Gasohol: Does It or Doesn't It Produce Positive Net Energy?

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Summary. A detailed analysis of energy inputs and outputs is performed on grain-based gasohol (10 percent grain-based ethanol, 90 percent gasoline). Existing differences of opinion on the energy balance derive mainly from variations in interpretation which are several examples of inherent methodological problems in energy analysis. The result is strongly dependent on assumptions about use of crop residues for fuel and the miles-per-gallon rating of gasohol. In terms of total nonrenewable energy, gasohol is close to the energy break-even point. On the other hand, in terms of petroleum or petroleum-substitutable energy, gasohol is an unambiguous energy producer, since most energy inputs to the process can be supplied by nonpetroleum sources such as coal.

Gasohol, a mixture of 10 percent ethyl alcohol (fermented from agricultural materials) and 90 percent unleaded gasoline (10/90), is one of the more controversial topics of the current energy debate (*1*). Widespread media coverage plus the fact that gasohol is now being sold in at least 14 states, have increased its visibility (*2*). Proponents claim that widespread use of gasohol would reduce oil imports while providing a market for grain surpluses: farm prices would stabilize and the national trade deficit would be reduced. Opponents argue that farm prices would skyrocket as a result, and that too much energy is required to process grain into alcohol: total fossil-fuel consumption would increase rather than decrease, and the program designed to reduce oil imports would actually raise them.

The gasohol debate includes a host of other issues, such as those of automobile performance, air pollution, and land depletion (*3*). In addition, there is the issue of using foodstuffs to power cars. Economic feasibility, however, is no longer an issue because of federal and state subsidies. Besides a 4¢ per gallon (1 gallon = 3.8 liters) exemption from the federal automobile fuel tax (*4*), gasohol currently receives additional tax breaks in several states; for example, in Iowa, 10¢ per gallon minus a state sales tax of 3 percent ≃ 7.0¢ per gallon (*5*); Montana, 2¢ per gallon (*6*); Nebraska, 5.5¢ per gallon (*7*); Colorado, 5¢ per gallon (*8*); and Arkansas, 9.5¢ per gallon minus a sales tax of 3 percent ≃ 6.5¢ per gallon (*9*). The total subsidies therefore range from 4¢ to 11¢ per gallon of gasohol, or ten times these amounts per gallon of ethanol (ethyl alcohol). Since current prices for an unsubsidized gallon of ethanol vary from \$1.30 to \$1.60, the subsidies often make ethanol cheaper than the gasoline it is mixed with. Largely in response to these subsidies, sales of gasohol are brisk. But as gasohol production expands, a central energy question persists, "Will gasohol production yield positive net energy; will it provide more energy than it consumes?"

In this article we consider the gasohol energy balance in some detail as it applies to present U.S. agriculture and technology. While many fermentable materials are potentially usable, our approach concentrates on one crop, corn, and stresses a consistent framework and approach. We also discuss a number of "classic" difficulties of energy analysis (see Table 1), and we identify them in context (*10–13*). There have already been several energy analyses of ethanol or gasohol, but they are characterized by rather extreme differences in conclusions. Reconciling these differences is a major purpose of this article. A more important goal, however, is to establish a consistent system in which the numerous future gasohol projects can be quantitatively evaluated and compared. The energy balance for these projects is impossible to determine until the actual details of gasohol production and use are more clearly established.

Before proceeding we illustrate the disagreements. At the University of Nebraska, for example, researchers find that "the production of industrial ethanol by the fermentation of grain is an attractive process from both economic and energy considerations" (*14*). In contrast, at Iowa State University it is concluded that "it cannot be claimed that ethanol by fermentation of corn produces energy. The opposite is instead true" [see (*15, 16*)]. Recently published results from Brazil (*17, 18*) show that sugarcane has a "very favorable energy balance" in the production of ethanol. A mixed response can also be found in political circles: Representative Edward Madigan (R-Ill.) has criticized gasohol because "it takes as much energy to make a gallon of gasohol as that gallon will give you" (*19*); Senator Birch Bayh (D-Ind.) contends that alcohol fuels "will make a significant contribution toward reducing our nation's dependence on petroleum products, while at the same time, opening new markets for American farmers" (*20*).

As the debate continues, significant gasohol legislation has been introduced that explicitly requires an energy balance analysis. The Food and Agriculture Act of 1977 (*21*) has authorized four loan guarantees of up to \$15 million each for construction of plants to produce industrial hydrocarbons (such as ethanol) from biomass. Explicit in the law is the requirement that "the total energy content of the products and by-products manufactured in the operation must exceed the total energy input from fossil fuels used in the manufacture of such products and by-products." More recently, Representative Berkeley Bedell (D-Iowa) has introduced much more extensive legislation to promote a national gasohol program (*22*). Up to \$600 million in loan guarantees are to be provided for the construction and operation of plants for the production of alcohol fuel from agricultural commodities. It is required that an applicant "has taken steps to ensure that the total energy content of the alcohol fuel manufactured by such applicant will exceed the total energy input from *petroleum* or *petroleum-based* products used directly in the manufacture of such alcohol fuel. . . ." Requirements such as these, as we shall show, are subject to several interpretations.

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The Process

Throughout this analysis corn is considered as the starch source or substrate (*23*). In principle, any material containing sugar, starch, or cellulose could be considered, although the conversion of cellulose has not been proved economically. As an indication of magnitude, the entire corn surplus in the United States could be as high as 1×10^9 bushels per year (about one-sixth of the crop) (*24*) and would produce 2.5×10^9 gallons of alcohol per year. (One bushel of corn weighs approximately 56 pounds or 25.4 kilograms.) This is only 2.3 percent of the total gasoline consumed by surface vehicles in the United States, about 110×10^9 gallons per year.

