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Appendix A: Energy Use and Emissions From the Lifecycle of Diesel-Like Fuels Derived From Biomass: An Appendix to the Report, "A Lifecycle Emissions Model (LEM): Lifecycle Emissions From Transportation Fuels, Motor Vehicles, Transportation Modes, Ele...

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An Appendix to the Report, "A Lifecycle Emissions Model (LEM): Lifecycle Emissions From Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials"

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APPENDIX A: ENERGY USE AND EMISSIONS FROM THE LIFECYCLE OF DIESEL-LIKE FUELS DERIVED FROM BIOMASS

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1 BIODIESEL AS A HEAVY DUTY VEHICLE FUEL

Transesterified, biomass-derived oil or biodiesel can be mixed with standard diesel in any proportion and burned in diesel engines. The oils needed to produce biodiesel can be obtained from a variety of plant and animal sources, including soybeans, rapeseed (canola), sunflower seed, beef tallow, and from waste tall oil produced from pine pulping operations (Cvengros and Povazanee, 1996; Muniyappa, et al., 1996; Stumborg, et al., 1996) . Interestingly, the concept of using vegetable oils to fuel diesel engines is not at all novel and dates back to the days of the invention of the compression-ignition engine. Rudolph Diesel himself is known to have combusted peanut oil in 1900 (Muniyappa, et al., 1996) . The recent literature on biodiesel production and combustion shows global interest, including investigations on biodiesel produced from canola and tall oil in Canada (Stumborg, et al., 1996) , rapeseed oil in Austria (Mittelbach, 1996) and the Slovak Republic (Cvengros and Povazanee, 1996) , and soy and rapeseed oil and beef tallow in the U.S. (Muniyappa, et al., 1996; Romig and Spataru, 1996; Schumacher, et al., 1996) .

When blended with standard diesel in modest proportions of 10 to 40% biodiesel, no engine modifications are required, and biodiesel's low sulfur and aromatic levels produce reduced emissions relative to combustion of pure diesel (Booz-Allen and Hamilton, 1994; Schumacher, et al., 1996) . Biodiesel is non-toxic, and biodegrades readily; for example, rapeseed-oil-derived biodiesel reaches 99% decomposition within 21 days, versus only 72% decomposition for conventional diesel (Cvengros and Povazanee, 1996) . Different types of biodiesel exhibit slightly different characteristics, and all are somewhat different than standard diesel. Some characteristics of different representative diesel and biodiesel fuels are shown in Table A-1.

2 BIODIESEL PRODUCTION

Raw vegetable oils cannot be combusted in classic, direct-injection diesel engines because they are too viscous to be sprayed, their volatility is low, and they burn incompletely, leaving engine deposits (Cvengros and Povazanee, 1996) . Through the process of transesterification, the large, branched triacylglycerol molecules are altered to become smaller, unbranched methyl ester molecules, which are comparable in size to the components of classic diesel fuel (Cvengros and Povazanee, 1996; Muniyappa, et al., 1996). This process of converting vegetable oils to their esters results in the complete removal of glycerides, and the lowering of the boiling point, flash point, and viscosity of the oil (Karaosmanoglu, et al., 1996) .

The production of biodiesel from raw vegetable material requires several steps. First, raw oil must be extracted from the rapeseed or soybean feedstock. Rapeseed oil can be readily obtained by pressing the seed without prior conditioning. While pre-press extraction methods can produce significantly higher yields (about 97% versus

83%), the simple cold-press method is simpler and cheaper (Cvengros and Povazanee, 1996) . Hence, small-scale, farm-based biodiesel production operations likely would employ the simple cold-press method, while larger scale and more sophisticated production settings might favor the use of higher yield pressing techniques. In the U.S., the soy oil extraction and refining industry is well established and mature. The industry uses a solvent extraction system to produce oil from the crushed seed, using the solvent n-hexane. Most of this solvent is recycled, but approximately 0.7 gallons (2.65 liters) of solvent per ton of soybeans processed are lost due to the high volatility of the solvent (Ahmed, et al., 1994).

Once obtained, the raw oil is filtered, collected in a tank, and then periodically pumped into an agitating transesterfication reactor. In the reactor, the oil is heated to 60-70 °C, and gradually brought into contact with a mixture of sodium hydroxide (NaOH) and methanol (MeOH). The mixture used is typically 3-6% NaOH by weight (Cvengros and Povazanee, 1996) . KOH can be used in place of NaOH. However, NaOH has a lower molar weight than KOH, so smaller amounts are required, it is cheaper and its salts are less soluble in methyl esters than are those of KOH (Cvengros and Povazanee, 1996) . After an hour of agitation, the mixture is allowed to separate into an upper layer of methyl esters and a lower layer of glycerin diluted with active methanol. The unreacted MeOH is then air-stripped or vacuum distilled away, and then the methyl esters are again mixed with methanol, and allowed to react for 30 minutes. Finally, the excess MeOH is again removed (Cvengros and Povazanee, 1996; Muniyappa, et al., 1996) .

