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How Much Energy Does It Take to Make a Gallon of Soydiesel?

Vegetable oils extracted from soybeans have for many decades been widely used both as a food and industrial product. Recently industry has converted the oil into an ester called methylated ester of soybean oil. This has proved to be a viable alternative to diesel fuel. Popularly known as soydiesel, the esterified soybean oil is beginning to move into the marketplace. As this occurs one of the questions raised concerns the energy balance of making soydiesel. Is more energy used to grow soybean feedstock and to process it into soydiesel than is contained in soydiesel fuel itself?

This study addresses this question. Our conclusion is that soydiesel production in the United States is a net energy generator. Even under a worst case scenario, more energy is contained in esterified soybean oil and its co-products – glycerine and soy meal – than is used to grow the soybean crop and process it into soydiesel fuel and associated products. If soybean is grown as a rotation crop with corn using state of the art farm practices as much as four times the energy input can be realized from the various products generated.

The U.S. soydiesel industry is very much in its infancy. As it develops, further improvements in energy efficiency will occur.

European countries have been producing similar esterified fuels from rapeseed oil for several years and now produce significant quantities of biodiesel. Their experiences show that energy efficiency improves with both scale of operation and increased recovery of materials. In addition, co-product energy credits play an important role in determining the overall energy efficiency of the ester production system.

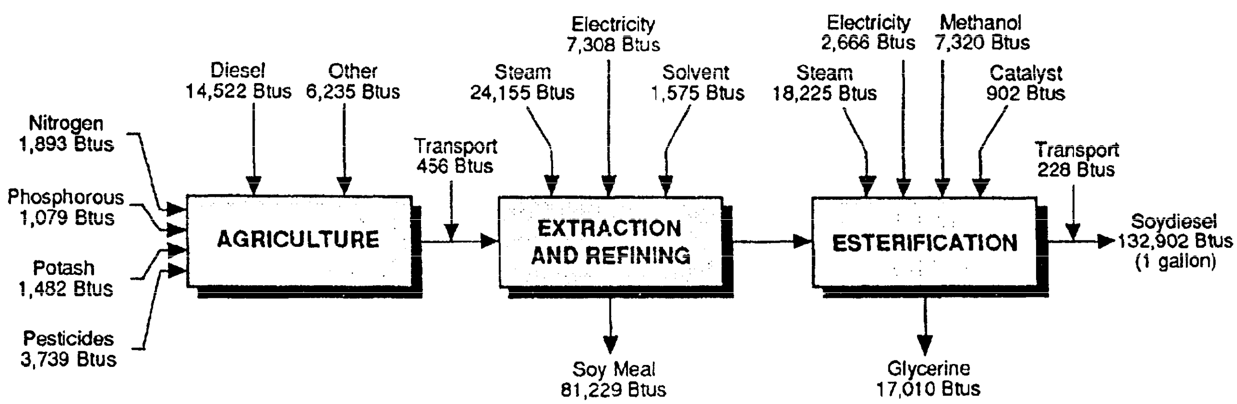
To answer the question, how much energy does it take to make a gallon of soydiesel, we must address four sub-questions.

1. How much energy is used to grow the feedstock?
2. How much energy is used to extract and refine oil?
3. How much energy is used for soy oil esterification?
4. How do we allocate the energy used in steps 1, 2, and 3 into soydiesel and co-products produced from the feedstock?

The answers to these questions are contained in Tables 2 through 7. Table 1 summarizes our conclusions. Our findings are also summarized in Figure 1, which presents all energy input/output flows through the soydiesel production system – from agriculture, through oil extraction and refining, to esterification of the oil into soydiesel.

We evaluated the energy used in growing and harvesting the crop, in extracting the oil and in esterifying the oil based on three scenarios: national average; existing industry best; and industry potential.

Figure 1. Energy Inputs and Outputs per Gallon of Soydiesel Produced



National Average

The first column presents the energetics of soydiesel production based on average practices. Based on the energy used on the average soybean farm and in the average oil extraction, refining, and esterification facilities we conclude that for every 1 Btu of energy input into the production system, an average 2.51 Btus of energy output is realized – a 151 percent energy gain.

Assuming a conventional agriculture practice of growing soybean in rotation with corn, the agricultural energy input accounts for roughly one-third or 32 percent of all energy input into soydiesel production. Oil extraction, refining, and esterification combined account for the remaining 68 percent.

Industry Best

The second column presents the energetics of soydiesel production based on the current best agriculture and oil processing practices in the United States. This analysis combines the best existing energy-efficient soybean cultivation data with the most efficient oil extraction, refining, and esterification technologies to determine the overall energy balance of soydiesel production. We conclude that 20,500 Btus less energy is used to make a gallon of soydiesel if the best existing farming and industry practices are used than when average farming and industry practices are used. Much of this difference occurs because of improved efficiency at the extraction level, a difference of about 13,000 Btus per gallon of soydiesel. The ratio of agricultural energy inputs to total energy inputs remains the same under best practices as under average practices at about one-third of the total.

