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Ethanol's Energy Return on Investment: A Survey of the Literature 1990−Present

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Various authors have reported conflicting values for the energy return on investment (r_E) of ethanol manufacture. Energy policy analysts predisposed to or against ethanol frequently cite selections from these studies to support their positions. This literature review takes an objective look at the disagreement by normalizing and comparing the data sets from ten such studies. Six of the reviewed studies treat starch ethanol from corn, and four treat cellulosic ethanol. Each normalized data set is also submitted to a uniform calculation of r_E defined as the total product energy divided by nonrenewable energy input to its manufacture. Defined this way $r_E > 1$ indicates that the ethanol product has nominally captured at least some renewable energy, and $r_E > 0.76$ indicates that it consumes less nonrenewable energy in its manufacture than gasoline. The reviewed corn ethanol studies imply $0.84 \leq r_E \leq 1.65$; three of the cellulosic ethanol studies imply $4.40 \leq r_E \leq 6.61$. The fourth cellulosic ethanol study reports $r_E = 0.69$ and may reasonably be considered an outlier.

Introduction

Over the past twenty-five years the energy return on investment of ethanol has been hotly debated, both verbally and in the literature. This paper is a survey of ten key studies published by United States researchers since 1990. We do not provide any new data on ethanol's performance here. Instead, we neatly line up existing data so that it is much easier to understand and compare results. At the end of the paper, we explain our opinion about what those results could mean for ethanol policy.

Defining the Terminology. Understanding the meaning of the debate means carefully understanding the types of energy that are being talked about, and how they relate. The terms defined here have been defined in many ways over the years, and no clear terms of art have evolved around the topic of fuel energy ratios. For every publication on the topic, this one included, it is critical that the reader understand exactly how the authors define their terms.

1. Energy return on investment, r_E, is the ratio of energy in a liter of ethanol to the nonrenewable energy required to make it. Specifically

$$r_E = \frac{E_{out}}{E_{in,nonrenewable}}$$

where E_{out} is the energy in a certain amount of ethanol output, and $E_{in,nonrenewable}$ is nonrenewable energy input to the manufacturing process for that same amount of ethanol. Because r_E is a ratio, as long as E_{out} and $E_{in,nonrenewable}$ are reported in the same units the units will cancel out and r_E will be unitless.

2. Nonrenewable energy includes natural gas, coal, oil, and nuclear energy. The studies we review vary in their definitions of $E_{in,nonrenewable}$, and in some cases do not define it clearly at all. Each author may or may not include nuclear energy, or may ignore the distinction between renewable and nonrenewable energy since most of the energy used in the United States today is nonrenewable anyway. This can be particularly justifiable when evaluating ethanol, because the majority of energy inputs in the agricultural and industrial processes are primary fossil fuels, rather than electricity.

3. Gross energy input is the sum of $E_{in,nonrenewable}$ and any additional, nonrenewable energy required to manufacture coproducts in the same industrial process. The role of coproducts will be explained further below.

4. Net energy input is simply $E_{in,nonrenewable}$, nonrenewable energy input to the ethanol manufacturing process.

What r_E Tells Us. Energy return on investment, r_E, as we define it tells us how well ethanol (or any other energy technology) leverages its nonrenewable energy inputs to deliver renewable energy. The higher the value of r_E, the more renewable energy return we get for our nonrenewable investment.

One is an important threshold value for r_E. If $r_E < 1$, then the total energy in the ethanol is less than the nonrenewable energy that went into it, and we might as well have made direct use of the nonrenewable fuels instead. If $r_E > 1$, then we have managed to capture at least some renewable energy value with our nonrenewable investment. This threshold may need to be adjusted in the context of a particular application of ethanol; see the remarks on gasoline displacement at the end of Policy Discussion below.

r_E can be calculated for completely nonrenewable energy resources too. By definition, r_E for a nonrenewable resource (for example, gasoline) will be less than one, because at least some of the gross energy input (crude oil, for the example of gasoline) will be lost when generating or refining energy products; that is, E_{out} will be less than $E_{in,nonrenewable}$.

r_E is always greater than zero, since E_{out} and $E_{in,nonrenewable}$ are both positive numbers.

Higher vs Lower Heating Values. All of the energy values in this report, including E_{out} and $E_{in,nonrenewable}$, will be reported in units of megajoules (MJ). A liter of gasoline contains 36.1 MJ of energy; a liter of ethanol contains 23.6 MJ of energy.

When we say that a liter of ethanol "contains" 23.6 MJ of energy, we mean that 23.6 MJ of heat energy is released when the ethanol is burned. When any carbon-based fuel like ethanol or gasoline is burned, the two main combustion products are carbon dioxide (CO_2) and water vapor. Some of the heat released in burning is not perceivable as temperature, but is instead used up vaporizing the water during combustion; this heat does not finally get released until the water vapor condenses later, for example as clouds, morning dew, or even against the sides of the car's exhaust pipe. Some energy analysts exclude this relatively useless latent heat of vaporization from the energy values in their work, and report what is known as the lower heating value, or LHV, of each fuel. The LHV of a liter of ethanol is 21.2 MJ.

