Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels

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This is not the actual paper. It is only a detailed synopsis. It's purpose is to make the original paper more accessible to the press and public. If you want to quote the authors, you must buy their paper here for $10–a very fair price. This synopsis was produced by Dr. Steven Stoft for zFacts.com. [Bracketed comments are his.] This is currently the most careful and accurate paper on ethanol and biodiesel and is crucial to the public debate.

Abstract. Environmental concerns and shortages of fossil fuels have spurred interest in biofuels for transportation. Biofuels should provide a net energy gain, environmental benefit, a competitive cost, and not reduce food supplies if widely used. This paper evaluates corn ethanol and soybean biodiesel on this basis. Ethanol yields 25% more energy and biodiesel 93% more than used in their production. Biodiesel releases 100 times less agricultural nitrogen, and about 10 times less phosphorous and pesticides than ethanol. Ethanol use reduces greenhouse emissions by 12% and biodiesel by 41%. Neither biofuel can replace much petroleum without impacting food supplies. Even dedicating all U.S. corn and soybean production to biofuels would meet only 12% of gasoline demand and 6% of diesel demand. [While increasing other energy use.] Biodiesel provides sufficient environmental advantages to merit subsidy.

Concerns over energy shortages and global warming have stimulated interest in transportation biofuels. Both direct and indirect inputs must be tracked in full to determine if these are beneficial. This paper determiners the net societal benefits of corn ethanol and biodiesel relative to gasoline and diesel by using current farm and fuel production data.

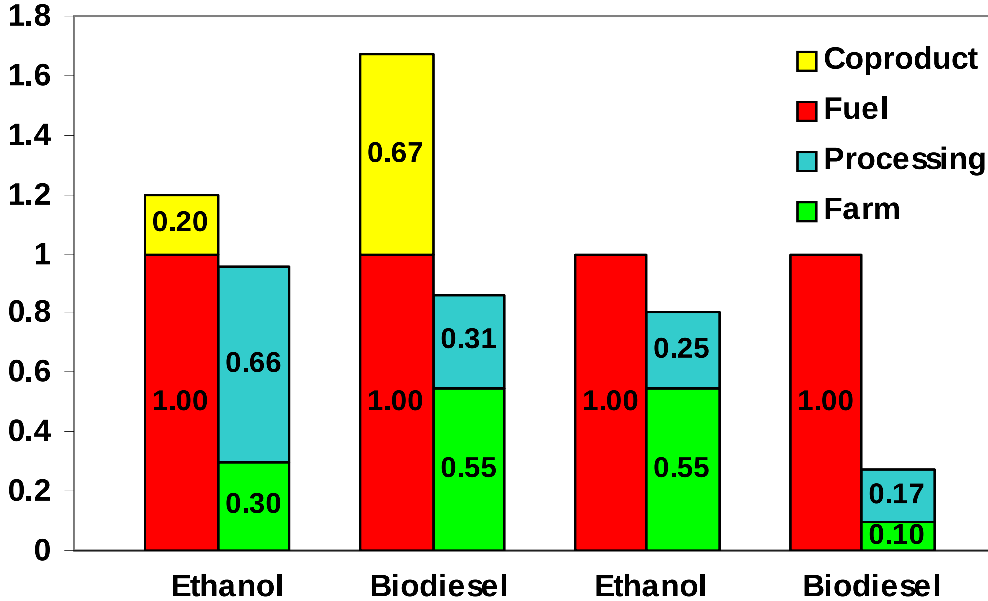
A desirable alternative fuel should be "economically competitive with" [by which the authors mean "almost as cheap as"] the fossil fuel it replaces, be environmentally superior, and be available in large quantities. It should also provide a net energy gain. Both fuels are analyzed as if produced by an "island economy" and considered to have a net energy gain only if the energy value of the island's exports of fuel and coproducts exceeds the sum of direct and indirect energy inputs. (See Tables 1–6).

This paper estimates farm energy inputs for corn and soybeans, including energy to grow seed, power and produce farm machinery and buildings, produce fertilizers and pesticides, and sustain farmers and their households. Similar inputs are considered for biofuel production. Production outputs include the fuels and their coproducts. The fuels are assigned the energy available from the combustion [lower heating value]. Coproducts, such as DDGS and glycerol, are assigned their energy equivalent values.

Results

Net Energy Balance (NEB). In spite of tracking indirect energy inputs so extensively, the paper shows that both corn ethanol and biodiesel have a positive NEB (see Fig. 1 and Tables 7 & 8). Energy out exceeds energy in. This reinforces recent finding (1–5). Although these earlier reports omit some indirect energy inputs, recent increases in crop yields and efficiencies offset the more complete inclusion of inputs found in this paper. These results counter the assertion that "expanding system boundaries" [including more indirect inputs] automatically causes negative NEB values (6–8). [Standard economic input-output analysis, developed in the 1930's, confirms this.[1]] This paper finds no evidence that either biofuel requires more energy to make than it contains, but corn ethanol provides only 25% more energy than needed to produce it. The advantage of soybean biodiesel, which provides 93% excess energy remains no mater which of five different coproduct accounting methods is used (see Table 9). [At least four of these methods are incorrect, but checking them should help convince skeptics.] [The original Figure 1 contains far more detail than this simplification.]