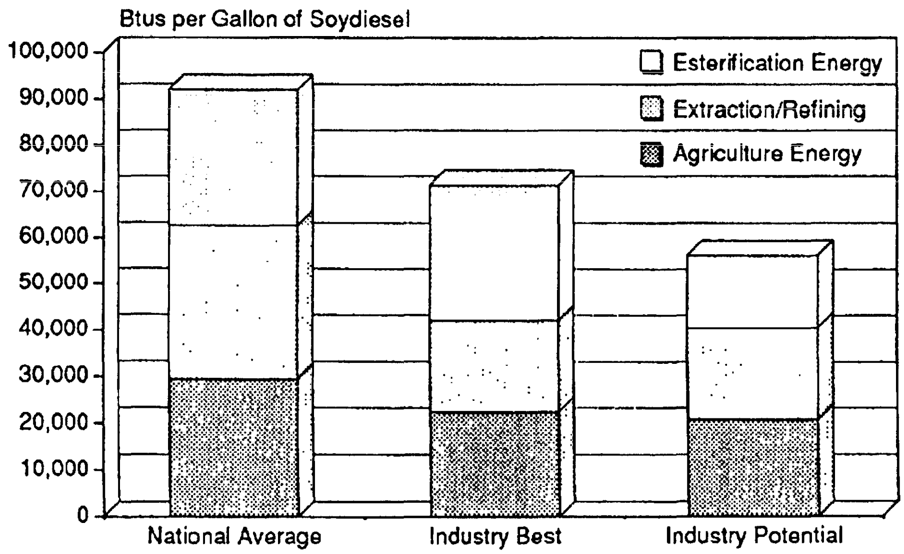
The net energy gain using the best existing industry practices is 224 percent. For every Btu of energy used, 3.24 Btus of energy was available in the soydiesel and co-products.

Industry Potential

The data in the third column of Table 1 assumes state-of-the-art agricultural practices and the integration of the latest technological advances in the extraction and esterification of the soy oil. This column assumes dedicated esterification plants producing soydiesel fuel in an integrated fashion with oil extraction and refining operation. Our examination of the European industry suggests that integrated systems equipped with superior material recovery options and better downstream separation equipment could cut the esterification energy needs into half.

If farmers and the process industry were to use the best techniques currently available, there would be a 310 percent net energy, benefit and an input/output ratio of 1:4.10.

Figure 2. Energy Input Components of Soydiesel Production



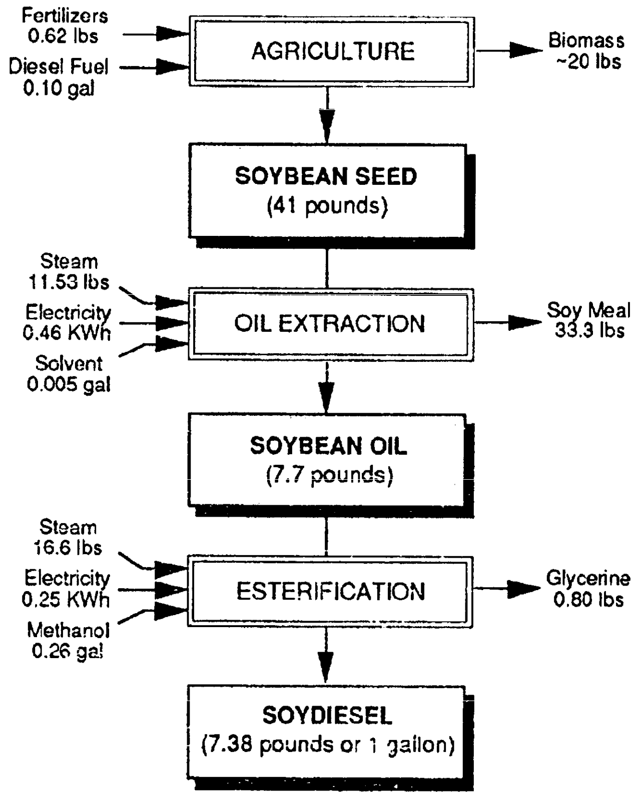
NOTE: A gallon of soydiesel contains 132,902 Btus of energy. Glycerine and soy meal co-products combined contain an additional 98,239 Btus per gallon of soydiesel produced. Total energy output from the system is 231,141 Btus per gallon of soydiesel produced.

Table 1. Energy Used to Make Methyl Ester (Soydiesel) from Soybean Crop in the United States (Btus per gallon of soydiesel)

		National Average	Industry Best	Industry Potential
AGRICULTURE ENERGY INPUT	Fertilizer	4,454	2,472	603
	Pesticide[1]	3,739	2,965	5,306
	Fuel	14,552	11,044	8,319
	Other (feedstock)[2]	6,691	5,967	6,691
	Total (feedstock)	**29,435**	**22,447**	**20,919**
PROCESSING ENERGY INPUT	Oil Extraction	32,053	18,768	18,768
	Oil Refining	1,092	984	984
	Esterification	29,341	29,172	15,727
	Total (processing)	**62,485**	**48,925**	**35,479**
	Total Energy Input	**91,921**	**71,372**	**56,398**
ENERGY OUTPUT	Energy in Soydiesel	132,902	132,902	132,902
	Co-Product Credits[3]	98,239	98,239	98,239
	Total Energy Output	**231,141**	**231,141**	**231,141**
ENERGY GAIN	**Net Energy Gain**	**139,220**	**159,769**	**174,743**
	Percent Gain	**151%**	**224%**	**310%**
	Input:Output Ratio	**1:2.51**	**1:3.24**	**1:4.10**

1 Energy input under pesticide also include herbicide and insecticide chemicals.
2 Other feedstock energy inputs include seed, on-farm electricity, lime, bulk transport of the crop for processing. A higher seed rate is employed in case of no-till cultivation method.
3 The co-product credits are based on replacement values for soy meal and glycerine produced during the soy oil extraction/refining and esterifications steps respectively.

Figure 3. Mass Flow Balance in the Production of a Gallon of Soydiesel



NOTE: A bushel of soybean is 60 pounds. To produce a single gallon of soydiesel, only 41 pounds of soybean is needed. The numbers presented here are based on one gallon of soydiesel produced.