After transfer from the transesterfication reactor to the finishing reactor, small amounts of concentrated phosphoric acid are added to the raw methyl esters to break catalyst residues and sodium soaps. Ammonium hydroxide is then added to neutralize any remaining free fatty acids or phosphoric acid. Excess ammonia is then air-stripped, and finally the esters are centrifuged to remove any solidified components (Cvengros and Povazanee, 1996) . Conversion rates of 99% have been obtained with this two-step method. It has also successfully been used for waste frying oil, as well as vegetable oil produced from raw seed (Ahn, et al., 1995) . Table A-2 shows the energy used in the transesterfication processes in the U.S. and Europe, and also reports the energy embodied in the chemical inputs used.

The transesterfication of beef tallow follows a similar procedure, and high yields (up to 98%) have been obtained in a one-stage process (Muniyappa, et al., 1996). Beef tallow produces esters of very similar density and viscosity to those of soybean oils, and the viscosity is only slightly higher than that of diesel fuel (Muniyappa, et al., 1996). However, the cloud point of beef tallow esters is high at about 10 to 12 (°C) when compared to soy esters at -1 to 2 (°C) and diesel at -19 to -15 (°C), due to the high concentration of saturated fatty esters. This creates a concern for their use as a diesel fuel in cold weather conditions (Muniyappa, et al., 1996).

Once raw oil has been obtained, the rapeseed, methyl ester production process used in the Slovak Republic uses 1000 kg of raw rapeseed oil, 157 kg of MeOH, 6.5 kg of

NaOH, 0.8 kg of 80% H_3PO_4 (in solution), 1.1 kg of 25% NH_4OH, and 16.6 kg of 35% HCl to produce 987 kg of methyl esters, 116 kg of raw glycerin, 47 kg of "organic layer" material, 30 kg of recycled MeOH and 1.5 kg of filtration cake (Cvengros and Povazanee, 1996). The "organic layer" consists of approximately 30-40% free fatty acids and 60-70% methyl esters that can be further refined into surfactants useful to the oleo-chemical industry. The recycled methanol contains 3-4% water and requires treatment to allow its reuse, but even in small methyl ester production plants the costs of treatment are lower than the costs of purchasing new methanol (Muniyappa, et al., 1996) . In the U.S., the soybean methyl ester production process uses 1000 kg of raw soy oil

Figure A-1 summarizes the energy used in the U.S. soydiesel production process. Further details of the energy used in producing biodiesel from soybeans are provided in Table A-3.

As of 1994, the biodiesel production capacity in the U.S. was 25 million gallons per year, and all U.S. biodiesel was supplied by Interchem Environmental, Inc. through an agreement with Procter and Gamble (Booz-Allen and Hamilton, 1994). In December 1993, biodiesel sold for $2.80 per gallon by Interchem, which was up from $2.20 per gallon in April of 1993. This price volatility is due to the fact that about 75 percent of the final cost of biodiesel is due to the cost of the vegetable oil feedstock, and the cost of the soy oil used by Procter and Gamble which fluctuated significantly throughout 1993 (Booz-Allen and Hamilton, 1994).

Recent efforts have focused on reducing the production costs of biodiesel, in order to make it more economically competitive with conventional diesel. One improved production process, devised by David Boocock of the University of Toronto, speeds up production and reduces costs. This method uses the co-solvent tetrahydrofuran to cause the transesterfication reaction to occur in one phase instead of two (Stambler, 1995) .

Finally, it is worth noting that at least one other method for producing biodiesel exists and is under investigation. Biodiesel can also be produced through a patented hydroprocessing technology developed in Canada (Stumborg, et al., 1996) . Under proprietary temperature and pressure conditions, the process consists of several reactions including hydrocracking, hydrotreating (removal of oxygen), and hydrogenation (saturation of double bonds) (Stumborg, et al., 1996) . This method offers the advantages of being familiar to oil companies (in that it resembles conventional refinery based hydroprocessing), and in allowing the use of existing hydroprocessing hardware. One estimate puts the processing cost associated with hydroprocessing at only 50% that of esterification (Stumborg, et al., 1996) , but this is only about 25% of total cost (Booz-Allen and Hamilton, 1994). Hydroprocessing is further from commercialization than esterification, and performs poorly in cold weather (due to the high cetane numbers of the fuels produced), unless costly additives are used (Stumborg, et al., 1996) .

3 BYPRODUCTS FROM BIODIESEL PRODUCTION

Of importance to the overall economics of biodiesel production are the quantities and values of any byproducts produced. The lower phase from the vegetable oil transesterfication process contains about 75% glycerin, along with small amounts of esters, alcohol, and impurities (Muniyappa, et al., 1996) . With the soydiesel production process used in the U.S., 564 kg of soydiesel and 436 kg of glycerin are obtained from 1000 kg of raw soy oil (Ahmed, et al., 1994). Using a byproduct calculation method based on the weight of the products and byproducts of the U.S. soydiesel process, the energy value of the glycerin byproduct is 2,865 BTUs per gallon of soydiesel produced. Using an economic- value based calculation, the energy credit is 12,802 BTUs per gallon of soydiesel, and using a replacement credit method, the energy credit is 17,010 BTUs per gallon of soydiesel (Ahmed, et al., 1994)(See Table A-4 for further details of these calculations). The glycerin can be recovered by distillation, or converted to its mono- and diester derivatives by using triglycerides (this process is known as glycerolysis) (Muniyappa, et al., 1996). Many economic applications exist for mono- and di-glycerides, including use as a food emulsifier, a modifying agent in the manufacture of detergents, and in the production of cosmetics, pigments, floor wax, synthetic rubbers and coatings, and textiles (Muniyappa, et al., 1996).