Fig. 1 Input and Output Energies for Corn Ethanol & Biodiesel with and without coproduct credits



	Corn Ethanol	Biodiesel	Ethanol w/o coproducts	Biodiesel w/o coproducts
NEB	0.24	0.81	0.20	0.73
NEB ratio	1.25	1.93	1.25	3.67

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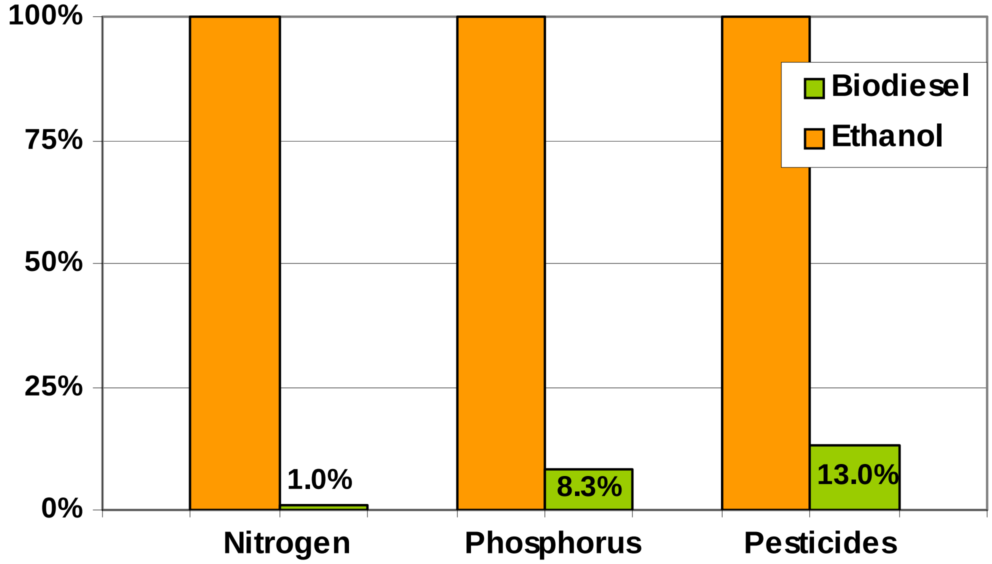
[1] Input-output analysis traces inputs back forever. This has been shown to give the correct answer, and input-output analysis provides the mathematics for doing these infinite sums. Suppose A requires 0.5 energy units plus half a unit of A as input. Then the total energy used by A is 0.5 + 0.25 +0.125 + ... forever. This infinite sequence simply sums to 1, which is the correct total energy use.

Life-Cycle Environmental Effects. Corn and soybean farming both degrade the environment by contaminating other habitats and water supplies with chemicals, especially nitrogen,

Fig. 2a,b Relative Fertilizer and Pesticide Use for Corn Ethanol and Biodiesel



phosphorus, and pesticides. Contamination of water by nitrogen and phosphorus causes over-enrichment and excessive plant growth, loss of biodiversity, and increased nitrate and nitrite in drinking water. Accounting for coproducts, per unit energy gained, biodiesel uses only 1.0% of the Nitrogen used by ethanol. Similarly, biodiesel uses 8.3% of the Phosphorus and 13% of the pesticides used by ethanol (Fig. 2ab; see also Table 10). These differences have substantial consequences, including nitrogen fertilizer for corn being a major contributor to the "dead" zone in the Gulf of Mexico (11) and to nitrate, nitrite, and pesticide residues in well water. Corn pesticides tend to be more harmful and long-lived than those used on soybeans (Fig 2b and Table).

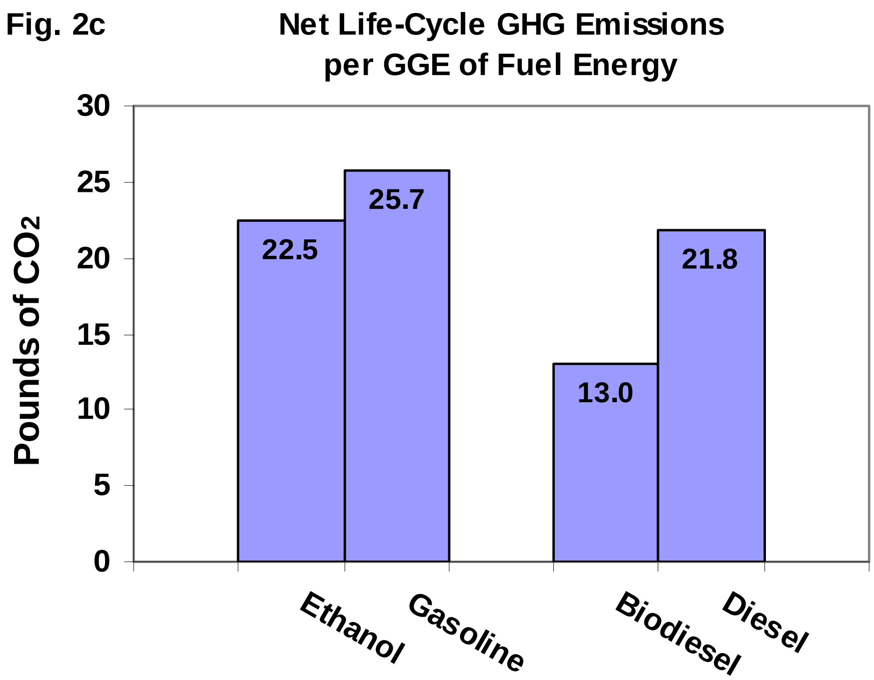
"E10" (10% ethanol and 90% gasoline) can lower emission of carbon monoxide (CO), volatile organic [bad organic] compounds (VOC) and very small particulate matter (PM10). However, with "E85," total-life-cycle emissions of five major air pollutants are higher per unit energy than with gasoline (12). These are CO, VOC, PM10, sulfur oxides (SOx) and nitrogen oxides (NOx). Low levels of biodiesel blended into diesel reduce VOC, CO, PM10, and SOx during combustion, and biodiesel blends show reduced life-cycle emissions for CO, PM10, and SOx relative to diesel (5).