1. HOW MUCH ENERGY IS USED TO GROW THE FEEDSTOCK?

Determining the energy used in growing soybeans is complicated by the fact that a wide variation in farming practices and conditions exist and the majority of soybeans grown in the country are cultivated as a rotation crop with corn.

Table 2 presents the energy input data for soybeans grown in the Midwest. We present both the national agriculture energy consumption based on the 1992 average crop yield of 37.6 bushels per acre and data from the state with the best yield returns to energy inputs. Iowa exhibited the best combination of low chemical application rates and high yields among the sixteen major soybean states.

Table 3 presents energy consumption of state-of-the-art soybean farms using no-till cultivation methods. No-till cultivation method utilize residual fertilizers from corn crop, although more pesticides and herbicides are applied and a higher seed application rate is used. For simplicity, we include herbicides and insecticides applications under pesticide.

The chemical application levels used in Table 2 are based on figures compiled by the National Agricultural Statistics Service of the U.S. Department of Agriculture for the top 16 soybean-growing states, accounting for 90 percent of the total soybean acreage.

For the 1992 crop year, we examined each of the three fertilizer components individually – nitrogen, phosphorous, and potash. Nitrogen is the most energy intensive chemical of all fertilizers with an energy content of 31,100 Btus per pound, followed by phosphorous with 5,560 Btus per pound, and potash containing 4,280 Btus per pound. For nitrogen, 15 percent of the acreage used an application rate of 22 pounds per acre.

The total nitrogen applied was 172.6 million pounds on 53.1 million acres surveyed. This translates into an average 3.25 pounds per acre. Applications of other chemicals are accounted the same way.

The soybean plant "fixes" its own nitrogen directly from the atmosphere. This reduces the need for nitrogen fertilizers. The energy in synthetic nitrogen applied to corn is a major factor in the overall energy balance of that crop, but for soybeans, this category is a much smaller fraction of energy.

The two columns under the national average and best existing sections of Table 2 present energy inputs in terms of Btus per gallon of soydiesel produced. This may require some explanation.

The national average soybean yield for 1992 was 37.6 bushels. A bushel of soybeans (60 pounds) yields 1.42 gallons of soy oil. The esterification of soy oil yields soydiesel on a one-to-one volumetric basis (a difference in density results into a less than one to one yield based on mass). Thus the net average yield of soydiesel per acre is 53.4 gallons. Energy inputs which are caluculated on a per acre basis can be converted to a per gallon of soydiesel basis by this factor.

For our "Industry Best," a state wide average soy bean yield of 44.0 bushels per acre translates to a yield of 62.5 gallons of soydiesel per acre.

Based on the national average, the single largest agricultural energy input is on-farm fuel consumption, accounting for almost half of all energy used. Fertilizer energy accounts for 15 percent of the total. Pesticides and herbicides account for about 13 percent of the total.

The "other" energy input category includes en-

Table 2. Agricultural Energy Inputs into Soybean Production in the United States

	National Average (yield: 37.6 bushels per acre)			Industry Best (yield: 44.0 bushels per acre)		
	Soybean (pounds per acre)	Soybean (Btus per acre)[1]	Soydiesel (Btus per gallon)[2]	Soybean (pounds per acre)	Soybean (Btus per acre)[1]	Soydiesel (Btus per gallon)[3]
Nitrogen	3.25	101,086	1,893	2.33	72,463	1,160
Phosphorous	10.36	57,618	1,079	6.82	37,919	607
Potash	18.49	79,139	1,482	10.30	44,084	706
Pesticide[4]	1.11	199,663	3,739	1.03	185,233	2,964
Fuel (gallons)	5.63	776,940	14,552	5.00	690,000	11,044
Other[5]	—	357,299	6,691	—	372,938	5,967
Total	—	1,571,745	**29,435**	—	1,402,937	**22,447**

1 Absolute energy content for individual input components used to convert pounds per acre to Btus per acre are: Nitrogen, 31,100 Btus per pound; Phosphorous, 5,560 Btus per pound; Potash, 4,280 Btus per pound; Pesticides, 179,838 Btus per pound; Diesel Fuel, 138,000 Btus per gallon.
2 In 1992, the average national soybean yield was 37.6 bushels per acre; the average soybean oil yield per bushel of soybean is 1.42 gallons. The overall soydiesel yield is 53.4 gallons per acre. The average 1992 soybean crop yield was about 10 percent higher than historical yields, however, the fertilizer and pesticide use was also recorded slightly higher than previous years.
3 Best existing data is based on the state with the lowest chemical application per bushel of the crop. The state of Iowa has been the most energy efficient state in the recent years with consistant higher yields than national average. The average Iowa state yield of 44 bushels per acre corresponds to 62.5 gallons of soydiesel per acre.
4 Pesticide figures include insecticide and herbicide application inputs.
5 Other energy inputs include seed, on-farm electricity, lime, and bulk transport of seeds for processing.

SOURCES: U.S. Department of Agriculture, National Agricultural Statistics Service, Agricultural Chemical Usage: 1992 Field Crop Summary, Washington, D.C., March 1993; Pimentel, D., ed., Handbook of Energy Utilization in Agriculture (Boca Raton, Florida.: CRC press, 1980); Turhollow, A., Oak Ridge National Laboratory, personal communication, August, 1993; Institute for Energy Analysis, Oak Ridge Associated Universities, Roles of Electricity: Agriculture (Palo Alto, California.: EPRI, 1987).