Additionally, the rapeseed cake or soy meal left over from the initial rapeseed or soy-pressing process is a valuable addition to fodder for farm animals. With the biodiesel production process used in the Slovak Republic, approximately 660 kilograms of rapeseed cake and 340 kilograms of raw rapeseed oil are obtained from 1000 kilograms of rapeseed (Cvengros and Povazanee, 1996) . The soy diesel production process used in the U.S. produces 812 kg of soy meal and 188 kg of raw soy oil. Use of the mass, economic value, and replacement value credit calculations produce energy credit values for soy meal of 49,931, 42,576, and 81,229 BTUs, respectively, per gallon of soydiesel produced (see Table A-4) (Ahmed, et al., 1994) .

4 BIODIESEL DEMONSTRATIONS, FUEL CONSUMPTION AND MAINTENANCE

Many demonstration programs have been conducted in the U.S. alone, particularly in California, Missouri, Colorado, and Washington. The demonstration programs have shown that a perceptible decrease in visible smoke emissions occurs when 20-30% biodiesel blends are substituted for pure diesel. Furthermore, no negative responses to biodiesel use have been reported from either drivers or passengers (Booz-Allen and Hamilton, 1994).

Various studies indicate that engine performance and fuel economy are only slightly affected by the 10-30% biodiesel blends that have been used in the U.S.

demonstration programs and engine performance tests (Booz-Allen and Hamilton, 1994; FEV Engine Technology, 1994; Ortech International, 1993). In one test, using a DDC 6V-92TA engine, fuel consumption varied between 74 and 77 pounds per hour with biodiesel blends of 10-40%, relative to 75 pounds per hour with pure diesel. There was no apparent trend with increased levels of biodiesel (Ortech International, 1993). Another test with a Navistar T 444E engine demonstrated slight (and approximately linear) increases in brake-specific fuel consumption (BSFC) with increasing blends of up to 50%. However, when pure biodiesel was used fuel consumption increased by 12.4% (FEV Engine Technology, 1994).

Engine performance tests show that power and torque are not significantly affected when biodiesel blends of up to 40% are used, although a small drop in rated power has been observed at the 40% level. One power check test determined that peak engine torque with 10%, 20%, 30%, and 40% biodiesel blends was 700, 707, 693, and 670 ft-lbs respectively, at an engine speed of 2100 revolutions per minute, in comparison to a peak torque of 701 ft-lbs with pure diesel (Ortech International, 1993). With the same blend levels at an engine speed of 1200 revolutions per minute, torque was measured at 889, 885, 877, and 881 ft-lbs, relative to 882 ft-lbs with pure diesel (Ortech International, 1993).

Few analyses have been conducted on the long-term effects on engine wear of biodiesel use. The University of Idaho conducted a 1,000 hour durability test with a 50%/50% biodiesel and number 2 diesel blend, and with 100% biodiesel. The study employed three Yanmar 3-cylinder direct injection engines (one for a control with pure number 2 diesel), and the biodiesel fuel used was a methyl ester of winter rape oil, produced at the University of Idaho. The study used a test cycle similar to the Engine Manufacturers Association standard 200-hour screening test, but extended the test to a full 1,000 hours. The results indicate that at the beginning of the test the two biodiesel fuels produced less engine power than the conventional diesel fuel. However after 500 hours the engine power produced with the 100% biodiesel fuel exceeded that from the conventional fuel, and beyond the 800 hour mark, the engine power from the 50%/50% blend exceeded that from the pure number 2 diesel. Furthermore, no significant problems of oil viscosity were observed with any of the engines. Engine wear evaluations indicated that the conventional diesel fueled engine showed the highest crankcase oil concentrations of iron, aluminum, and chromium than did the biodiesel fueled engines.

Interestingly, the 100% biodiesel fueled engine showed the lowest metal wear concentrations of the three engines, a finding the investigators attribute to the lower pressure rise observed in the combustion of rape methyl ester. The engine coking levels among all of the fuels were similar. Inspections after the tests found that the engine fueled with conventional diesel had the highest levels of deposits on exhaust valve seats and faces, the combustion chamber, and oil rings. The researchers concluded that rape methyl ester was essentially the equivalent to number 2 diesel fuel with regard to long term performance and engine wear (Perkins, et al., 1991) .

Finally, maintenance requirements do not seem to increase with blends of up to 40% biodiesel, although above this level, more frequent oil changes may be required and some deterioration of the rubber and the polyurethane foam may occur (Booz-Allen and Hamilton, 1994).