If CO_2 from fossil fuel combustion was the only GHG (greenhouse gas) considered, a biofuel with NEB > 1 should reduce GHG emissions. [This is likely because the solar energy (plant) input is CO_2 neutral, but the use of coal as an input tends to counteract this.] However nitrogen fertilizer and microbes can work together to release N_20, a potent GHG (13). Analyses reported in Table 11 suggests that the use of corn ethanol releases 88% as much GHG as the equivalent use of gasoline (Fig. 2c). Another recent study found 87% using different methods (1). In contrast, biodiesel use releases 59% as much as equivalent diesel use. It is important to note that these estimates assume crops are harvested from land already in production; starting with intact ecosystems would result in reduced GHG savings or even reverse it.

Economic Competitiveness and Net Social Benefits.
Because the environmental costs of fossil fuels are not capture in market prices, biofuels that impose fewer non-market costs deserve a subsidy to level the playing field. [Or we could tax fossil, or better yet, tax fossil fuel just enough to pay the biofuel subsidies.]

At average 2005 gasoline prices, it cost $1.74 to produce ethanol (14–16) compared with

Fig. 2c



$1.67 for gasoline (17), while biodiesel (14–16) cost $2.08 compared with $1.74 for diesel (17). All of these values are wholesale prices per gasoline-gallon equivalent (GGE) of energy content. Although not cost competitive, the may have been profitable because of large subsidies. The federal government provides subsidies of $0.76 per GGE for ethanol [$0.51/gallon] and $1.10 per GGE for biodiesel (19). Demand for ethanol is also enhanced by laws and regulations which require blending some ethanol with gasoline [in some locations]. [This has recently raised wholesale prices above the level determined by the subsidy.] Ethanol and biodiesel producers also benefit from federal crop subsidies that lower corn prices (which are approximately half of ethanol production's operating costs) and soybean prices.

Potential U.S. Supply. In 2005, 14.3% of the U.S. corn harvest was processed to produce 3.91 billion gallons of ethanol (20, 21), containing the same energy as 1.72% of U.S. gasoline usage (22). Similarly, 1.5% of the soybean harvest produced 67.6 million gallons of biodiesel (20, 23), which was 0.09% of U.S. diesel usage (22). Using the entire corn and soybean crops would have replaced 12% and 6% of gasoline and diesel usage. Because of their large fossil energy input requirements, this would have provided net energy gains of only 2.4% and 2.9% respectively. Using the all corn and soybeans for biofuels is unlikely because they are major food sources (e.g., high-fructose corn syrup and soybean oil), and sources of livestock feed.

Discussion

Soybean biodiesel has major advantages over corn ethanol. It provides 93% more energy than its production consumes in fossil fuel, reduces several major air pollutants and reduces GHGs by 41%. It has minimal impact on human and environmental health through Nitrogen, Phosphorus, and pesticide release. By contrast corn ethanol provides only a 25% energy gain and a 12% reduction in GHGs and has greater environmental and human health impacts.

Biofuels would provide greater benefits if their agricultural inputs required less fertilizer, pesticide, and energy, and were produced on low-value land and required less energy to convert these inputs to biofuel. Neither corn ethanol nor soybean biodiesel do well on the first two criteria. Soybean biodiesel, however, requires far less conversion energy than corn ethanol (Fig. 1) because soybeans create long-chain triglycerides that are easily extracted. Corn starches must be converted to sugars with enzymes, the sugar fermented to alcohol by yeast, and the alcohol distilled to remove the water.

The NEB of both biofuels could be improved, and perhaps their costs reduced, by use of low-input crops or agricultural residues (such as corn stover) in place of fossil fuel in the conversion process. Switchgrass, diverse mixtures of prairie grasses and forbs (24, 25), and woody plants, can all be converted into synfuel hydrocarbons or cellulosic ethanol. These can be produced on marginal lands with no, or low, fertilizer, pesticides, and energy inputs (24, 25). For cellulosic ethanol, combustion of waste biomass, could power processing plants. Although gains may be reduced by increased energy for transport, construction of larger plants, and perhaps greater labor needs, resultant NEB ratios as high as 4.0 might still be possible (26, 27)—a major improvement on corn ethanol's ratio of 1.25 and even biodiesel's 1.93. Combined-cycle synfuel and electric cogeneration (30) may do as well or better than cellulosic ethanol. In sum, low-input biofuels save much more energy and have much lower environmental impacts per unit of fuel energy than do food-based biofuels.