From the viewpoint of an energy analyst, the gasohol process may be represented by Fig. 1. Within the solid-line boundary of gasohol production we find (usually): (i) grinding of grain and mixing with water; (ii) cooking to convert starch to sugar by enzymatic action; (iii) fermentation of sugar into ethanol; (iv) distillation to produce either anhydrous ethanol or an ethanol-gasoline mixture; (v) blending (or further blending) with unleaded gasoline to produce the desired grade of gasohol; and (vi) preparation (for example, drying) of the feed by-product. Step (v) could take place at the distillery, at a gasoline distribution depot, or at the filling station, but the blending location is irrelevant to the energy balance.

By bringing the gasoline supply into the system boundary a considerable amount of ambiguity is eliminated. First, it is apparent that the energy balance can pertain only to the mixture—gasohol—and not to either component alone. Second, the energy cost of producing the gasoline component (an important energy term that is often neglected) is automatically included. Third, one of the processes discussed here does not produce pure ethanol to be blended later with gasoline, but instead distills gasohol directly from a mixture of gasoline and a fermented grain-water mixture. A possible disadvantage of discussing only gasohol (10/90) is, of course, that the energy balance for ethanol is now diluted: even if ethanol could be produced with zero energy cost, gasohol would require 90 percent as much energy as gasoline.

The significant energy inputs include all nonrenewable or "primary" energy requirements at the distillery, on the farm, at the petroleum refinery, and for all intermediate transportation. In general, we have used empirical data for the various material and service inputs, which have been converted to energy required to produce them (*25*). Consistent with the aim of energy analysis, we have tried to include all indirect energy costs such as refinery losses for refined petroleum, fertilizer for crops, and depreciation of capital equipment in every associated economic activity. The various aspects of energy analysis techniques are documented in (*26*). We emphasize that we account for nonrenewable energy (coal, oil, gas, nuclear fuel) in the inputs, but not solar energy (except for hydroelectricity which is treated, according to convention, as if it were produced by burning fossil fuel). The gasohol process is thus evaluated as a technology to convert nonrenewable energy resources into useful energy, the solar input being considered "free" and ignored (*27*).

The process has two significant outputs: the gasohol and a high-protein by-product, which is a valuable part of a cattle feed ration. In addition, one may consider corn stalks and cobs as a gasohol by-product. These may be available to the distillery or, perhaps, to the open market as fuel.

In Table 2 we list the nonrenewable energy requirements for gasohol production according to three different sources: Scheller and Mohr (*14*, *28*), Reilly (*15*, *16*), and ACR (*29*). Scheller and Mohr, and Reilly refer to conventional distillation of ethanol for subsequent blending with gasoline; the ACR report refers to a new process that has been designed specifically to produce gasohol (not ethanol) with a low energy consumption. There are other energy saving processes being developed for the distillation industry (*30*), but ACR is the only process for which detailed and quantitative data have been presented (*31*). Also included in Table 2 are the output quantities reported by the three sources. We ignore all other outputs, such as CO_2 and fusel oil, which are insignificant to an energy balance.

Data Comparisons

Table 2 shows Scheller and Mohr (*14*, *28*) and Reilly (*15*, *16*) agree on conventional process energy inputs, 370 and 368 kBtu per bushel of corn, respectively (1 kBtu = 1000 Btu $\times$ 1.055×10^6 joule). Energy consumption data from Midwest Solvents, Atchison, Kansas, for the production of ethanol by industrial fermentation agree very well with these estimates (*32*). On the other hand, ACR (*29*) claims by "extensive heat exchange and novel distillation practices" to have reduced the process input energy to 120 kBtu. There are a few small discrepancies in accounting procedures among the three sources (for example, inclusion of capital equipment), but the ACR process does appear to reduce process energy significantly.

Scheller and Mohr, and Reilly agree on the agricultural energy consumption (*33*). The ACR estimate of agricultural energy consumption is somewhat higher, a consequence of using data that better account for indirect energy requirements (*34*).

There are no significant discrepancies in the output production quantities except Scheller and Mohr's inclusion of corn stalks (*35*), ignored by others. (This is problem 1 in Table 1.) This turns out to be crucial, however, because of its magnitude. The inclusion of gasoline as a process input by ACR is of no consequence in the energy balance since the same quantity of gasoline is both an input and an output.

As we have indicated, many interpretations of these data are possible. Our approach is to construct a set of options

Table 1. Methodological problems in energy analysis. These problems are discussed in (*26*).

Problem*	Examples for gasohol
1. Specification of system boundary.	Should agricultural energy be included as an energy input? Are the crop residues a valid output of the process?
2. Comparison of different energy types.	Should the energy balance be calculated for total nonrenewable energy, or for only one type, particularly petroleum (that is, does the process save oil even if it does not save coal)?
3. Consideration of end use.	Does gasohol get better miles per gallon than one would expect on the basis of its heat of combustion?
4. Consideration of joint product.	How is the energy content of feed by-product counted? Is it credited to gasohol or is it neglected?
5. Question of negative costs versus positive benefits.	Should feed by-product energy be added to output or subtracted from input? (This does not change balance but does change energy ratio.)

*Note that the problems are not independent; for example, problems 1 and 4.

for gasohol production that reflect the various interpretation possibilities. Then, for any specific project the appropriate options can be selected for a quantitative energy balance. Differences of opinion may remain, of course, but it is hoped that the issues will be more clearly defined.

