This high degree of variability warrants testing the range of these assumptions in our model to assess the uncertainty of our overall results related to this assumption. Furthermore, energy inputs for soybean oil conversion are a substantial part of the life cycle, making this variability even more important.

Resource requirements for petroleum diesel and the three cases for conversion energy inputs are presented in Table 139.

Table 139: The Effect of Soy Oil Conversion Energy Demands on Life Cycle Consumption of Raw Materials

Primary Resources	Petroleum Diesel	B100 High Energy Conversion	Biodiesel Base Case	B100 Low Conversion Energy
Coal (in ground)	0.005893	0.007488	0.007028	0.006203
Limestone ($CaCO_3$, in ground)	0.001118	0.001228	0.001140	0.000983
Natural Gas (in ground)	0.016195	0.035795	0.030748	0.026587
Oil (in ground)	0.188939	0.010128	0.010112	0.010084
Perlite (SiO_2, ore)	4.297E-05	1.87E-06	1.866E-06	1.87E-06
Phosphate Rock (in ground)	0	0.009397	0.009397	0.009397
Potash (K_2O, in ground)	0	0.004417	0.004417	0.004417
Sodium Chloride (NaCl)	0	0.003499	0.003499	0.003499
Uranium (U, ore)	1.405E-07	1.98E-07	1.873E-07	1.68E-07
Water Used (total)	0.026292	86.3637	86.3636	86.3636

The effect of conversion energy variability on primary energy resources is shown in Figure 168. Overall effects on primary energy are considerably smaller than the range of variation in energy inputs. Oil consumption is not affected at all. Because natural gas is the sole source of process energy in the conversion model, it is the most impacted by the assumptions for this step. Natural gas consumption increases 16.41% for the high energy inputs and decreases by 13.5% for the low energy inputs. Coal consumption ranges from +6.55% to –11.7% of the base case.



	Oil	Coal	Natural Gas
% High	0.16%	6.55%	16.41%
% Low	-0.3%	-11.7%	-13.5%

Figure 168: The Effect of Conversion Energy Requirements on Primary Energy Resource Demands for Biodiesel

The only other raw material affected in this sensitivity study is limestone, which tracks the changes for coal consumption. Both coal and limestone reflect changes in electricity demand.

Air emissions for this sensitivity study are presented in Table 140. Significant changes in the emissions related to variation of energy demands for soybean oil conversion can be identified in Figure 169. Changes in steam requirements (and hence natural gas consumption) have a large effect on CH_4 emissions, which can vary by 14% in both directions. From a greenhouse gas perspective, this is probably the most significant change observed in this sensitivity study. CO_2 shows similar responses. PM and SO_x emissions are also affected significantly, probably because of the effect of combustion for electricity generation. No other emissions show much response to the energy inputs for soy oil conversion.

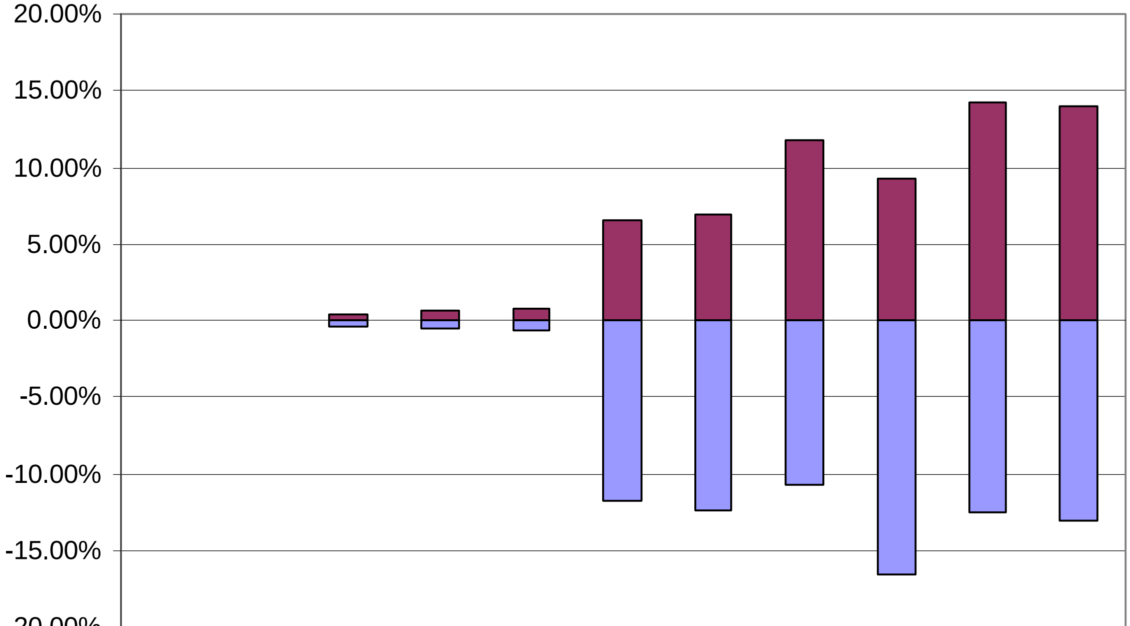
Table 140: The Effect of Soybean Oil Conversion Energy Demands on Air Emissions from Biodiesel