Global demand for food is expected to double within the coming 50 years (31), and more than double for transportation energy (32). Food-based biofuels, which tend to be more damaging to the environment, can play only a small roll in meeting these needs, while energy conservation and non-food biofuels show far greater long-term promise (33).

Methods

Energy Use in Crop Production. This study uses 2002–2004 USDA data on fertilizer, soil treatment, and pesticide usage for corn (Table 1) and soybeans (Table 2). Estimates of the energy needed to produce each of these inputs are derived from recent studies (2–7). The study also estimates energy use for operating equipment, manufacturing this equipment, constructing buildings used in crop production (Table 3), and for producing the hybrid (corn) or varietal (soybeans) seed planted. We transform these per-acre estimates into per-gallon estimates based on 388 gallons of ethanol per acre and 58 gallons of biodiesel per acre. The study also estimates the per-gallon-of-biofuel energy use to sustain farm households (Table 4).

Energy Use in Converting Crops to Biofuels. This study estimates the energy used to build conversion plants (Table 6), to transport crops and biofuels (Table 5), and to power the plants. Again, energy use by households of laborers is included (Table 4).

Energy Yield from Biofuel Production. This paper defines NEB and the NEB ratio as follows:

NEB = (energy in biofuel + energy credit of coproducts) – (total energy inputs)
NEB ratio = (energy in biofuel + energy credit of coproducts) / (total energy inputs)

For coproducts DDGS and glycerol, energy credit is assigned by the "economic displacement" method which assigns them the energy required to produce the marketplace products which are their closest substitutes. [This is the correct method because it answers the question, how much more energy would be used if we did not produce the biofuel? The choice of method for evaluating coproduct energy is not a matter of convention as many have asserted. For the question under examination, this is the only correct method. —zFacts] Specifically corn and soybean meal are evaluated to find the energy credit fo DDGS, and synthetic glycerol is evaluated for soybean-derived glycerol.

Soybean meal does not have an adequate substitute in the marketplace based on both its availability and protein quality, so this paper uses a "mass allocation" method to estimate its coproduct energy credit. This assigns the coproduct a credit equal to the total energy input to the production process times the ratio of coproduct weight to the weight of soybeans processed. [This method is incorrect, but it provides a rough guess of the correct energy credit. —zFacts] The paper also applies alternative methods of calculating coproduct credits including issuing energy values based on caloric content and market value (Table 9). [All of these methods are also incorrect, but they may give some idea of the inaccuracies caused by using incorrect methods. It would probably have been better make an estimate of what the market would have done in the absence of soybean meal. —zFacts]

Environmental Effects. Life-cycle environmental impacts include combustion and production, and are computed per unit of energy gained as measured by NEB. If the impact is X per gallon of biofuel, and the NEB is 0.24 GGE per gallon, then the impact is calculated as 0.24×X per gallon. This is done for fertilizer and pesticide application rates (Table 10) and for GHG savings. GHG savings includes savings from replacing the fossil fuel with the biofuel and emissions from producing the biofuel and from GHG released on the farm.

End of Synopsis

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Table 1. Farm energy inputs into corn grain ethanol production

	Application rate, kg/ha	Production energy requirement, MJ/kg		Per hectare energy usage, MJ/ha		Input energy in ethanol production, MJ/liter*	
Hybrid seed	-	-		215†	(2)	0.06	
Nitrogen	146.1	51.47‡	(2, 4, 5)	7,523		2.07	
Phosphorus	53.1	9.17	(3-5)	486		0.13	
Potash	65.6	5.96	(2-5)	391		0.11	
Lime	-	-		313§	(2, 5, 6)	0.09	
Herbicide	2.23	319¶	(3-6)	713		0.20	
Insecticide	0.08	325	(3-6)	26		0.01	
Fossil fuel	-	-		8,484‖		2.34	
Farm capital	-	-		769	(Table 3)	0.21	
Household	-	-		-		1.18	(Table 4)
Total						6.39	

Application rates of nitrogen, phosphorus, potash, herbicides, and insecticides are 2003 averages of the nine top corn-producing states (IL, IN, IA, MI, MN, NE, OH, SD, and WI) weighted by state production (1). Production energy requirements are average values of five studies representing recent independent estimates of corn grain ethanol NEB (2-6), with exceptions as noted.

* The 2000-2004 average annual yield of the top nine corn-producing states weighted by their total production is 9,296 kg/ha (7, 8). These nine states accounted for 79.1% of domestic corn production in 2004. The dry-mill conversion efficiency of ethanol from corn is 0.3908 liters/kg, which is an average of three estimates (2-4). We exclude wet-milling conversion efficiencies (5). The dry-milling process currently accounts for 75% of the corn grain ethanol production market share and is expected to increase (9). We omit estimates based on older technologies (e.g., 0.3726 liters/kg) (6) that are dramatically lower than recently documented dry-mill plant efficiencies (e.g., 0.3979 liters/kg) (9, 10).

† Hybrid corn seed, which is planted to grow the corn used to generate ethanol, requires additional production steps when grown, processed, and distributed. Our estimate of the energy required to produce hybrid corn seed is derived from the only study that both uses current USDA data and provides the formula used to derive this estimate (2). We exclude studies that do not account for the energy to grow the hybrid seed (4), are based on research > 25 years old (6), do not thoroughly explain how they derived their estimate (3), or are not well supported (5).