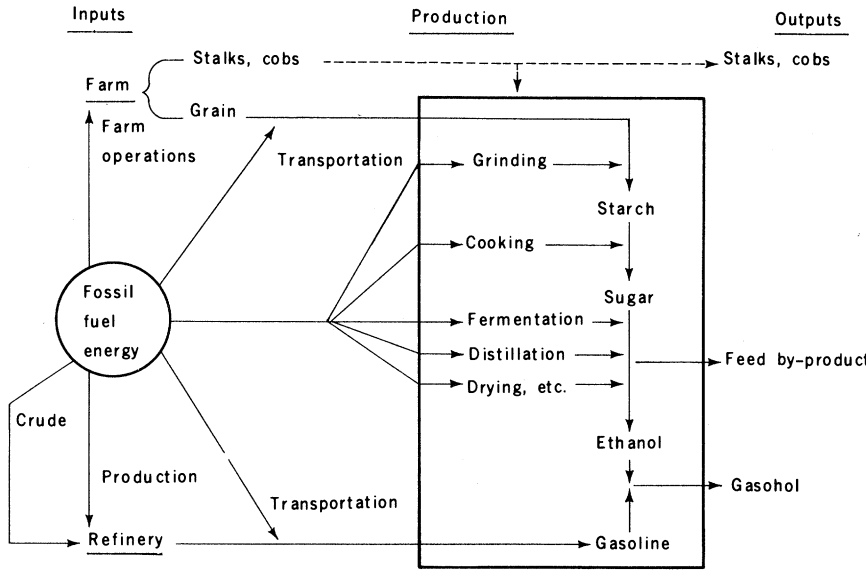

Fig. 1. Schematic of gasohol production. Stalks and cobs may be used for fuel in production or treated as an output. Gasoline may be blended with alcohol during production or at a distribution point, but the blending location is irrelevant to the energy balance. Only the major streams are shown.

Options

Examples of options in gasohol production are listed in Table 3 along with their qualitative effects on the energy balance. We repeat that many of the options do not reflect changed technology, but merely opinions on what factor should or should not be considered. For purposes of comparison we select a "base case" and compare the effect of the options to it. While the choice of the base case is arbitrary, we believe its general features reflect current distillation practices. We do, for example, include the energy inputs to agriculture since most distilleries buy corn on the open market. We assume that the feed by-product is dried because today a typical ethanol producer relies heavily on the sale of the by-product, and it must be dried to be transported any distance without spoilage. (Only when the distillery is close to the feedlot can the animals consume the undried slop.)

To discuss the energy balance it is easiest to compute the energy value for the base case, and for energy debits or credits of the various input and process options. In addition, all material outputs must be assigned an energy output and all by-products an energy credit. We find that while assigning values to the energy inputs is straightforward, calculating the output energies and credits is more ambiguous.

If we desire a calorimetric energy balance, it is appropriate to use the energy content (enthalpy of combustion) of the various input and output materials. However, effectiveness in accomplishing a given task (such as distance traveled in an automobile) may not be proportional to the enthalpy of combustion. Since our goal in this energy analysis is to estimate the overall impact of gasohol production and *use* on nonrenewable energy consumption, an end-use analysis of the outputs is often more appropriate. Several examples of end-use analysis follow.

Energy value of agricultural residues (stalks and cobs). (This is problem 4 in Table 1.) To take an energy credit for the stalks (or any combustible by-product in general) one must actually burn the stalks to produce energy. In addition, several energy "penalties" should be subtracted from the energy content of the by-product. These include the energy consumed on the farm to prevent soil depletion (if any), energy "harvesting" and transportation costs associated with the by-product, and energy costs of manufacture or modification of furnaces or boilers (including special pollution controls). While two sources (*17*, *28*) have assumed use of crop residues for fuels, they have not dealt with these difficulties. In our analysis we rather arbitrarily assume that half of the energy content of the by-product is required to account for these factors; that is, 1 Btu

Table 2. Total nonrenewable energy inputs and material outputs as presented by three sources. All are for 1 bushel of corn (energy units = 10^3 Btu).

Energy	Scheller and Mohr (*28*)	Reilly (*16*)	ACR (*29*)
	Inputs		
Agricultural energy, including	119[a]	135[b]	184[c]
Direct on-farm			66
Fertilizer and chemicals			80
Transport			21
Capital equipment			17
Process energy, including[d]	370	368	120
Cooking and fermentation	64		
Distilling and centrifuging	105		
Purifying (95 → 100) percent	37		113[e]
Evaporation	113		
Drying	51		
Capital equipment			7[f]
Process plus agricultural total	489	503	304
Petroleum energy, including[g,h]			3398
Content			2813
Energy production cost			585
	Outputs[i]		
Ethanol (gallons)	2.6	2.6	2.5
Feed by-product (pounds)	18.6	17.1	16.8
Stalks, for example (pounds)	53.7[j]	0	0
Gasoline (gallons)[h]			22.5

[a]Scheller and Mohr attribute this to Pimentel *et al.* (*33*). [b]In his first analysis, Reilly (*15*) chose to neglect the agricultural energy. [c]Based on (*34*) with additional calculations. [d]Assuming a boiler efficiency of 80 percent. [e]The process produces an alcohol-gasoline mixture and a dry feed by-product (*29*). [f]Estimated from dollar cost and 10^5 Btu per dollar. [g]Based on (*36*). The ratio of nonrenewable energy consumed to the energy produced is 1.208. This number is expected to increase as petroleum reserves dwindle. [h]All processes assume a final product of 10 percent ethanol, 90 percent gasoline. Since the first two sources assumed conventional distillation to produce pure ethanol, they did not discuss the gasoline explicitly. ACR does so because gasoline actually passes through the distillation process. The figures given are for 9 × 2.5 = 22.5 gallons of gasoline. [i]Small energy outputs such as fusel oil are ignored. [j]Based on (*35*) which assumes 75 percent removal from the field and 6000 Btu's per pound.

of corn stalk in the field yields 0.5 Btu to be used productively.

Energy value of distillers' grains. (This also is problem 4 in Table 1.) Although the distillery feed by-product has some heating value when burned, it will probably continue to be used as a foodstuff for cattle. We shall treat the energy content of this by-product as an "upper limit" option to the feed by-product energy credit. The option of burning this by-product yields an energy credit equal to the enthalpy of combustion; with the option of feeding this by-product to cattle we try to estimate how much less nonrenewable energy would then be consumed throughout all sectors of the cattle feed industry. On the basis of its food caloric content, one bushel of input corn displaces about 0.3 bushel of normal market corn (*29*). The energy credit of the by-product is equal to the nonrenewable energy saved, $0.3 \times (184 - 21) = 49$ kBtu. (The transportation energy, 21 kBtu, cannot be credited, since the entire bushel is transported to the distillery.) Another possible option here is to account for the fact that distillers' grains are higher in protein than corn and can actually displace soybean meal; we do not consider this.