5 BIODIESEL COMBUSTION AND EMISSIONS

Table A-5 presents the results of several emissions tests using various types of biodiesel in varying blends with conventional diesel fuel. In general, and in the absence of engine and catalyst system modifications, these emissions tests show a linear decrease in particulate emissions and a linear increase in NOx emissions with increasing blends of biodiesel up to a 40% blend. Carbon monoxide and hydrocarbon emissions are also reduced through the use of biodiesel in unmodified engines. Hydrocarbon emission reductions are typically on the order of 14-22% with 20% biodiesel blends. Similarly, carbon monoxide emission reductions with 20% biodiesel blends are typically in the range of 3%-20%. Only one test reported in Table A-5 measured sulfur dioxide emissions, and a reduction of 40% was measured with the use of BIONAPTHA MDT, relative to standard diesel. Carbon dioxide emissions are apparently not substantially affected through the use of biodiesel, but modest increases have been observed with 10% to 40% blends (Cvengros and Povazanee, 1996; FEV Engine Technology, 1994; FMD Ltd., 1995; Romig and Spataru, 1996; Schumacher, et al., 1996; Sharp, 1994) .

While most biodiesel emissions investigations have focused on relatively modest blends of biodiesel with conventional diesel, at least one study has been conducted on emissions from the use of pure biodiesel. This study, conducted at the University of Idaho with rape methyl ester produced at the university, arrived at the following conclusions with regard to the comparison between 100% biodiesel and 100% low sulfur diesel: HC emissions were reduced by 52.4%, CO emissions were reduced by 47.6%, NOx emissions were reduced by 10.0%, and particulate matter increased by 9.9%. These results, presented in more detail in Table A-5, suggest that particulate emissions are reduced with relatively low percentages of biodiesel mixed with diesel. Particulate emissions increase as the percentage of biodiesel exceeds 20%, and increase to the point where they exceed emissions from pure low sulfur diesel with biodiesel contents of 50%, or greater. The apparent conclusion is that the benefits of biodiesel blends with regard to particulate emissions are highest with blends of about 20%, but that HC and NOx emissions (the latter contrary to some other studies) continue to decline roughly in proportion to the percentage of biodiesel used (Peterson and Reece, 1996) .

Given the increase in NOx emissions that has been observed in most studies with the addition of biodiesel, considerable efforts have focused on methods to reduce these emissions. Three primary methods have been explored: the use of catalysts, the use of exhaust gas recirculation (EGR) systems, and retarded injection timing. One

investigation of the use of an oxidation catalyst demonstrated significant reductions in CO and HC emissions downstream of the catalyst. However, slightly higher HC emissions were noted in some areas of the engine map. Reductions in CO emissions with the oxidation catalyst seem to depend primarily upon engine load, and not engine speed, with reductions observed mainly at full load. Particulate emissions tend to increase with the use of the oxidation catalyst, particularly at higher engine load levels, although some reductions at lower load levels have been observed. NOx emissions were only very slightly affected through the use of the catalyst, increasing slightly at higher loads and remaining essentially unchanged at lower loads. In general, the use of an oxidation catalyst provides some reduction in CO and HC emissions, but at the expense of particulate emissions. The investigation reported here did not attempt to optimize the position or doping level of the catalyst for biodiesel blended fuel, and additional investigations have been recommended (FEV Engine Technology, 1994).

The use of an EGR system generally can provide decreased NOx emissions without increases in particulate or other emissions, and without increases in fuel consumption. At medium speed and low load conditions, the use of the EGR system reduces fuel consumption, and gaseous and particulate emissions, but at full load conditions, black smoke emissions increase dramatically with even very low levels of EGR ratio. At rated speed levels (2600 rpm) and low loads, EGR improves all gaseous emissions, while holding fuel consumption constant, but increases particulate emissions. As the load level is increased at this rated speed level, emissions of species other than NOx, and fuel consumption, increase. These results suggest that EGR ratios should be optimized such that the EGR ratio drops with load. One such strategy successfully reduced NOx emissions from 6.7 g/kWh to 6.0 g/kWh without substantially affecting fuel consumption, particulate emissions, or other gaseous emissions (FEV Engine Technology, 1994).

Retarding injection timing generally reduces NOx emissions without increasing particulate emissions. However, retarded timing tends to result in increased fuel consumption and, with a 50% biodiesel blend, retarded injection timing results in significant load losses due to injection system limitations. With 100% methyl ester, full load points could not be achieved, even with advanced injection timing. In general, NOx emissions can be reduced by about 0.37 grams per horsepower-hour without increasing particulate emissions through the injection timing retardation strategy. It is not possible to reduce both NOx and particulate emission levels simultaneously. It should be noted that the lowest NOx levels observed with the use of biodiesel (at about 4.5 grams per horsepower-hour) are obtained with 10-20% biodiesel blends (FEV Engine Technology, 1994).