‡ Estimates of fertilizer production energy requirements from one study (6) are excluded because they are from sources that do not reflect current domestic production efficiencies (e.g., the Food and Agriculture Organization, which is not specific to the U.S.). Additionally, for nitrogen we exclude an estimate that includes transportation energy (3), and for phosphorus we exclude an estimate that is substantially lower than others (2).

§ Unlike fertilizer and pesticide use, lime use is not systematically reported by the USDA. Therefore, we rely on other studies for lime application rates as well as energy intensity. We exclude those studies that either exclude this input analysis (4) or have too low a value (3). We divide liming energy inputs equally between corn and soybean production.

¶ We exclude the estimate that provides a combined pesticide input (2) because it is not parsed into insecticides and herbicides.

‖ This category includes fossil fuels directly used in crop production (diesel, gasoline, electricity, natural gas, and LP gas), custom work, farm-related transportation, and personal commutes. We exclude an estimate of fossil fuel use that is substantially lower than those of the other studies (4). We prorate the energy for irrigation of one of the studies (6) to reflect that only 15% of corn acreage in the nine states is irrigated. We exclude estimates for custom work that include worker sustenance energy (5, 6), which we account for separately as part of our expanded category of household energy usage. Our farm-related transportation estimate is from one study (2), and we specifically exclude another (6) because the assumption that machinery, fuels, and seeds were shipped an estimated 1,000 km is unrealistic. Our personnel commute energy estimate is based on the only study that includes this input (5), although we modify this estimate by using our corn yield rate and corn to ethanol conversion rate.

Table 2. Farm energy inputs into soybean biodiesel production

	Application rate, kg/ha	Production energy, MJ/kg		Per hectare energy use, MJ/ha		Input energy in biodiesel production, MJ/liter*	
Varietal seed	-	-		420†		0.77	
Nitrogen	5.7	51.47‡	(2, 4, 5)	291		0.53	
Phosphorus	17.2	9.17	(3-5)	158		0.29	
Potash	30.1	5.96	(2-5)	179		0.33	
Lime	-	-		313§		0.58	
Pesticide	1.2	475¶		605		1.11	
Fossil fuel	-	-		3,361‖		6.18	
Farm capital	-	-		769	(Table 3)	1.41	
Household	-	-		-		6.79	(Table 4)
Total						17.99	

Fertilizer application rates are 2002 and 2004 U.S. annual averages (11, 12). Pesticide application rates are 2004 weighted averages of the top 11 soybean-producing states (AR, IL, IN, IA, KS, MN, MO, NE, ND, OH, and SD) (12).

* The 2000-2004 average yield of the 31 soybean-producing states weighted by total production is 2,661 kg/ha (7, 8), and 4.89 kg of soybeans are crushed per liter of biodiesel produced.

† Given a weighted soybean yield of 2,661 kg/ha and a national average seeding rate of 76.1 kg/ha (13), 2.86% of one year's crop can be used to plant the same acreage the next year. We assume that growing, processing, packaging, and transporting soybean seed for planting requires 150% of the energy used to grow soybeans used for feed or industrial purposes (14). We therefore estimate the energy to produce the soybeans needed to plant 1 ha of land as 4.29% the energy to produce 1 ha of soybeans for direct use for feed and fuel (9,791 MJ/ha).

‡ Fertilizer production energy is the same as in corn production.

§ Because we assume corn and soybeans are grown in rotation, we divide the liming energy input between corn and soybeans equally.

¶ In 2004, glyphosate, which requires approximately 475 MJ/kg to produce and distribute (15), accounted for 81% of all pesticide use (12). We assume that the energy to produce glyphosate is similar in all pesticides used in soybean farming; however, this is likely an overestimate as glyphosate tends to be more costly in energy terms to produce than other pesticides (2).

‖ Estimates of farm fossil fuel use for truck and tractor use, irrigation, and drying were taken from 2002 ERS-USDA survey data (16) and weighted by average state production. Energy content and average usage rates are as follows: diesel (36.6 MJ/liter and 38.4 liters/ha), gasoline (32.05 MJ/liter and 12.2 liters/ha), electricity (3.6 MJ/kWh and 69.4 kWh/ha), natural gas (37.3 MJ/m^3 and 3.7 m^3/ha), and LP gas (25.5 MJ/liter and 3.7 liters/ha). We also estimate custom work diesel use of 6.6 liters/ha (14), and farm-related transportation and personal commute energy use equal to those of corn farming.

Table 3. Energy to produce machinery and capital used on a representative 120-ha farm with a corn/soybean crop rotation

Machinery and capital	Weight of equipment, Mg	Production energy, GJ*	Per hectare annual production energy, MJ/ha/yr†	Equipment energy per unit of biofuel production, MJ/liter ‡	
				Ethanol	Biodiesel
Tractor - large	10.2	383	210	0.029	0.193
Tractor - small	5.6	210	115	0.016	0.106
Field cultivator	2.4	89	49	0.007	0.045
Chisel plow/ripper	3.6	134	74	0.010	0.068
Planter	3.4	128	70	0.010	0.064
Combine	11.9	445	244	0.034	0.224
Soybean combine head	2.8	104	57	0.008	0.052
Corn combine head	3.6	136	75	0.010	0.069
Gravity box (x4)	6.6	248	136	0.019	0.125
Auger	0.8	28	15	0.002	0.014
Grain bin (x3)	9.5	358	197	0.027	0.181
Irrigation§	4.8	179	98	0.014	0.090
Sprayer	0.5	17	9	0.001	0.008
Agricultural buildings	9.1	341	187	0.026	0.172
Total	74.8	2,800	1,538	0.212	1.414

* For each piece of machinery and equipment, we assume for purposes of calculating its embodied energy that it consist entirely of steel. It takes 25 MJ/kg to produce steel (17, 18) and an additional 50% energy use for assembly (2).