Energy value of gasohol. (This is problem 3 in Table 1.) Since the gasoline component is both input and output, it presents no problem in the energy balance. From (*36*) the nonrenewable energy input is 151 kBtu per gallon; 26 kBtu of this is consumed in the production of gasoline. Any gasoline that is consumed by the agricultural or production sector has already been included elsewhere.

The combustion energy of the alcohol component, about 77 kBtu per gallon (lower heating value), is only 62 percent of that of gasoline. Whether this is important depends on the end use. The predominant use of gasohol will probably be for automobiles (*37*). If fuel efficiency were proportional to enthalpy of combustion, one would expect an approximate 4 percent decrease in miles per gallon, compared with gasoline. Supporting this is a report by the American Petroleum Institute which concludes that for alcohol-gasoline blends as vehicle fuels, "fuel economy measured in miles per gallon generally decreases, approximately in proportion to the alcohol content of the blends" (*38*). Yet Ecklund (*39*) of the U.S. Department of Energy has concluded in the past that "most researchers agree that with regard to fuel economy . . . there is no significant technical advantage or disadvantage to use of 10 volume percent alcohol/gasoline blends compared to gasoline. This in itself is an advantage, since the blend contains 4 or 5 percent less energy than the gasoline alone." More recently, a number of dynamometer tests have indicated that there is an approximate 2 percent average decrease in miles per gallon with gasohol, as compared with gasoline (*40*). These tests, however, usually compare gasohol with indoline and not with the gasoline that is actually available to the consumer (*41*).

In contrast with the dynamometer research data, a number of claims have been made in the popular press that gasohol improves miles per gallon. At present, however, no scientifically defensible road tests have been completed for gasohol. The most widely publicized study, the Nebraska "two-million-mile test" (*14*), reports an average 6.7 percent increase in miles per gallon for automobiles operated on gasohol, compared with gasoline, but a final report has never been released.

With so many conflicting conclusions, there can be no consensus at present on the miles-per-gallon question. Pending further study, we leave the choice of fuel efficiency as an option. From existing fuel-efficiency data, however, some observations should be made.

1) The relative fuel efficiency of gasohol with respect to gasoline is dependent on technology and can change as different vehicle motors and fuels are marketed. Gasohol (10/90) and pure gasoline can be used interchangeably in today's cars, which are now tuned for optimal gasoline-use efficiency.

2) Extrapolation from studies on alcohol-rich fuels (for example, containing more than about 15 percent alcohol) appear to be invalid, since alcohol as an additive component affects combustion of the gasoline component.

Table 3. Options for energy analysis of gasohol.

Option	Effect on energy balance compared with base case[a]	Comment
Input		
Use corn from corn belt, not national average	Decrease inputs	Better crop yields
Use wheat, instead of corn	Increase inputs slightly	
Do not dry corn on farm	Decrease inputs	Requires short distance between farm and plant
Use surplus, inferior, or spoiled crop	Decrease inputs or leave unchanged	A dilemma, probably best to treat it like an unspoiled crop
Use waste materials from other processes (for example, cheese, starch, dog food)	Uncertain	Need to analyze specific source
Production process		
Do not dry feed; sell as slop	Decrease inputs	Requires proximal consumer
Burn corn stalks and cobs in process	Decrease inputs greatly	Questions of soil depletion, technical feasibility
Improve distillation technology	Decrease inputs	
Do not cook substrate	Decrease inputs	Usually applies only to such crops as sugar beets, not to grain, which is mostly starch
Increase fermentation yield	Decrease inputs proportionately	Speculative
Produce gasohol on the farm	Uncertain	Less efficient than large-scale production but easier to use biomass fuels and to consume the feed by-product
Use distillation waste heat	Decrease inputs	Usual problems of waste heat use
Output		
Sell excess stalks and cobs for fuel	Increase outputs	Questions of soil depletion, suitability as a fuel, pollution
Correct for miles per gallon of gasohol	Increase outputs greatly	Very sensitive; evidence indicates that gasohol (10/90) gets better miles per gallon than expected on Btu basis
Credit feed by-product with energy cost of corn production instead of caloric content	Decrease outputs	Energy input to corn production is less than caloric value of crop

[a]Base case: National average corn production, conventional fermentation, conventional distillation energy as given by Scheller and Mohr (*28*), dried feed by-product.

3) Carefully controlled laboratory tests are less useful than carefully monitored motor vehicle road tests in determining gasohol's practical fuel efficiency.

Total Energy Balance

The net energy balance of gasohol production is defined to be positive if the nonrenewable energy requirement of producing gasohol to perform a specific task is less than the nonrenewable energy cost of producing gasoline to perform the same task. In this analysis the end-use "task" is distance traveled in a motor vehicle. We normalize to the farm production of 1 bushel of corn.

In Table 4 we assign quantitative values to a base case and to several options that reflect various interpretations in the gasohol energy debate. Energy credits for the by-products are listed as negative inputs (problem 5 in Table 1). The base case is computed from national average market corn with agricultural inputs from Penner and Joyce (*34*), conventional inputs from Scheller and Mohr (*28*) and the "corn substitution" option for the feed by-product credit:

Agricultural input	184 kBtu
Process input	370
By-product credit	−49
Base case total	505 kBtu

The reader may add or subtract the options as he wishes (*42*). The total thus obtained is defined as the total input energy, x, and is the net input energy to produce alcohol from a bushel of corn.