Air Pollutant	Petroleum Diesel	B100 High Conversion Energy	Biodiesel Base Case	B100 Low Conversion Energy
Ammonia (NH_3)	3.15E-08	0.073471	0.0734713	0.073471
Benzene	4.24E-05	1.84E-06	1.84E-06	1.84E-06
Carbon Dioxide (CO_2)	633.275	152.586	136.447	121.903
Carbon Monoxide (CO)	1.26981	0.83695	0.831723	0.827155
Formaldehyde	0.00056761	2.48E-05	2.48E-05	2.48E-05
Hydrocarbons (except CH_4)	0.131467	0.444689	0.44451	0.444352
Hydrocarbons (unspecified)	0.249053	0.151852	0.151814	0.151746
Hydrogen Chloride (HCl)	0.00316426	0.003841	0.0035927	0.003148
Hydrogen Fluoride (HF)	0.000395532	0.000365	0.000334188	0.000279
Methane (CH_4)	0.202839	0.225332	0.197616	0.171671
Nitrogen Oxides (NO_x as NO_2)	5.00856	5.7017	5.67728	5.65307
Particulates (PM10)	0.0840937	0.046925	0.0465724	0.046285
Particulates (unspecified)	0.130281	0.104814	0.0983287	0.086711
Sulfur Oxides (SO_x as SO2)	0.926335	0.973351	0.851949	0.745081

Model results for water and solid waste emissions are presented in Table 141 for the range of energy inputs considered in this sensitivity study. The relative changes in emissions are presented in Figure 170. Wastewater and hazardous solid waste emissions are hardly affected. Nonhazardous solid waste does show a moderate response.

Table 141: The Effect of Soybean Oil Conversion Energy Demands on Water and Solid Waste Emissions for Biodiesel (kg/bhp-h)

	Base	Low	High
Wastewater	0.098961	0.098899	0.098997
Solid Waste (Hazardous)	1.82E-05	1.82E-05	1.82E-05
Solid Waste (Non-hazardous)	0.012704	0.012402	0.012873



	HC unspec	HC less CH4	NOx	CO	PM10	PM unspec	HCl	CO2	HF	SOx	CH4
% High	0.03%	0.04%	0.43%	0.63%	0.76%	6.60%	6.91%	11.83%	9.29%	14.25%	14.03%
% Low	-0.04%	-0.04%	-0.43%	-0.55%	-0.62%	-11.82%	-12.39%	-10.66%	-16.65%	-12.54%	-13.13%

Figure 169: The Effect of Soybean Oil Conversion Energy Demands on Air Emissions for Biodiesel

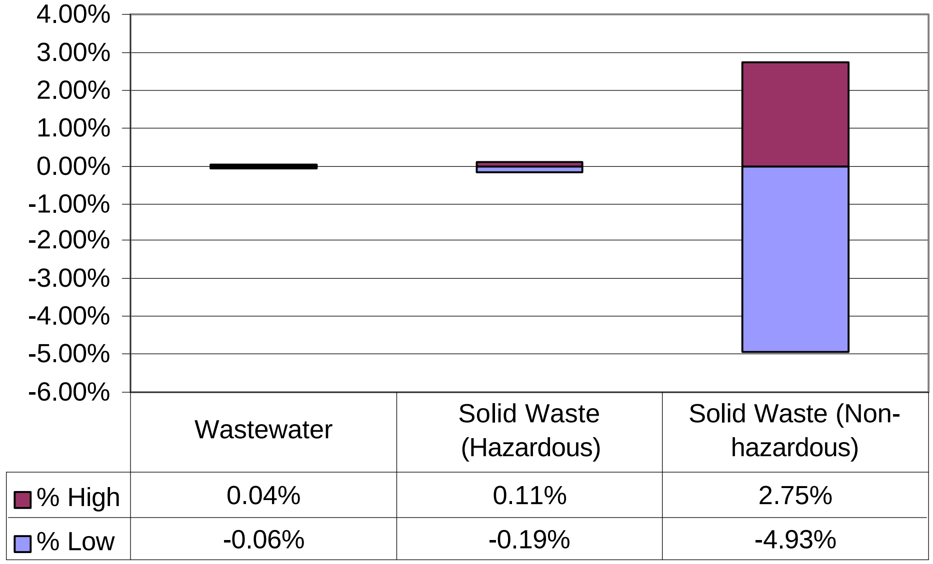


Figure 170: The Effect of Soybean Oil Conversion Energy Demands on Water and Solid Waste Emissions for Biodiesel