† All items are assumed to have a service life of 15 years.

‡ We use values of 3,632 liters of ethanol and 544 liters of biodiesel produced per hectare.

§ We assume that 15% of farms have two 50-ha center pivot irrigation systems (3).

Table 4. Farm and biofuel labor household energy use

	Farm household members in biofuel production*	Nonfarm labor household members in biofuel production†	Annual U.S. non-biofuel per capita energy consumption, MJ‡	Total household energy use in biofuel production, MJ	2005 U.S. biofuel production, liters	Total household energy use per unit of biofuel production, MJ/liter§	Allocated household energy use on farm / off farm, MJ/liter
Corn grain ethanol	49,160	6,250	3.54×10^5	1.96×10^{10}	1.48×10^{10}	1.33	1.18 / 0.15
Soybean biodiesel	4,900	774	3.55×10^5	2.01×10^9	2.56×10^8	7.87	6.79 / 1.08

* In 2005, 4.71×10^6 ha were devoted to corn farming for ethanol (19). As the average farm size was 120 ha in the top nine corn-producing states (20), the equivalent of 3.93×10^4 farms provided the corn for ethanol production. Approximately 2.56×10^8 liters of biodiesel were produced in 2005 (21), 90% of which derived from soybean oil. With an average farm size of 120 ha in the top 15 soybean-producing states (20), the equivalent of 3.91×10^3 farms were devoted to growing soybeans for biodiesel production. We assume an average of 2.5 people on each farm (22) and that 50% of farm household labor is devoted to farming (23).

† An average of 40 people work in an ethanol plant, which includes those involved in corn and ethanol transportation (24), and as of 2005 there were ≈100 ethanol plants in the U.S. (25). Off-farm soybean biodiesel production is done at both soybean crushing and soybean oil conversion facilities. With ≈75 crushing facilities nationwide and 50 laborers at each facility (George Anderson, personal communication), 3,750 workers were involved in crushing; however, only 1.65% of crushed soybeans were needed to produce the soybean oil used to make biodiesel. We assume 10 larger and 35 smaller soybean oil conversion facilities nationally, each with 25 and 5 laborers, respectively (26). The total off-farm laborers in corn grain ethanol and soybean biodiesel production are, therefore, 4,000 and 487, respectively. Given the 2000-2005 annual average of employment/population ratio of 63% (27), we assume that each laborer supports 1.59 people.

‡ The U.S. energy consumption in 2004 was 1.05×10^{14} MJ (28). Also, 1.48×10^{10} liters of corn grain ethanol (19) and 2.56×10^8 liters of soybean biodiesel (21) were produced in 2005 at 20.38 and 28.37 MJ/liter, respectively. Therefore, the total national energy usage excluding that used in the entire ethanol production cycle was 1.05×10^{14} MJ, or 99.7% of national energy consumption. For biodiesel, the corresponding estimates are 1.05×10^{14} MJ and 100.0%. The average U.S. population in 2004 was 2.96×10^8 people (29).

§ Average annual household energy use divided by average annual industry biofuel production.

Table 5. Off-farm energy inputs/outputs of soybean biodiesel and corn grain ethanol production and coproduct energy credit

	Production energy, MJ/liter			
	Corn grain ethanol		Soybean biodiesel	
	Input	Output	Input	Output
Crop and biofuel transportation*	1.07		1.17	
Conversion of crop to biofuel†	12.73		8.08	
Production facility capital	0.04		0.06	
Nonfarm household energy use	0.15		1.08	
Energy in biofuel‡		21.26		32.93
Coproduct credit§		4.31		21.94

* Energy use to transport corn from the farm to ethanol plants and to transport ethanol from the plants to end users is an average of five studies (2-6). For soybean biodiesel production, we used reported energy input values for transporting soybeans from farm to crushing facility, soybean oil from crushing facility to soybean oil conversion facility, and biodiesel from the soybean oil conversion facility to the point of use (14).

† Dry-mill ethanol production energy use is an average of estimates from three studies (2-4), excluding the study that assumes wet-milling (5) and that which includes in this value energy to produce an ethanol plant (6), which we calculate separately. For soybean biodiesel, we use current steam and electricity production efficiencies to estimate the energy required to produce oil and meal from seed at a crushing plant and convert the oil to biodiesel and glycerol at a conversion facility (George Anderson, personal communication). At the crushing plant, 0.260 kg of steam and 0.027 kWh of electricity are required per kg of soybeans for seed preparation, oil extraction, and meal production. At the conversion facility, 0.395 kg of steam and 0.024 kWh of electricity are needed per kg of soybean oil for degumming and transesterification. Energy inputs for steam and electricity are 2.44 MJ/kg and 3.60 MJ/kWh. We include production energy of solvents and reagents used in processing (i.e., hexane, methanol, sodium hydroxide, hydrochloric acid, and sodium methoxide) (14).