NOTE: Numbers in rows and columns may not converge and add-up exactly due to truncation or round-off errors.

ergy costs due to seed, on-farm electricity, lime, and transporting the crop for processing. This comes to about 6,700 Btus per gallon of soydiesel, or 23 percent of the total energy input on a national average basis. Transportation energy costs are based on a 50 mile crop transport distance by truck.

As presented in Table 3, no-till state of the art cultivation systems produce higher crop yields of about 50 bushels per acre, while using less chemical energy in terms of fertilizers. However, they use higher pesticide (herbicides) rates.

We have observed that any fertilizer use in a no-till system mainly uses potash fertilizers over the phosphorous. The soil tests indicate that potash depletion is higher than phosphorous in corn crop cultivation, and since soybean is almost always grown in rotation with corn, a potash application is needed.

More and more soybean farms are converting to no-till cultivation systems. This is particularly true in corn-soybean rotations. In such a system, the soy planting can also utilize some of the nutrients applied to a previous corn crop and either taken up by the corn and stored in the unharvested part of the plant or still present in the soil as the raw nutrient.

To gather data on state of the art practices we examined several individual farms.

The Thompson Farm in Jackson, Iowa, is a well-documented commercial enterprise. This farm has been able to grow no-till soybeans without using pesticides. A higher seed rate is needed so the soybeans can out-compete weeds. This higher seeding rate is reflected in the "other" energy input category. We estimated a net energy input of 17,623 Btus per gallon of soydiesel.

Another farm we examined uses no-till practices, but with higher pesticide (herbicides) application rates and lower fertilizer inputs. This calculates to an input of 20,919 Btus per gallon of soydiesel.

Table 3. Energy Input into Soybean Production in State-of-the-Art Farms

	No-Till with Herbicides[1] (yield: 50 bushels per acre)			No-Till without Herbicides[2] (yield: 50 bushels per acre)		
	Soybean (pounds per acre)	Soybean (Btus per acre)	Soydiesel (Btus per gallon)[3]	Soybean (pounds per acre)	Soybean (Btus per acre)	Soydiesel (Btus per gallon)[3]
Nitrogen	0	0	0	0	0	0
Phosphorous	0	0	0	0	0	0
Potash	10	42,800	603	30	128,400	1,808
Pesticide	2.73	376,740	5,306	0	0	0
Fuel (gallons)[4]	4.28	590,640	8,319	4.28	590,640	8,319
Other[5]	—	475,061	6,691	—	532,216	7,496
Total	—	1,485,241	**20,919**	—	1,251,256	**17,623**

1 Based on conversations with no-till farmers who used chemical applications to reduce weeds in the standard no-till crop cultivation system. In rotation with corn, soybean crop is excellent at utilizing residual nutrients applied to the previous corn crop. As with all legumes, soybean also "fix" nitrogen from the atmosphere instead of nitrogen uptake from soil.
2 Based on integrated crop-livestock culivation farming method as employed on the Thompson Farm in Jackson, Iowa.
3 The reported yield for no-till soybean production is 50 bushels per acre. Based on an average oil yield from soybean crop of 1.42 gallons per bushel, the overall methyl ester yield is calculated at 71 gallons of soydiesel per acre.
4 The on-farm fuel usage is calculated based on the fuel requirement for each of the steps employed in no-till cultivation.
5 Other energy inputs include seed, on-farm electricity, lime and bulk transport of the crop for processing. In the case of no-till without herbicides, the seed application rate is about 25% higher than average rates.

SOURCES: National Research Council: Board on Agriculture, Alternative Agriculture (Washington, D.C.: National Academy Press, 1989); Thompson, D., and Thompson, S., "No-Till Soybeans Without Herbicides," The New Farm, September/October 1982; Personal communication with several no-till soybean-corn farmers in the Mid-West, August-November, 1993.

NOTE: Numbers in rows and columns may not converge and add-up exactly due to truncation or round-off errors.

2. HOW MUCH ENERGY IS USED IN OIL EXTRACTION AND REFINING?

Among major oilseeds, soybeans have a relatively low oil content, roughly 20 percent. To be economical, soy oil extraction yields must be maximized.

The soy oil extraction and refining industry is well established. The industry uses solvent extraction systems that employ an organic solvent to extract oil from the crushed seeds, thus maximizing yield.

Over the years, the solvent extraction system has become a very well-established and technically mature operation. The standard solvent extraction process employs n-hexane as the solvent – most of which is recovered and recycled. Some loss is inevitable since n-hexane is a volatile solvent. The American Soybean Association estimates losses at between 1 and 2 gallons per ton of soybeans processed.

Improvements in extraction equipment and process management during the last decade has reduced the loss of hexane per ton of seed crushed to an estimated 0.7 gallons. That is about 0.015 gallons per gallon of soydiesel.

The fuel value of n-hexane is 106,522 Btus per gallon. We use the straight fuel value for n-hexane since it is a direct product of petroleum distillation requiring no extra energy in synthesis. Thus, n-hexane loss represents an energy input of 1,575 Btus per gallon of soydiesel.

The direct energy used for soy oil extraction is a significant portion of a crushing facility's operating costs and thus is closely guarded proprietary information. One source estimates the industry average energy requirements for the process as 285 Btus of electrical energy and 2,454 Btus of steam per pound of oil.