The quantitative energy balance for gasohol production is then calculated as follows. The alcohol yield, y, of the bushel has a typical value of 2.5 gallons (*43*). The total amount of gasohol produced is ten times the alcohol yield. The total nonrenewable energy consumed to produce the gasohol is therefore equal to $x + 9\,yc$, where c is the nonrenewable energy cost to produce a gallon of gasoline. The present value for c is 151 kBtu per gallon, which includes processing losses. If one wishes to omit processing losses for gasoline, c is set equal to the energy content of gasoline, 125 kBtu per gallon (*44*).

The gasoline that must be produced to move a vehicle the same distance as the gasohol produced from a bushel of corn is equal to $10\,ym$, where the end-use multiplier, m, is defined as the relative volume efficiency of gasohol with respect to gasoline (*45*). The total nonrenewable energy consumed to produce this gasoline is equal to $10\,ycm$.

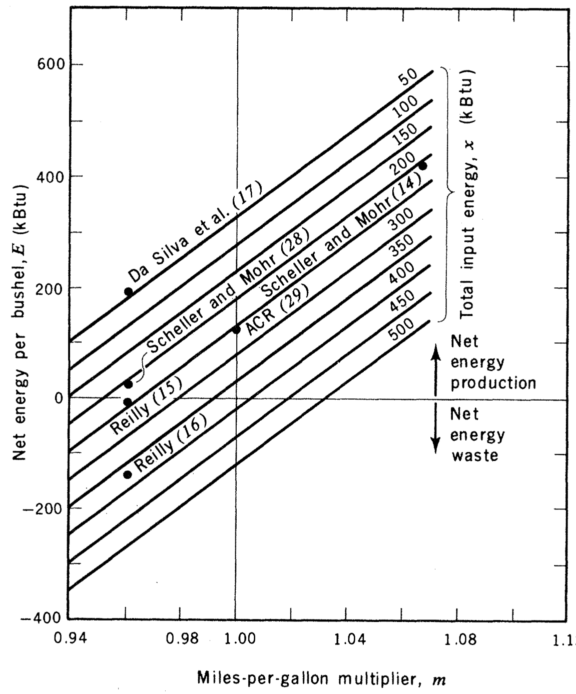

Fig. 2. Net energy per bushel, E, plotted against miles-per-gallon multiplier, m, for gasohol, assuming an alcohol yield of 2.5 gallons per bushel and a nonrenewable energy cost of 151 kBtu per gallon for gasoline. For a given input energy, x (calculated from Table 4 and indicated by the diagonal lines), and miles-per-gallon multiplier one can read the net energy. The various points indicate the stated or implicit positions of several authors. [Reilly (*16*) includes agricultural energy; Reilly (*15*) ignores agricultural energy.] All of the authors implicitly assume that $m = 0.961$, which is equivalent to assuming that gasohol's miles-per-gallon rating is proportional to its heat of combustion. Only Scheller and Mohr (*28*) and Da Silva *et al.* (*17*) show positive energy; this is because Scheller and Mohr include the use of crop residues for fuel, and Da Silva *et al.* assume reduced agricultural energy consumption and use of crop residues in industrial processing [see (*18*)]. Scheller and Mohr (*14*) assume $m = 1.067$, the result claimed from the Nebraska two-million-mile test. The ACR report (*29*) assumes $m = 1.0$.

The difference in nonrenewable energy consumption between gasohol production and gasoline production, E, is therefore given by

$$E = 10\,ycm - (9\,yc + x) \qquad (1)$$

or

$$E = yc\,(10\,m - 9) - x \qquad (2)$$

If E is positive for a given set of options then the net energy balance of gasohol production, subject to these options, is positive. Note that E is strongly dependent on m.

Figure 2 can be used for $y = 2.5$ gallons per bushel and $c = 151$ kBtu to determine graphically the net energy balance for a particular set of options. One computes x using Table 4, selects the appropriate line on Fig. 2, and reads the energy balance, E, as a function of the end-use multiplier, m.

We can use Fig. 2 to identify the two conflicting positions quoted earlier. For Reilly (*15, 16*), we select corn-belt corn, option 2 (Table 4), and use the energy content of the feed by-product for the by-product energy credit, option 13, to obtain $x = 505 - 66 - 68 = 371$ kBtu (*46*). Reilly implicitly assumes an end-use multiplier which is consistent with the relative heats of combustion of the two fuels; that is, by discussing only heat of combustion he implies that gasohol's usefulness will be proportional to it. Hence,

$$m \approx 120.1/125 = 0.961 \qquad (3)$$

This set of options is plotted on Fig. 2 [see curve for Reilly (*16*)]. The energy balance is negative and is the basis for the statement that we referred to earlier: "fermentation of grain to produce ethanol does not produce net energy" (*15, 16*).

Even if agricultural energy is ignored altogether (option 1 instead of option 2), the energy balance, although much improved, is still slightly negative [see curve for Reilly (*15*) on Fig. 2]. Scheller and Mohr (*28*) propose the use of corn stalks and cobs as boiler fuel (option 11) (*46*). There is much energy here, if it can be so used. (Scheller and Mohr assume that 75 percent of the stalks and cobs are removed from the field and take full credit for the energy content, that is, assume it can be delivered with no further energy cost.) Combining this with Reilly's selections (options 2 and 13) the net input energy is

$$x = 505 - 66 - 68 - 161 = 210 \text{ kBtu} \qquad (4)$$

If $m = 0.961$, as before, the net energy balance, although small, is positive [see curve for Scheller and Mohr (*28*) on Fig. 2]. This is the basis for the statement in Scheller and Mohr (*14*): "the process is attractive energetically." In this case, the simple option of the inclusion or exclusion of stalks and cobs as boiler fuel explains the controversy.

From Fig. 2 it is evident that the effect of increasing the end-use multiplier is to increase dramatically the output energy.