5.1   EPA summary of biodiesel emissions tests

Recently, the EPA (2002) has produced what it calls a "comprehensive" summary of publicly available data on the impacts of biodiesel fuel use on emissions of CO, NMHCs, PM, and NOx. They found that emissions of NOx, PM, and CO varied linearly

with biodiesel concentration (Table A-6). The results of the EPA analysis are broadly consistent with our findings reported above, which are based on a much smaller data set (and most if not all of, which are included in the EPA analysis).

TABLE A-1: CHEMICAL PROPERTIES OF REPRESENTATIVE DIESEL AND BIODIESEL FUELS

Parameter	#1 Diesel	#2 Low S Diesel	100% Soy diesel	100% Soy diesel	100% SME	SME /ARB	100% CME	100% bio-diesel
Density (g/ml)	0.815	0.849	0.884	0.883	0.887	0.848	0.886	0.88
Viscosity (cs at 40° C)	1.48	2.6	4.06	3.77	4.33	2.65	n.r.	6.0
Flash Point (°C)	n.r.	76	179	n.r.	>110	60	>250	n.r.
Cloud Point (°C)	n.r.	-13	-1	n.r.	n.r.	n.r.	n.r.	n.r.
API Grav. (degrees)	42.1	35.0	28.5	28.7	28	35.3	28.2	n.r.
Sulfur (% wt.)	0.09	0.04	0.01	<0.01	n.r.	n.r.	n.r.	0.0054
Carbon (% wt.)	n.r.	86.2	76.5	78	n.r.	n.r.	n.r.	77.8
Hydrogen (% wt.)	n.r.	13.8	12.5	11.5	n.r.	n.r.	n.r.	n.r.
Oxygen (% wt.)	n.r.	n.r.	11	10	n.r.	n.r.	n.r.	n.r.
Aromatics (% vol.)	n.r.	33	n.r.	n.r.	n.r.	n.r.	n.r.	0
Olefins (% vol.)	n.r.	1	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
Saturates (% vol.)	n.r.	66	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
Cetane number	46	44.5	45.8	48	45.7	50.4	n.r.	55
Heat (kJ/kg)[b]	n.r.	42,869	39,465	41,820	n.r.	n.r.	n.r.	40,370
Source	*Schumacher et al. (1996)*			*FEV[a]*	*Romig & Spataru (1996)*			*EPA (2002)*

Notes: SME = Proctor and Gamble Soya methyl ester; SME/ARB = 20/80 blend of SME and California ARB #2 diesel; CME = canola methyl ester; n.r. = not reported.

[a] FEV Engine Technology (1994).

[b] EPA (2002) shows 37,458 kJ/kg lower heating value (LHV). We estimate higher heating value (HHV) assuming a HHV/LHV ratio of 1.078 (Davis, 2000).

TABLE A-2: ENERGY INPUTS INTO SOY AND RAPE OIL ESTERIFICATION PROCESS

Input Category	United States (BTUs per gallon of soy methyl ester)		Europe (BTUs per gallon of rape methyl ester)	
	Present Industry	**Industry Potential**	**Present Industry**	**Industry Potential**
Direct Energy:				
Electricity	2,666	2,082	3,612	2,745
Steam	18,225	3,744	6,779	3,393
Total Direct	20,891	5,826	10,391	6,138
Chemical Inputs:[a]				
Reactant (MeOH)	10,933	12,919	25,840	12,919
Catalyst (NaOH)	902	1,128	1,353	1,128
Total Chemicals	11,835	14,047	27,193	14,047
Transport	228	123	127	123
Total	*32,954*	*19,996*	*37,711*	*20,312*

Source: All calculations are from Ahmed, et al. (1994), except where noted.

Notes: MeOH = methanol; NaOH = sodium hydroxide.

[a] Ahmed, et al. based their calculations of methanol reactant energy input on an estimate of 66,542 BTUs per gallon for the energy content of the methanol, based on the lower heating value of methanol (56,560 BTUs), and a value of 85% for the thermal efficiency of the production of methanol from natural gas. Here we revise their calculations using an estimate of 99,385 BTUs per gallon for the energy content of the methanol reactant, based on its HHV of 64,600 BTUs per gallon and a more moderate estimate of 65% thermal efficiency for the methanol production process. As a result, the values shown here for the methanol portion of the energy input to the soy and rape oil esterification process are approximately 1.5 times higher than those given in Ahmed, et al. The energy input for the sodium hydroxide catalyst is based on an assumption by Ahmed, et al. that the catalyst requires 11,275 BTUs per gallon for its manufacture.

TABLE A-3: ENERGY USED IN SOY METHYL ESTER PRODUCTION PROCESS IN THE U.S.