Taking into account energy efficiencies of 80 percent for steam generation and 32 percent for electrical power generation we estimate the total steam energy used per gallon of soydiesel produced

Table 4. Energy Input for Solvent Extraction and Primary Refining of Soy Oil

		Industry Average		Industry Best	
		Soybeans[1] (unit per ton)	Soydiesel[2] (Btus per gallon)	Soybeans[1] (unit per ton)	Soydiesel[2] (Btus per gallon)
EXTRACTION	Electricity (kWh)[3]	30.44	6,858	24.80	5,596
	Steam (pound)[4]	1,015	23,620	546	12,681
	Solvent (gallon)[5]	0.70	1,575	0.22	491
	Sub-Total	—	32,053	—	18,768
REFINING	Electricity (kWh)[3]	2.00	450	2.00	450
	Steam (pound)[4]	27.61	642	23.01	535
	Sub-Total	—	1,092	—	984
	Total	—	**33,145**	—	**19,753**

1 Soybean is roughly 20 percent oil by weight. One ton of soybeans yields 47.33 gallons of soy oil.
2 Soy oil is converted to soydiesel on a one-to-one volume basis where same amount of glycerin is replaced with methanol.
3 A kWh is equivalent to 3,412 Btus. The power generation efficiency of converting heat to electricity is taken at 32 percent.
4 Saturated steam at 150 psi has a heat of vaporization of 880 Btu per pound. Boiler efficiency for steam production is 80%.
5 The most common solvent used by the industry is n-hexane which has a fuel energy value of 106,522 Btus per gallon.

SOURCES: Singh, R.P., ed., Energy in Food Processing (New York: Elsevier Science, 1986); George Anderson, Crown Iron Works, personal communication, September-October 1993.

NOTE: Numbers in rows and columns may not converge and add-up exactly due to truncation or round-off errors.

is 23,620 Btus. For process electricity, the total energy consumption comes to about 6,858 Btus per gallon of soydiesel.

A minor component of the energy in processing is that required to "once refine" the raw oil (degum and drying processes). This totals to about 1,000 Btus and should not be confused with the more extensive refining which food-quality oil usually undergoes. The vast majority of soy oil is currently consumed in food and feed uses, so energy estimates quoted elsewhere may or may not include these extra steps. For all the steps of extraction and refining, an average of 33,145 Btus is required per gallon of soydiesel.

The trend over the last decade has been toward larger scale, dedicated soybean extraction plants. The resulting improvements in energy efficiency are reflected in the Best Existing section of Table 4. The basis for these calculations is a large-scale, new plant that would be built today. These figures are also used for the "state-of-the-art" category since the industry is technically mature and significant efficiency improvements are not expected.

Crown Iron Works, an engineering design and construction firm that builds oil extraction and refining plants, estimates that a 2,200 tons of soybeans per day extraction plant would require 21.6 kWhs and 545 pounds of steam per ton of soybeans. Considering the efficiency for steam and electrical generation, this comes to 17,547 Btus per gallon of soydiesel. New equipment would also reduce n-hexane losses to 0.22 gallons per ton of soybeans, or 491 Btus per gallon of soydiesel produced.

Based on these best existing facilities, 19,753 Btus of energy are needed per gallon of soydiesel for extraction and refining. In the industry best scenario, oil extraction and refining contributes about 27 percent of the total energy used in the system.

Although the use of cogeneration (not considered here) could improve the steam and electrical generation efficiency, its overall effect on the energy used in the process would be minimal.

The use of super-critical carbon dioxide as an extraction fluid has been explored. Substantial energy savings may result from this technology in the long run. In the near term, however, the capital costs and scale-up issues will limit its use to high-value industries like pharmaceuticals and in niche markets like organic edible oils where solvent extraction is not ideal.

3. HOW MUCH ENERGY IS USED IN OIL ESTERIFICATION?

The esterification of soy oil with methanol into methyl ester for fuel is an emerging industry.

Esterification is the only segment in the production cycle of soydiesel which is yet to be established exclusively for soydiesel production in the United States.

Soybean oil esterification is done currently as part of the production process of making surfactants. In this process the ester is further processed into vegetable-based surfactants for use in soaps and detergents and other consumer product industries. In other words, esters are an intermediate chemical in the manufacture of surfactants.

Since a commercial soydiesel industry does not yet exist in the United States and current soydiesel demonstration projects have been supplied with the ester fuel from fatty acid and surfactant production plants we have based our energy estimates by prorating the energy needs of these existing plants.

The energy calculations for this transesterification procedure for making intermediate esters and surfactants are based on data from the Procter & Gamble Co. plants. Since this is not a process optimized to produce the simple fuel-grade ester, we believe the energy requirements are slightly higher than would be expected in a dedicated fuel esterification plant.

Chemical inputs for P&G's esterification reaction include methanol as a reactant and sodium hydroxide (NaOH) as a catalyst.

In the case of surfactant methyl ester production, chemical input rates are low since a double distillation system is used to recover excess methanol and glycerine by-product.

Any new fuel ester production facility would have to make a trade-off between chemical recovery levels, energy expenditures, and capital costs. Distillation recovery of materials is an energy intensive process and involves a significant capital expenditure for distillation columns, especially for small-scale production. Hence the economics of smaller scale operations may dictate a lower recovery rate. Thus the reactants supplied in excess would be lost in the reaction, increasing chemical energy inputs.

We have used 66,541 Btus per gallon as the energy embodied in methanol. This is the fuel value of this alcohol plus a surcharge for its production from natural gas That synthesis reaction has been calculated at 85 percent thermal efficiency. NaOH production by electrolysis of salt is an energy intensive process. This inorganic catalyst represents an energy value of 11,275 Btus per pound.

The overall energy consumed in the esterification step is 29,341 Btus per gallon of soydiesel produced.

The U.S. industry potential is based on an estimate from Crown Iron Works, a major supplier of oil extraction and processing equipment. The hypothetical nature of this estimate prompted us to assume the high end of the quoted range for direct heat energy input (steam).