If a multiplier consistent with the Nebraska two-million-mile road test is selected [Scheller and Mohr (*14*)], $m = 1.067$ and the energy balance is much more positive [see the curve for Scheller and Mohr (*14*) on Fig. 2].

The stated position of ACR (*29*) is also shown on Fig. 2. ACR assumes the base case with option 7, the process energy savings. The net input energy is

$$x = 505 - 250 = 255 \text{ kBtu} \qquad (5)$$

ACR explicitly assumes no change in miles per gallon, making a "conservative" assumption that $m = 1.0$, and conclude that the net energy balance is positive.

For comparison, we have also plotted the results from Da Silva *et al.* (*17*) on Fig. 2, although their data are for ethanol production, not gasohol. A relatively low agricultural energy input, combined with the use of crop residues to offset industrial energy inputs (*18*) produces a positive energy balance.

Thus the energy balance one obtains depends on what options are assumed. Reilly, and Scheller and Mohr differ almost entirely because of the latter's assumption that the stalks and cobs are burned productively. Figure 2 shows, however, that without a significant increase in the fuel efficiency of gasohol with respect to gasoline, all U.S. processes (including ACR's) have energy balances that are uncomfortably close to or less than zero. Some efforts may "pay" but not spectacularly. In contrast, because of the sensitivity to the end-use question, if it is conclusively established that gasohol gets better miles per gallon than gasoline, the energy balance for gasohol production will be positive for several different options.

Until now, we have refrained from discussing a net energy ratio (problem 5 in Table 1). It is necessary, however, to make some normalizing statement to put Fig. 2 in perspective. For example, from Fig. 2 we see that a net energy saving (or loss) relative to gasoline of the order 100 kBtu per bushel of corn (or 100 kBtu per 2.5 gallons of ethanol, or 100 kBtu per 25 gallons of gasohol) is possible. This amounts to a saving (or loss) of about 100 kBtu per 3100 kBtu, or about 3.2 percent. In this example, to move a car a unit distance would require about 3.2 percent less (or more) nonrenewable energy than using pure gasoline.

Options Dictated by Legislation

The choice of options is not always arbitrary. The present and proposed federal ethanol legislation specifies that certain options must be selected. The Food and Agriculture Act of 1977 (*21*) requires a comparison of the total energy contents of products and by-products with the fossil fuel consumed in manufacture. It therefore allows the selection of virtually all agricultural and production energy input options (options 1 to 11) (*47*), subject to the proposed agricultural methods and production technology. It requires, however, output option 13 and a miles-per-gallon multiplier of 0.961.

The bill proposed by Bedell (*22*), moreover, stresses only the petroleum-derived or petroleum-substitutable energies. The energy value of the feed by-product (option 14) is ignored, and a miles-per-gallon multiplier of 0.961 is implied, but unlike the earlier bill, coal, natural gas, and electricity not derived from petroleum can be ignored in the energy balance (problem 2 in Table 1).

Table 4. Quantitative energy effects of options on base case (national average corn production, conventional processing, feed by-product dried with "corn substitution" energy credit). The data are normalized to 1 bushel of corn that produces ~2.5 gallons of ethanol to produce ~25 gallons of gasohol (units = 10^3 Btu).

Option[a]	Input
Base case	505
Agricultural energy input options	
1. Ignore agricultural energy	−184
2. Use corn-belt corn (better yields)	−66
3. Use wheat instead of corn	+6
4. Do not dry corn[b]	−15
5. Harvest corn with the cob[b]	−13
6. Use surplus, inferior, or spoiled crop	0[c]
Production energy input options	
7. ACR process	−250
8. Do not cook substrate	−52[d]
9. Do not dry feed by-product; sell as slop	~−70[d]
10. Burn cobs in process[e]	−42
11. Burn cobs and stalks in process[e]	−161[f]
Output options	
12. Sell excess stalks for fuel[e] (after use in option 11)	0
13. Credit feed by-product with the by-product energy content[g]	−68
14. No by-product energy credit	+49

[a]The following additional options are so speculative or peripheral that no analysis was performed: (i) use unconventional fermentation. Schemes to increase yields to 4 gallons per bushel are discussed but unproved; (ii) use waste materials from other processes; (iii) use distillation waste heat. [b]Either option 4 or 5 may be selected. [c]This point is always debatable. The energy inputs to a surplus, inferior, or spoiled crop have already been consumed; hence we think they ought to be counted. [d]Options 8 and 9 cannot be used with option 7. [e]The energy credit is given as half of the energy content of the by-product removed, up to 75 percent of total removal. The maximum combined energy credit for options 10, 11, and 12 is 161 kBtu. [f]If option 7 is selected the correct figure is −109. [g]This option assumes an energy content value of 117 kBtu, from Scheller and Mohr (*28*).

Petroleum-Only Balance

We therefore ignore the coal, gas, hydroelectric, and nuclear energy and calculate the amount of crude petroleum energy required to produce the petroleum substitute. Petroleum is unnecessary for almost all inputs to ethanol, with one major exception, agriculture. We assume that today's technology regarding agricultural inputs persists: about 59 percent of that energy comes from crude petroleum (*34*). Otherwise, we assume that almost all energy can be nonpetroleum, such as coal. (Coal is the boiler fuel in many ethanol distilleries today.) The base case is the same as that chosen for the total energy balance. The petroleum energy base case is given by

Agricultural	+109 kBtu
Processing	+ 5
By-product credit	− 29
	85 kBtu

Here the petroleum inputs are much less than even the heat of combustion of the ethanol component (typically, 193 kBtu per 2.5 gallons). Applying the options in Table 4 has a much smaller effect on the petroleum energy balance, since their savings in boiler fuel affect only nonpetroleum inputs.

To obtain a quantitative estimate for the reduction in petroleum consumption per input bushel of corn, one can express the energy balance in Eq. 2, in terms of petroleum energy

$$E_p = yc_p(10m - 9) - x_p \qquad (6)$$

where E_p is the net petroleum energy, c_p is the total petroleum energy cost of petroleum production [147 kBtu/gal (*36*)], and x_p is the net petroleum input energy (85 kBtu for the base case).