‡ The combustible energy of corn grain ethanol and soybean biodiesel are assumed to be 21.26 MJ/liter (2-6) and 32.93 MJ/liter (14), respectively.

§ *Coproduct credit for DDGS*: Enough DDGS is produced per liter of ethanol to displace 0.78 kg of corn and 0.59 kg of soybean meal (30). As it takes 2.04 and 4.60 MJ to produce 1 kg of corn and 1 kg soybean meal, respectively, 4.31 MJ are credited per liter of ethanol. *Coproduct credit for soybean meal*: With a soybean oil content of 18%, the soybean meal coproduct credit is 18.43 MJ per liter of biodiesel, which is 82% of the energy used to grow soybeans, transport them to a crushing facility, extract their oil, and prepare the meal (14). Energy inputs for soybean oil transportation and conversion, and biodiesel distribution are not allocated as these steps are specific to biodiesel production from soybean oil. *Coproduct credit for glycerol:* 0.071 kg of glycerol is produced per liter of soybean biodiesel. It takes 49.5 MJ/kg to produce synthetic glycerol (31). Therefore, the coproduct credit of glycerol per liter of biodiesel is 3.51 MJ. Because synthetic glycerol is of a higher purity than raw glycerol, however, this coproduct credit overestimates the displacement energy.

Table 6. Material and building energy requirements for constructing ethanol and biodiesel production facilities

Building material	Dry mill ethanol plant: Material weight, Mg	Dry mill ethanol plant: Embodied energy, GJ	Dry mill ethanol plant: Ethanol input energy, kJ/liter*	Soybean crushing plant: Material weight, Mg	Soybean crushing plant: Embodied energy, GJ	Soybean crushing plant: Biodiesel input energy, kJ/liter†	Biodiesel conversion facility: Material weight, Mg	Biodiesel conversion facility: Embodied energy, GJ	Biodiesel conversion facility: Biodiesel input energy, kJ/liter
Concrete	14,200	42.6	18.8	17,800	53.3	21.8	3,600	10.7	4.7
Structural carbon steel	635	23.8	10.5	907	2.7	1.1	272	10.2	4.5
Building siding carbon steel	181	6.8	3.0	272	10.2	4.2	91	3.4	1.5
Carbon steel liquid storage tanks	91	3.4	1.5	91	3.4	1.4	272	10.2	4.5
Stainless steel liquid storage tanks	272	10.8	4.8	45	1.8	0.7	45	1.8	0.8
Stainless steel piping	91	3.6	1.6	45	1.8	0.7	45	1.8	0.8
Carbon steel piping	23	0.9	0.4	45	1.7	0.7	0	0.0	0.0
Other stainless steel equipment	227	9.0	4.0	340	13.5	5.5	113	4.5	2.0
Total		100.9	44.4		88.4	36.1		42.6	18.7

The throughput of each facility is as follows: dry mill ethanol plant (1.14×10^8 liters of ethanol/yr), soybean crushing plant (6.0×10^8 kg of soybeans/yr) and biodiesel conversion facility (1.14×10^8 liters of biodiesel/yr). Plant material requirements for representative facilities were provided by industry sources (George Anderson and Mark Vermeer, personal communications). The energy used to produce concrete, carbon steel, and stainless steel is assumed to be 2, 25, and 26.5 MJ/kg, respectively (17, 18, 32). We include an additional 50% energy input for construction and assembly. We assume a 20-year plant life for all facilities.

* Allocation calculated by embodied energy divided by throughput.

† A total of 4.89 kg of soybeans are crushed per liter of biodiesel produced.

Table 7. Biofuel production energy inputs (MJ/liter) per unit of biofuel energy output (MJ/liter)

	Corn grain ethanol		Soybean biodiesel		
Production stage	Ethanol	DDGS	Biodiesel	Soybean meal	Glycerol
Production of hybrid or variety seed for planting	0.002	0.000	0.004	0.019	0.000
Farm fossil fuel energy use	0.091	0.019	0.031	0.154	0.003
Farm fertilizer and pesticide production	0.102	0.021	0.014	0.071	0.001
Farm machinery production	0.008	0.002	0.007	0.035	0.001
Farm household energy use	0.046	0.009	0.034	0.169	0.004
Processing facility energy use	0.498	0.101	0.141	0.089	0.015
Processing facility construction	0.002	0.000	0.001	0.001	0.000
Processing facility laborer household energy use	0.006	0.001	0.026	0.003	0.003
Crop and biofuel transportation	0.042	0.008	0.015	0.018	0.002
Total	0.797	0.162	0.273	0.560	0.029

Energy input numbers are from Tables 1-6. Biofuel energy output numbers are from Table 5. Estimates from this table are presented in Fig. 1.

Table 8. Energy inputs to produce biofuels and coproducts (MJ/liter) per unit of biofuel energy output (MJ/liter)

	Corn grain ethanol		Soybean biodiesel	
Product	Input	Output	Input	Output
Biofuel	0.797	1	0.273	1
Coproducts	0.162	0.203	0.589	0.666
Total	0.959	1.203	0.861	1.666

Input energy allocation, coproduct energy credits, and energy output numbers are from Table 5. Estimates from this table are presented in Fig. 1.