For comparison, we have included data from the European fuel ester industry. In Europe, rapeseed is the crop used. The primary difference in the overall production cycle is because of the higher oil content of rapeseed. This results in a difference in the energy used in oil extraction but not in oil esterification.

The first European estimate is based on an average dedicated fuel production plant located in France. The European potential is an estimate of improvements possible in the short term.

The energy requirements for the existing French plant are shown in Table 5 in the "Present Industry" column. This plant represents a dedicated vegetable oil esterification facility set up for fuel production only from rape seed oil.

Table 5. Energy Inputs into Vegetable Oil Esterification Process

		United States[1] (Btus per gallon of soy methyl ester)		Europe[2] (Btus per gallon or 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
	Sub-Total	20,891	5,826	10,391	6,138
CHEMICAL INPUTS[3]	Reactant	7,320	8,650	17,301	8,650
	Catalyst	902	1,128	1,353	1,128
	Sub-Total	8,222	9,778	18,654	9,778
Transport (ester)		228	123	127	127
	Total	**29,341**	**15,727**	**29,172**	**16,043**

1 In the U.S., the existing esterification industry is set up to process vegetable oils as part of the surfactant production process. Processes idealized for fuel ester production would show a significant direct energy savings. Both in the U.S. and the Europe columns, the Industry Potential is based on full-scale ester-dedicated facilities designed to produce at least 5 MGPY soydiesel.
2 In Europe, methly ester fuels are made primarily from rapeseed oil. The Existing Industry column is based on a 20,000 metric tonnes per year plant in France producing approximately 6 million gallons of biodiesel annually.
3 The energy content value for the reactant (methanol) is 66,542 Btu per gallon; Methanol has a fuel value of 56,560 Btus per gallon plus a synthesis thermal efficiency of 85 percent for production based on natural gas. The catalyst, sodium hydroxide (NaOH), is manufactured using 11,275 Btus per pound of the product.

SOURCES: Pittinger, C.A., et al., "Environmental Life-Cycle Analysis of Detergent-Grade Surfactant Sourcing and Production," Journal of the American Oil Chemists Society, Jan 1993; Richard Peters, The Procter & Gamble Company (Cincinnati, Ohio), personal communication, November, 1993; George Anderson, Crown Iron Works, personal communication, September-October 1993; Staai, F., and Vermeesch, G., "Rape Methyl Esters as Diesel Fuel: Energy Balance," Revue Francaise des Corps Gras, May-June, 1993; International Energy Agency, Production of Alcohols and Other Oxygenates from Fossil Fuels & Renewables, Report No. 2 of the IEA Program of Research and Development on Alternative Motor Fuels, April 1990.

The Industry Potential column in Table 5 is based on a full-scale esterification plant. We estimate that the best esterification techniques could use slightly less than 16,000 Btus per gallon of soydiesel.

Our industry potential analysis does not account for possible energy credits from burning the organic residue resulting from the glycerine purification step. Recent systems designed at the University of Idaho indicate that organic residue produced during the soydiesel production process could provide most of the boiler fuel to supply process steam to an efficiently designed excess alcohol recovery and glycerine purification distillation systems.

Accounting for residual energies combined with other improvements would substantially increase the net energy balance of soydiesel production.

4. HOW DO WE DIVIDE THE ENERGY USED AMONG THE PRODUCTS?

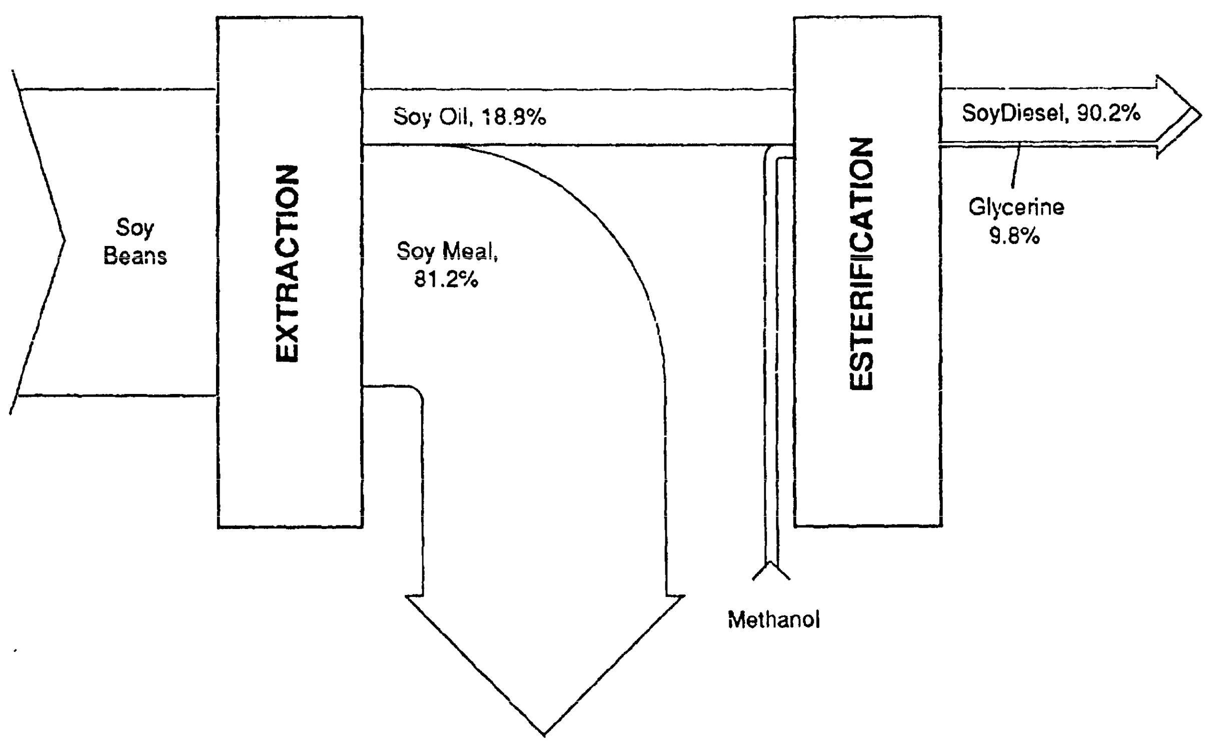
Conversion of the soybean into soydiesel consists of two separate steps, each of which generates a single coproduct. Soy meal results during the oil extraction from the bean and glycerine is the coproduct of esterification of soy oil.