Input Category	National Average (BTUs per gallon soydiesel)	Industry Best (BTUs per gallon soydiesel)	Industry Potential (BTUs per gallon soydiesel)
Agricultural Energy:			
Fertilizers[a]:			
Nitrogen	1,893	1,160	
Phosphorous	1,079	607	
Potash	1,482	706	
Total Fertilizers	4,454	2,473	603
Pesticides[b]	3,739	2,965	5,306
Fuel	14,552	11,044	8,319
Other Feedstock[c]	6,691	5,967	6,691
Total Agricultural	29,435	22,447	20,919
Processing Energy:			
Oil Extraction	32,053	18,768	18,768
Oil Refining	1,092	984	984
Esterification[d]	32,954	37,711	19,996
Total Processing	66,099	57,463	39,748
Total Energy Input	95,534	79,910	60,667
Energy Output:			
Soydiesel Energy	132,902	132,902	132,902
Co-product Credit[e]	98,239	98,239	98,239
Total Energy Output	231,141	231,141	231,141
Net Energy Gain	135,607	151,231	170,474
Percent Gain	142%	189%	281%
input/output Ratio	1:2.42	1:2.89	1:3.81

Source: All calculations are from Ahmed et al. (1994), except where noted.

[a] Ahmed, et al.'s calculation of fertilizer BTUs per gallon assumes the following: 3.25 pounds (1.474 kg) per acre of nitrogen are applied and nitrogen contains 31,100 BTUs per pound (or

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68,600 BTUs per kg); 10.36 pounds (4.699 kg) per acre of phosphorous are applied and phosphorous contains 5,560 BTUs per pound (or 12,260 BTUs per kg); and 18.49 pounds (8.39 kg) per acre of potash are applied and potash contains 4,280 BTUs per pound (or 9,440 BTUs per kg). The "National Average" category assumes a yield of 37.6 bushels of soybeans per acre, and the "Industry Best" category assumes a yield of 44.0 bushels of soybeans per acre.

b The figure for fertilizers also includes pesticides and herbicides. Ahmed, et al.'s calculation assumes that 1.11 pounds per acre of these chemicals are applied, and that they contain an average of 179,838 BTUs per pound (or 396,475 BTUs per kg). The yield figures used are the same as in note a.

c Other feedstock energy inputs include seed, on-farm electricity, lime, and bulk transport of the crop to the processing site.

d The values for esterification energy input have been modified from those values given in Ahmed, et al. as discussed in Table A-2, note a.

e The co-processing credits are based on the replacement value of the soy meal and glycerin produced during the soy oil extraction and refining and the esterification processes.

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TABLE A-4: BYPRODUCTS AND ENERGY CREDITS FROM U.S. SOYDIESEL PRODUCTION

Byproduct and credit type	Percentage of byproduct relative to feedstock	Energy value of byproduct per 1000 liters of soydiesel (kWh)	Energy value of byproduct per gallon of soydiesel (BTUs)
Soy Meal:			
weight energy credit	81% of raw soybeans	3,864.78	49,931
economic value energy credit	68% of raw soybeans	3,295.48	42,576
replacement energy credit[a]	N/A	6,287.32	81,229
Glycerin:			
weight energy credit	10% of raw soy oil	221.76	2,865
economic value energy credit	44% of raw soy oil	990.91	12,802
replacement energy credit	N/A	1,316.61	17,010
Total Byproducts:			
weight energy credit	N/A	4,086.54	52,796
economic value energy credit	N/A	4,286.39	55,378
replacement energy credit	N/A	7,603.93	98,239

Source: All calculations are from Ahmed et al. (1994).

[a] The replacement energy credit for soy meal is based on a calculation that one kg of soy meal replaces 2.3 kg of feed barley (on a price and protein equivalency basis), that the energy used to produce feed barley is 1,069 BTUs per pound (0.69 kWh per kg), and that 33 pounds (15 kg) of soy meal are produced with each gallon of soydiesel.

[b] The replacement credit for glycerin assumes that the glycerin produced displaces synthetic glycerin. The production of one pound of synthetic glycerin requires 0.62 pounds (0.281 kg) of propylene, 2.00 pounds (0.907 kg) of chlorine, 0.45 pounds (0.204 kg) of sodium chloride, and 0.45 pounds (0.204 kg) of sodium hydroxide. The energy contents of these raw materials are 8,577, 5,319, 592, and 11,275 BTUs per pound (or 5.539, 3.435, 0.382, and 7.281 kWh per kg), respectively. Based on these figures, the energy required to produce a pound of glycerin is 21,296 BTUs (or 13.75 kWh per kg), ignoring the small amount of energy used in the final synthesis of the glycerin (the reaction is exothermic, requiring no heat or pressure, and only a

small amount of electricity is used to stir the reactors), and any potential recovery of the (very inexpensive) reactants.