In contrast to the inconclusive comments we have made about the total energy balance, because x_p is so small, the petroleum-only balance is positive for most practical situations.

In this case a normalizing statement can be made in terms of the displacement of crude oil input. Dividing Eq. 6 by c_p, we obtain the net volume, v_p, of crude oil displaced per bushel of corn (or per 2.5 gallons of ethanol, or per 25 gallons of gasohol),

$$v_p = y(10m - 9) - x_p/c_p \qquad (7)$$

For $m = 0.961$, $v_p = 0.95$ gallon, while for $m = 0.98$, $v_p = 1.42$ gallons. Thus, in contrast to the inconclusive statement about total energy balance, for a petroleum-only consideration, we can say that to move a car a unit distance by burning gasohol requires about 5 percent less crude oil than by burning pure gasoline.

Conclusion

There is no simple answer to the question of net energy from gasohol. We have discussed a number of options in both technology and interpretation that can affect the conclusion. In broad terms these cover the agricultural production of the grain, the processes of fermentation and distillation, the disposition of crop residues, and the efficiency of end use. An analysis assuming the use of standard agricultural production techniques and conventional distillation technology leads to a conclusion that the net energy balance for gasohol production is negative. If, however, energy-conserving farming practices are developed, energy-conserving industrial technology is utilized, or crop residues are burned productively in the distillation process, it is possible to construct a realistic set of options with a modestly positive energy balance. It should also be noted that reduction of the energy requirements for the distillation process increases the probability that the energy can be supplied from crop residues without soil depletion. Conclusions are very sensitive to end use. If it is assumed that gasohol gets better mileage than gasoline in automobiles, then the chances of obtaining a positive energy balance are greatly increased.

If one analyzes the petroleum-only energy balance, then gasohol unambiguously produces positive net petroleum energy. This is a consequence of the fact that except for some inputs to agriculture and transportation, all energy inputs to the production of ethanol can be provided from nonpetroleum sources such as coal; hence consideration of the various options has little effect on this conclusion.