We have used three methods to assign an energy value to these co-products: weight fractionation, value fractionation, and calculation of a replacement credit based on the displaced energy value of a similar product.

Weight Energy Credit

Energy credit based on weight fraction is the most straight-forward of all the coproduct valuations. Out of each processing step comes two products to which a fraction of the processing energy is charged. To calculate the energy value of soy meal, we first calculated that meal represents 81.2 percent of the total mass of material leaving the oil extraction step. This weight fraction of 0.812 is then used to allocate a proportion of the energy going into the agricultural

Figure 4. Mass Flow in Conversion of Soybeans to Soydiesel (percentage output of each processing step)



production of soybeans as well as the energy going into oil extraction. This represents 49,931 Btus per gallon of soydiesel. Figure 4 presents the weight fraction allocation in a schematic form.

The same rationale can be used to assign to glycerine a fraction of the energy used in esterification. With each gallon of soydiesel produced about 0.8 pounds of glycerine is also produced. This 0.8 pounds represents 9.8 percent of the mass of the soydiesel and glycerine together.

The total energy for esterification is 29,341 Btus per gallon of soydiesel,, Thus the share assigned to glycerine is 2,865 Btus. The two coproducts combined total to 52,796 Btus per gallon of soydiesel.

Value Energy Credit

To assign the coproduct credits based on value, the allocation procedure is essentially the same as that used for weight credits. The energy involved in a given processing step is no different, but the proportion of the energy assigned to each product is different. Under this method, it is not the raw mass of the products which determines the assignment of energy, but the market value of those products.

Soy meal is a high-volume, low-value product while glycerine is a high-value, low-volume product. The value fraction for soy meal is lower than the weight fraction, while for glycerine, the opposite is true.

Soy meal at $189 per ton ($0.09 per pound), represents 68.2 percent of the value of the products of oil extraction. Using this fraction as the dividing function of the agricultural and extraction energies, we arrive at a value of 42,576 Btus per gallon of soydiesel for the meal. Figure 5 schematically presents this analysis.

In the case of esterification, glycerine represents 43.6 percent of the value of those products (when soy-diesel is assigned the same dollar value as petroleum diesel fuel). Thus 12,802 Btus per gallon of soydiesel are assigned to glycerine. The total energy for coproducts calculated in this manner is 55, 378 Btus per gallon of soydiesel.

Replacement Credit

Since the coproducts will be sold into a specific product market, the best way to assign an energy credit to the soydiesel coproducts may be to evaluate

Figure 5. Value Flow in Conversion of Soybeans to Soydiesel (percentage output of each processing step)