TABLE A-5: EMISSIONS FROM REPRESENTATIVE DIESEL AND BIODIESEL BLENDS[A]

Pollutant	BIONAPHTA MDT/diesel	CME-ARB diesel: 20%/0%	SME-ARB diesel: 20%/0%	SME-#1 diesel: 0%/10%/20%/20% cat./ 30%/40%
PM (g/bhp-hr)	35.1/55.5[b]	0.238/0.265	0.257/0.270	0.20/0.19/0.18/ 0.14/0.17/0.16
Soot (mg/m^3)	18.2/26.2[b]	n.r.	n.r.	n.r.
HCs (g/bhp-hr)	7.3/28.7[b]	0.363/0.435	0.48/0.57	0.72/0.63/0.56/ 0.38/0.54/0.43
SO$_2$ (mg/m^3)	9.0/15.0	n.r.	n.r.	n.r.
CO (g/bhp-hr)	0.08/0.10[c]	1.04/1.19	1.12/1.22	1.51/1.43/1.32/ 1.19/1.14/1.07
NOx (g/bhp-hr)	n.r.	5.87/5.62	4.70/4.43	4.23/4.38/4.46/ 4.62/4.80/4.86
CO$_2$ (g/bhp-hr)	n.r.	652/653	682/671	654/657/657/ 686/685/684
Total PAH (ng/m^3)	4589/138824[d]	n.r.	n.r.	n.r.
Engine		1983 DDC 6V92TA MUI	1983 DDC 6V92TA MUI	1991 DDC 6V92TA (277 hp rated power)
Catalytic Converter	not specified	none	none	none/ platinum oxidation
Test Cycle	not specified	EPA heavy-duty hot transient	EPA heavy-duty hot transient	EPA heavy-duty transient
Fuel	30% rapeseed oil biodiesel/ 70% aliphatic HCs	20% CME/80% ARB diesel	20% SME/80% ARB diesel	0%/10%/20%/2 0% cat. /30%/40% Interchem methyl soyate[e]
Comparison Fuel	Unspecified diesel	Texaco Low Sulfur ARB diesel	Texaco Low Sulfur ARB diesel	#1 or #2 LSD
Source	*Cvengros and Povazanee (1996)*	*Romig and Spataru (1996)*	*Romig and Spataru (1996)*	*Schumacher et al. (1996)*

TABLE A-5 (CONT'D): EMISSIONS FROM REPRESENTATIVE DIESEL AND BIODIESEL BLENDS[A]

Pollutant	Methyl soyate-EPA #2 diesel: 20%/20% cat./20%(1.5° ITR)/20%(2.5° ITR)/ 20%(4.0°ITR)/0%	RME-diesel: 100%/50%/20%/0%	RME-diesel: 100%/20%/0%
PM (g/bhp-hr except as noted)	0.323/0.166/0.32/0.312/ 0.375/0.282	0.32/0.32/0.27/0.30[f]	0.51/0.35/0.41[f]
Soot (mg/m^3)	n.r.	n.r.	n.r.
Hydrocarbons (g/bhp-hr except as noted)	0.74/0.38/0.72/0.79/0.81/ 0.86	0.37/0.52/0.66/0.84[f]	0.65/1.00/1.25[f]
SO$_2$ (mg/m^3)	n.r.	n.r.	n.r.
CO (g/bhp-hr except as noted)	3.1/0.86/2.47/3.15/3.40/3.18	1.8/2.0/2.4/3.3[f]	2.1/3.0/4.5[f]
NOx (g/bhp-hr except as noted)	11.88/12.11/10.29/9.5/8.48/ 11.72	5.65/5.90/6.08/6.22[f]	6.30/6.60/6.83[f]
CO$_2$ (g/bhp-hr except as noted)	660/680/648/663/655/650	656/656/652/652[f]	704/709/699[f]
Total PAH (ng/m^3)	n.r.	n.r.	n.r.
Engine	1977 DDC 6V-71N MUI (180 hp rated @ 2000 rpm)	1994 Cummins DI 5.9L	1994 Cummins DI 5.9L
Catalytic Converter	none	none	none
Test Cycle	EPA heavy duty transient	Modified arterial cycle	EPA HD transient
Fuel	20% Interchem methyl soyate/80% EPA #2 diesel	100%/50%/20% Univ. of Idaho rape methyl ester blended with Phillips D2 LSD	100%/50%/20% Univ. of Idaho rape methyl ester blended with Phillips D2 LSD
Comparison Fuel	EPA #2 diesel	Phillips D2 LSD	Phillips D2 LSD
Source	*FMD Ltd., (1995)*	*Peterson & Reece (1996)*	*Peterson & Reece (1996)*

TABLE A-5 (CONT'D): EMISSIONS FROM REPRESENTATIVE DIESEL AND BIODIESEL BLENDS[A]