References and Notes

1. Other blends are possible (some with methyl alcohol). In Nebraska, Gasohol is a registered trade name and refers specifically to the 10/90 ethanol mixture; we adhere to this terminology.
2. A. L. Alm, "Statement of the Assistant Secretary for Policy and Evaluation Before the United States House of Representatives, the Subcommittees on Livestock and Grains, Family Farms, Rural Development and Special Studies, Conservation and Credit, of the Committee on Agriculture, 16 May 1979 (Department of Energy, Washington, D.C., 1979); see also "The Report of the Alcohol Fuel Policy Review" (Rep. No. 061-000-00313-4, Government Printing Office, Washington, D.C., June 1979).
3. See, for example, N. Wade, *Science* **204**, 928 (1979).
4. Energy Tax Act of 1978, Public Law 95-618.
5. D. Snyder, private communication. The Iowa exemption is effective until 30 June 1984.
6. N. Nichols, private communication. The present 2¢ exemption increases to 4¢ in 1985 and to 6¢ in 1987. The law (House Bill 402) expires in 1989 but contains a default clause allowing the governor to rescind the tax exemption instantaneously if he deems that the revenue losses are significantly affecting construction of state or interstate highways.
7. E. Dean, private communication. Duration is unlimited until the law is changed.
8. B. Spykstra, private communication.
9. E. Hicks, private communication.
10. For a critique of energy analysis see, for example; Webb and Pearce (*11*); Huettner (*12*); and Leach (*13*). We acknowledge the various criticisms of energy analysis, both in terms of its usefulness for policy (*11, 12*) and its own internal methodological problems (*13*). We view energy analysis as one of many valid inputs to decision-making.
11. M. Webb and D. Pearce, *Energy Policy* **3**, 318 (1975).
12. D. A. Huettner, *Science* **192**, 101 (1976).
13. G. Leach, *Energy Policy* **3**, 332 (1975).
14. W. Scheller and B. Mohr, *Chem. Technol.* **7**, 616 (1977).
15. P. Reilly, paper presented at Energy Conference, Iowa Farm Bureau, Des Moines, October 1977.
16. ______, "Economics and energy requirements for ethanol production," manuscript, Department of Chemical and Nuclear Engineering, Iowa State University, Ames, January, 1978. In this paper Reilly has discussed the effect of end use (miles per gallon) on the energy balance; he and we have developed this independently.
17. J. G. Da Silva, G. E. Serra, J. R. Moreira, J. C. Conçalves, J. Goldemberg, *Science* **201**, 903 (1978).
18. A few aspects of the Brazilian work (*17*) require comment. Agricultural energy consumption is about 25 percent (per gallon ethanol) of that in the United States, which is reasonable, given the relative degrees of mechanization. Process energy use is in agreement with that in the United States, given that sugarcane requires no cooking, the by-products are not dried, and the product is not anhydrous. No correction is made, however, for boiler efficiency to produce the process steam. In the United States this would increase the process fuel energy requirements by about 25 percent. The way in which the results are presented illustrates some of the difficulties of energy analysis. Table 2 of Da Silva *et al.* (*17*), for example, adds the combustion enthalpies of ethanol and crop residues to obtain "energy produced from ethyl alcohol." As we discuss later, whether or not residues should be included is a controversial issue in the United States and their omission or inclusion seriously affects the energy balance.
19. "Madigan backs gas hike, reactor," *The Morning Courier*, Urbana, Ill., 21 January 1978.
20. "News from Birch Bayh," press release LR 142-78, 12 June 1978.
21. Food and Agriculture Act of 1977, Public Law 95-113, Sect. 1420, and subsequent notice soliciting pilot project applications, *Fed. Reg.* (20 October 1977).
22. U.S. House of Representatives, 96th Congress, 1st Session, Bill H.R. 3905, introduced by Berkeley Bedell (D-Iowa) 3 May 1979.
23. The framework developed here can be used for substrates other than corn. All agricultural energy inputs, by-product credits, and outputs must be recalculated, with data from (*25*).
24. F. Dovring, private communication.
25. *Energy and U.S. Agriculture: 1974 Data Base* 76/459 (FEA/D-76/459, U.S. Department of Agriculture, Washington, D.C., September 1976), vol. 1.
26. *Energy Analysis* (Workshop Report S-10246, International Federation of Institutes for Advanced Study, Stockholm, Sweden, 1974).
27. If any solar technology were used to provide other inputs (for example, solar grain drying), it would be analyzed similarly. The nonrenewable energy used to develop the technology would be counted, the solar input ignored.
28. W. Scheller and B. Mohr, paper presented at the 171st National Meeting of the American Chemical Society, New York, 7 April 1976. We include the energy to produce anhydrous ethanol, but not the additional energy required for a last distillation to produce a beverage-quality product.
29. ACR Process Corporation, "Energy balance," part of a preliminary pilot project application to the U.S. Department of Agriculture (*21*), April 1978. A copy may be obtained from one of us.
30. Three examples: (i) The proposed Chemapec T.E.R. process integrates alcohol production with food processing (Chemapec, Woodbury, N.Y. 11797). Energy analysis of this joint product technology requires energy consumption and marketing data that are now unavailable. (ii) Process energy requirements should be vastly reduced if membrane technology can be utilized. See, for example, H. P. Gregor and C. D. Gregor, *Sci. Am.* **239**, 112 (July 1978). (iii) Energy savings similar to those of the ACR technology are discussed by R. Katzen in a report for the Department of Energy, contract No. EJ-78-C-01-6639 (Department of Energy, Washington, D.C., November 1978).
31. R. S. Chambers, Alcohol Fuels Policy Review, Department of Energy, Public Hearings in Chicago, 30 November 1978.
32. C. Cray, Jr., prepared testimony before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development, and Demonstration, U.S. House of Representatives, 13 July 1978. Cray stated that "it still takes 139,000 Btu to make one gallon of ethyl alcohol."
33. D. Pimentel, L. E. Hurd, A. C. Bellotti, M. J. Forster, I. N. Oka, O. D. Sholes, R. J. Whitman, *Science* **182**, 443 (1973).
34. P. S. Penner and J. J. Joyce, "Background energy cost calculations for ACR gasohol production," report to ACR Process Corporation, November, 1977. A copy may be obtained from one of us (R.S.C.). This study is based on data in (*25*). The national average corn yield in 1974, however, was unusually low, about 71 bushels per acre. Average yields (with the same energy inputs) could be 25 percent higher, but since the Food and Agriculture Act of 1977 (*21*) stipulates that this data base be used in calculating an energy balance, we have used it here. Readers wishing to correct for this may reduce the nontransportation portion of the agricultural energy by 20 percent; that is, 0.2 (184 − 21) = 33 kBtu per bushel of corn. A reviewer has questioned the use of these figures if marginal land were put into production as would be expected in a large-scale program. We have not addressed this; extrapolation to a national program using present data would have little value.
35. D. L. Miller, in *Proceedings of the 8th National Conference on Wheat Utilization Research, Albany, Calif.* (Publ. ARS W-19, U.S. Department of Agriculture, Washington, D.C., September 1974), pp. 106–109.
36. R. A. Herendeen and C. W. Bullard, III, *Energy Cost of Goods and Services, 1963 and 1967* (CAC Document No. 140, Center for Advanced Computation, University of Illinois at Urbana-Champaign, November, 1974).
37. The choice of a specific end use—propulsion of automobiles—bends our energy analysis to an economic constraint which is not certain, but likely, to obtain.
38. *Alcohols, A Technical Assessment of Their Application As Fuels* (Publ. No. 4261, American Petroleum Institute, Washington, D.C., July 1976).
39. E. E. Ecklund, "Alcohol fuels for highway vehicles," paper presented to U.S. Senate Agricultural Research and General Legislation Subcommittee, Indianapolis, Ind., 12 December 1977.
40. See for example, J. R. Allsup and D. B. Eccleston, in *Proceedings of the 3rd International Symposium on Alcohol Fuels Technology* (Asilomar, Calif., 28 May 1979), vol. 1.
41. Indoline and other research fuels may not be representative of commercial motor fuels. In addition, Allsup and Eccleston (*40*) conclude that "a much larger sampling of vehicles is necessary before a statistically meaningful number can be attributed to the fuel economy effect of large-scale usage of ethanol blended with gasoline."
42. In general, the increasing cost of energy makes the options in Table 4 practical in a wide variety of situations. At current energy prices the production cost of alcohol can be reduced by about 25¢ per gallon with new distillation technology, a strong incentive for technological change. Values listed in Table 4 may be somewhat conservative for some applications, but the reader should support any modification with reliable data. Additional options, of course, may be incorporated into the present framework (for example, steam generation from renewable energy sources).
43. The output yield normally ranges from 2.5 to 2.65 gallons per bushel and includes the starch loss to grow yeast and to produce enzymes at the distillery (*29*).
44. One reviewer has claimed that it is improper to charge the energy cost of processing and refining to produce gasoline since, without refining, crude oil has no alternative use. We feel there are sufficient uses for crude oil, or at least heavy less-refined fractions, to justify inclusion of the refining energy. Only by including refinery energy consumption can one compare the total nonrenewable energy consumed.
45. In practical terms, m = (miles per gallon for gasohol/miles per gallon for gasoline). We are neglecting a slight volume change that results when alcohol is mixed with gasoline.
46. The authors did not actually consider this analysis. We have constrained their analysis and data to the present framework.
47. The application rules in (*21*) place a few restrictions on the selection of options 1 and 6.