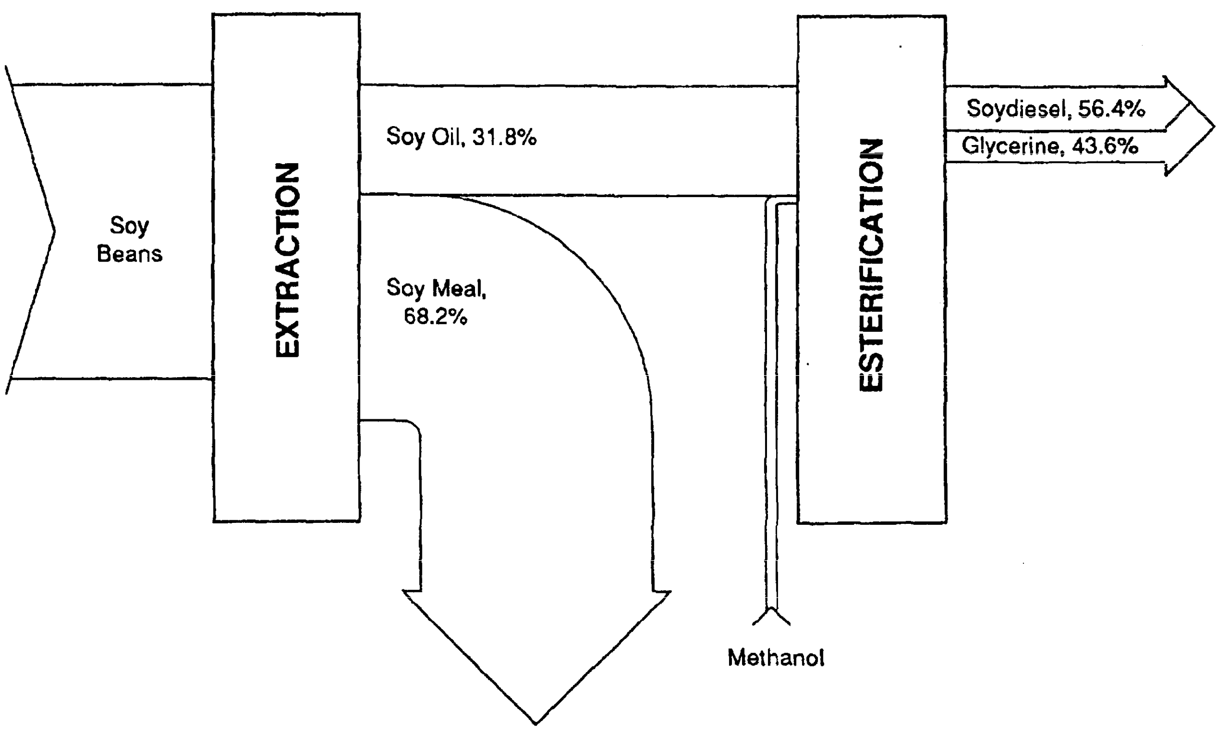


Table 6. Co-Product Energy Credit Methodologies for Soy Methyl Ester (Btus per gallon of soydiesel)

	Soy Meal[1]		Glycerine[2]		Total Co-Products
	Fraction	Value	Fraction	Value	
Weight Energy Credit	81%	49,931	10%	2,865	52,796
Value Energy Credit	68%	42,576	44%	12,802	55,378
Replacement Credit[3]	—	81,229	—	17,010	98,239

1 Soy meal coproduct credit is derived based on weight and value fraction of the feedstock soybean into oil and meal.
2 Glycerine coproduct credit is derived based on weight and value fraction of the soybean oil into glycerine and ester.
3 One pound of soy meal is replaced by 2.3 pounds of feed barley (on protein equivalency and price equivalency basis). Energy for producing barley is 1,069 Btus per pound. Glycerine is replaced by synthetic glycerine which is derived from propylene using chlorine and calcium hydroxide. Epichlorohydrin is a intermediate product in this petrochemical route. The energy totals to 21,296 Btus per pound of glycerine.

SOURCES: Pimentel, D., ed., Handbook of Energy Utilization in Agriculture (Boca Raton,, Florida: CRC Press, 1980); Austin, G.T., ed., Shreve's Chemical Process Industries, 5th ed. (New York: McGraw-Hill Co., 1984); and "Cash Prices, Selected U.S. Commodities," Agricultural Outlook, USDA-ERS, Washington, D.C., May 1993.

NOTE: Numbers in rows and columns may not converge and add-up exactly due to truncation or round-off errors.

the equivalent energy that would be displaced by not producing the replaced product (given no change in the market demand). A primary replacement for soy meal (primarily fed to cattle) is feed barley. For glycerine, a widely used specialty chemical, petrochemical derived glycerine is the major competitive product.

For feeds, protein content is the main determining factor of value. Soy meal at 48 percent protein is the protein equivalent of about 2.3 pounds of barley. Not surprisingly, the price ratio for the two feeds is practically the same as the protein ratio.

Producing and drying barley requires about 1,069 Btus per pound. The equivalent of 33 pounds of soy meal (the amount co-produced with each gallon of soydiesel) is 76 pounds of barley which represents 81,229 Btus. Tables 6 and 7 summarize our results.

Table 7. Raw Material Energy for Synthetic Glycerine Production

Raw Materials for Glycerine Production	Raw Material Input (lb/lb Glycerine)	Raw Material Energy Content (Btus/lb)	Glycerine Energy Input (Btus/lb)
Propylene	0.62	8,577	5,318
Chlorine	2.00	5,319	10,638
NaCl	0.45	592	266
NaOH	0.45	11,275	5,074
Total	—	—	21,296

NOTE: Production of glycerol from epichlorohydrin is an exothermic reaction requiring no heat and occuring at atmospheric pressure. The electricity required for stirring reactors is minimal and is neglected in this analysis.

SOURCES: Handbook of Petrochemicals and Processes. Austin, G.T. ed., Shreve's Chemical Process Industries (5th ed.) (New York: McGraw-Hill, 1984). Pittinger, C.A., et al., "Environmental Life-Cycle Inventory of Detergent-Grade Surfactant Sourcing and Production," Journal of the Americal Oil Chemists' Society, vol. 70, no. 1 (January 1993), 1-15.

Glycerine is produced from petrochemical sources using propylene, chlorine, and sodium hydroxide as raw materials. The energy required for this process is primarily in the production of these feedstocks. Electrolysis of sodium chloride to produce elemental chlorine and sodium hydroxide is energy intensive. The materials used are cheap, thus their extensive recovery is often ignored.

The final synthesis requires very little energy (the amount is ignored for this analysis) but the raw materials for synthetic glycerine represent 21,296 Btus per pound of glycerine produced. This value is taken as its replacement value. The production of one gallon of soydiesel produces 0.8 pounds of glycerine, so on a per gallon soydiesel basis, glycerine provides 17,010 Btus.

CONCLUSION

Soydiesel production is a net energy generator. Based on national averages, the growing and harvesting of soybeans, oil extraction and refining, and the esterification of oil into a fuel ester consumes 91,921 Btus per gallon of soydiesel produced. A gallon of soydiesel contains 132,902 Btus per gallon.

Even without assigning any energy value to the two co-products produced in the process – soy meal and glycerine – the net energy balance is a favorable 40,981 Btus for every gallon of soydiesel produced. When energy credits based on their respective replacement values are included, the net energy benefit rises to 98,239 Btus per gallon, resulting in an input/output ratio of 1:2.51.

Using farming and industry best practices improves the positive energy balance further.

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