Table 9. Effects of alternative coproduct calculations on NEB ratios

Biofuel	Base	No credit	Mass balance	Energy content	Market value
Corn grain ethanol	1.25	1.04	1.52	1.71	1.21
Soybean biodiesel	1.93	1.16	1.83	3.38	1.81

In addition to our base NEB ratio detailed in Table 5, we estimate the coproduct credit for both biofuels using mass balance, energy content, and market value. All three methods assume 0.914 kg of DDGS are made per kg of ethanol, and 4.56 kg of soybean meal and 0.08 kg of glycerol are produced per kg of biodiesel. For the mass balance method, the coproduct credit for each coproduct is equal to the energy input of all production steps leading to creation of the coproduct multiplied by the relative weight of the coproduct to the biofuel or biofuel intermediate product. For the energy content method, the coproduct credit is the amount of inherent energy (low heat value) within each product assuming complete combustion at 90% boiler efficiency (DDGS = 20.79 MJ/kg; soybean meal = 16.84 MJ/kg; glycerol = 16.55 MJ/kg) (33). For the market value method, the coproduct credit is equal to the relative value (2002-2004 wholesale averages) of each of the products of biofuel production (ethanol = \$0.37/kg; DDGS = \$0.10/kg; biodiesel = \$0.52/kg; soybean meal = \$0.22/kg; raw glycerol = \$0.88/kg) (34). Values shown are NEB ratios.

Table 10. Agricultural inputs in corn and soybean farming per unit of energy gained from biofuel production

Agricultural input	Application rate, kg/ha	Input per energy gained by biofuel production, g/MJ*	Input per energy gained by biofuel production allocated to biofuel, g/MJ†
Corn grain ethanol			
Nitrogen fertilizers	146.1	7.75	6.44
Phosphorus fertilizers	53.1	2.82	2.34
Pesticides	2.3	0.12	0.10
Soybean biodiesel			
Nitrogen fertilizers	5.6	0.39	0.06
Phosphorus fertilizers	17.2	1.19	0.19
Pesticides	1.2	0.08	0.01

* We assume corn grain ethanol and soybean biodiesel yields of 3,632 and 544 liters/ha, respectively. The NEB of corn grain ethanol and soybean biodiesel is 5.19 and 26.50 MJ/liters, respectively.

† As shown in Table 7, 83.1% of the agricultural inputs into corn farming are attributable to the ethanol itself [0.797 / (0.797 + 0.162)]. For soybean biodiesel, 82% of the agricultural inputs into soybean production are allocated to soybean meal, and of the remaining 18%, 90.4% is allocated to biodiesel [0.273 / (0.273 + 0.029)]; therefore, 16.3% of the fertilizer and pesticide use is attributable to biodiesel.

Table 11. Net greenhouse gas (GHG) savings per energy equivalent liter of biofuels used in lieu of fossil fuels

	Total life cycle GHG emissions from the fossil fuel that is displaced*	Fossil fuel GHG emissions avoided by using biofuel instead of fossil fuel†	Farm N_2O emissions in biofuel production ‡	Farm CH_4 mitigation in biofuel production§	Farm CO_2 liming emissions in biofuel production¶	Net GHG emissions saved by producing and using biofuel‖	Net fraction of GHG emissions saved by producing and using biofuel, %
Corn grain ethanol	96.90	19.66	5.60	0.43	2.48	12.02	12.4
Soybean biodiesel	82.32	39.76	4.72	0.36	2.09	33.32	40.5

All values are expressed in CO_2 equivalent g/MJ.

* Total life cycle GHG emissions of gasoline (for corn grain ethanol) or diesel (for soybean biodiesel) (35).

† Total life cycle GHG emissions from the fossil fuel that is displaced multiplied by the fossil fuel displacement rate of the biofuel, which is defined as $1-\frac{1}{\text{NEB Ratio}}$. Displaced fossil fuel GHG emissions may vary depending on the specific fossil fuels used in production (e.g., coal, natural gas, gasoline, and diesel). This accounts for the net energy gain from each biofuel but not the GHG release (N_2O and CO_2) or mitigation (CH_4) in crop production, which are estimated in the following two columns.

‡ With conventional tillage on a corn/soybean/wheat rotation farm, CO_2 equivalent N_2O emissions are 52 g/m^2 (36). As 3,632 liters of corn grain ethanol and 544 liters of soybean biodiesel are produced per hectare, 143 and 955 g of CO_2 equivalent N_2O are released per liter of ethanol and biodiesel, respectively. With a low heat value of 21.26 MJ/liter for ethanol and 32.93 MJ/liter for biodiesel, 6.73 and 29.03 g of CO_2 equivalent N_2O are released per MJ of ethanol and biodiesel, respectively. As in Table 10, 83.1% of this 6.73 g for corn farming is allocated to ethanol, and 16.3% of this 29.35 g is allocated to biodiesel.

§ Calculations are the same as for N_2O except that rather than release GHG, these agricultural practices mitigate 4 g/m^2 of CO_2 equivalent CH_4 emissions (36).

¶ Calculations are the same as for N_2O and CH_4 except for that these agricultural practices cause CO_2 emissions of 23 g/m^2 from liming (36).

‖ Net GHG emissions saved by producing and using biofuel equals the fossil fuel GHG emissions avoided minus the farm CO_2 (from liming) and N_2O emissions in biofuel production plus the farm CH_4 mitigation in biofuel production.

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