Pollutant	SME - diesel: 20%(3°ITR, cat) /0%/0%(OC)	Biodiesel - diesel: 20%/20%(1° ITR) /0%	Biodiesel - diesel: 20%/20%(1° ITR) /0%(1° ITR)	U.S. Emission Standard for Urban Buses 1994/96/98
Total PM (g/bhp-hr)	0.06/0.08/0.06	0.20/0.21/0.20	0.11/0.12/0.14	0.07/0.05/0.05
Soot (mg/m^3)	n.r.	n.r.	n.r.	N/A
HCs (g/bhp-hr)	0.03/0.10/0.06	0.53/0.55/0.60	0.21/0.25/0.29	1.3/1.3/1.3
SO$_2$ (mg/m^3)	n.r.	n.r.	n.r.	N/A
CO (g/bhp-hr)	0.24/0.90/1.0	1.39/1.59/1.60	0.95/1.05/1.21	15.5/15.5/15.5
NOx (g/bhp-hr)	4.46/4.60/4.6	8.93/8.20/8.52	9.12/8.35/8.18	5.0/5.0/4.0
CO$_2$ (g/bhp-hr)	n.r.	n.r.	n.r.	N/A
Total PAH	n.r.	n.r.	n.r.	N/A
Engine	1993 DDC 50/ 1993 DDC 50/ 1994 DDC 50	1988 DDC 6V-92TA DDEC II	1988 DDC 6V-92TA DDEC II	N/A
Catalytic Converter	unspecified /none/OC	none	diesel OC	N/A
Test Cycle	EPA transient cycle	Composite FTP	Composite FTP	N/A
Fuel	Unspecified biodiesel	20% Interchem biodiesel/80% Phillips 2-D diesel	20% Interchem biodiesel/80% Phillips 2-D diesel	N/A
Comparison Fuel	Unspecified diesel	Phillips 2-D diesel	Phillips 2-D diesel	N/A
Source	*BAH (1994)*	*Sharp (1994)*	*Sharp (1994)*	*BAH (1994)*

Notes: see next page.

PM = particulate matter; PAH = polycyclic aromatic hydrocarbons; LSD = low sulfur diesel; ARB = California Air Resources Board; HCs = hydrocarbons; CME = canola methyl esters; RME = rapeseed methyl esters; SME = Soya methyl esters; DDC = Detroit Diesel Corp; MUI = Mechanical Unit Injection; ITR = injection timing retard; n.r. = not reported; HD = heavy-duty; LSD = low-sulfur diesel; N/A = not applicable; OC = oxidation catalyst; BAH = Booze, Allen, and Hamilton.

[a] Results are reported as either: emission rate from X% biodiesel blend/emission rate from comparison diesel, or emission rate from X%/Y%/Z% biodiesel (blended with comparison diesel).

[b] Emission results are in units of mg/m^3.

[c] Emission results are in units of % volume.

[d] The breakdown of aromatic hydrocarbons is as follows (BIONAPTHA MDT/diesel comparison fuel): Naphthalene (ng/m^3) = 749/114,695; Acenapthene (ng/m^3) = 742/5798; Fluorene (ng/m^3) = 686/5362; Anthracene (ng/m^3) = 37/466; Fluoranthene (ng/m^3) = 912/1090; Pyrene (ng/m^3) = 1234/9000; Benzoanthracene (ng/m^3) = 152/2064; Benzofluoranthene (ng/m^3) = 57/216; Benzopyrene (ng/m^3) = 16/38; Dibenzanthracene (ng/m^3) = 3/95.
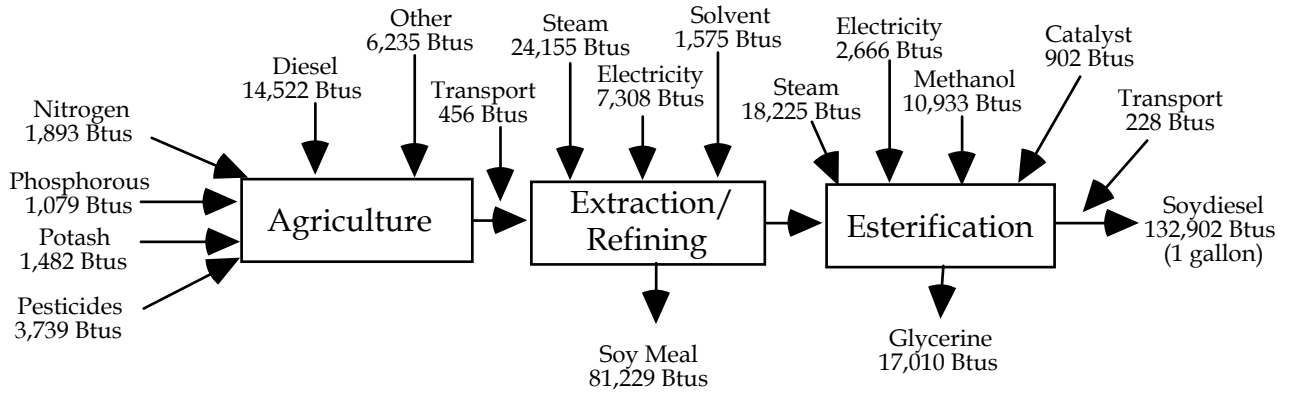
[e] The soydiesel used had a density of 0.887 kg/l at 21°C.

[f] Emissions results are in units of gm/mi.

TABLE A-6: EPA (2002) SUMMARY OF PUBLICALLY AVAILABLE DATA ON EMISSION IMPACTS OF BIODIESEL (% CHANGE IN EMISSIONS VS. DIESEL)

	20% biodiesel	100% biodiesel
NOx	2.0	+10
PM	10	-48
HC	21	-67
CO	11	-49

FIGURE A-1: ENERGY AND CHEMICAL INPUT AND OUTPUT IN THE BIODIESEL FUELCYCLE

Source: All values shown are from Ahmed et al. (1994), except that the methanol energy input value has been modified as discussed in Table A-2, note a.

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