A value that includes the latent heat of vaporization is called the higher heating value, or HHV, and this is the number 23.6 MJ we gave for a liter of ethanol. The reports reviewed here used both LHV and HHV, but we convert all values to HHV to make the different authors' data sets comparable. The conversion to HHV has no significant effect

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on the calculated values of r_E, since both E_{out} and $E_{in,nonrenewable}$ will be affected and the changes approximately cancel out.

Corn Ethanol vs Cellulosic Ethanol. Ethanol is a carbon-based fuel with the chemical formula C_2H_5OH. All ethanol is the same, but there are two fundamentally different sources of it.

1. Corn ethanol is made from the grain (the kernels) of corn. Corn grain includes a large amount of starch, which is easily fermented to create ethanol. It would be more consistent to call corn ethanol "starch ethanol," since it can be manufactured from any starch- or sugar-producing plant (in fact the mature, Brazilian fuel ethanol industry uses sugar cane as the principal feedstock.) However, in the United States almost all starch ethanol is manufactured from corn and "corn ethanol" has become a term of art, so we use it here to avoid confusion.

Corn ethanol production in the United States is growing quickly: from 2000 to 2004 the annual production more than doubled from 6.2 billion liters to 13 billion liters. The 13 billion liters produced in 2004 consumed some 11% of the nation's corn harvest (*1*). The technology for manufacturing corn ethanol can be considered mature as of the late 1980s. Corn ethanol studies reviewed in this paper, limited to publication in 1990 or later, can be considered to uniformly describe contemporary, industrial-scale production. Process efficiency is still improving, especially around agricultural efficiency and yield. These improvements will slowly decrease gross energy input over time but no large, sudden changes are expected.

2. Cellulosic ethanol is made from cellulose and hemicellulose, two basic building blocks of plant matter. Like corn ethanol, cellulosic ethanol is made by fermentation, but the wider variety of molecular structures in cellulose and hemicellulose requires a wider variety of microorganisms to break them down. Cellulosic ethanol manufacture also includes pretreatment of the raw plant matter to make the cellulose and hemicellulose accessible to the microorganisms. Both the pretreatment and the fermentation steps of cellulosic ethanol manufacture are undergoing laboratory research, but in the United States cellulosic ethanol is not manufactured on an industrial scale. Since the technology for manufacturing cellulosic ethanol is in development, all studies reviewed in this paper should be viewed in the context of their publication year and the assumptions they make about level of technology maturity.

Corn Ethanol Studies

For this paper we reviewed six key studies (*2*−*7*) published since 1990 that report r_E or a similar variant of energy return on investment for corn ethanol. These are not all such publications, but only the single, most representative work of each U.S. research team that has treated the topic in depth. This was done to avoid weighting the appearance of the results with multiple "votes" from research teams that publish more frequently. We also reviewed four studies treating cellulosic ethanol; these will be described in Cellulosic Ethanol Studies below.

The six teams' results are summarized in Table 1. In this section we explore the contents of the table, explaining what distinguishes upstream energy from fuel and electricity, what coproducts are, why "allocation" is important, and how to interpret the reference data.

Fuel and Electricity vs Upstream Energy. In Table 1 we classify $E_{in,nonrenewable}$ into two broad categories: (1) fuel and electricity, and (2) upstream energy.

1. Fuel and electricity include coal, diesel, natural gas, and other fossil fuels, and electricity, purchased and used by the farmer, transporter, or processing facility.

2. Upstream energy includes fuel and electricity used by the suppliers of commodities that the farmer or ethanol manufacturer buys. In all of the studies, the biggest single contributor to upstream energy is nitrogen fertilizer, which is an energy-intensive product.

Farmers often hire contractors to perform some of the agricultural work, a practice called "custom work" in the industry. When an author reports an energy value for custom work, in Table 1 it is grouped with fuel and electricity to represent that the energy consumption is actually occurring at the farm.

In Table 1, all of these values are reported per liter of ethanol produced.

Calculation of r_E. The quantities under the "fuel and electricity" and "upstream energy" headings are aggregated values taken directly from the published works. In contrast, the quantities under Table 1's "calculation of r_E" heading are calculated by us from the authors' original values; this allows us to apply exactly the same methodology for r_E to each study. The first line under "calculation of r_E", "gross energy input", is simply the sum of the "fuel and electricity" and "upstream energy" subtotals.

r_E is equal to the "net energy input" ($E_{in,nonrenewable}$) divided by the heating value of the ethanol produced (E_{out}). E_{out} is not listed in the table since it is the same for every process: 23.6 MJ per liter of ethanol. The net energy input is calculated by taking the portion of process energy assigned to coproducts and subtracting it from the gross energy input.

Coproducts and Allocation. Almost all ethanol plants do not manufacture ethanol alone; they also manufacture one or more **coproducts** that make effective use of the nonstarch components of the grain. Coproducts are often described in the literature as providing an "energy credit" against the gross energy input; this is the value reported as "coproduct energy input" in Table 1. However, this is a highly misleading concept; in practice there is no such thing as an energy credit. Instead, the agricultural and industrial inputs to the ethanol production process must be **allocated** among ethanol and the coproducts that are output along with it. Some of the process energy is spent manufacturing ethanol, and some is spent manufacturing the coproducts. In Table 1 the line "allocation factor (%)" is the net energy input divided by the gross energy input; this is the proper way to think of a fraction of the process energy being allocated to ethanol.

Of the studies reviewed here, only Kim & Dale have applied the most sophisticated allocation approach recommended by the International Standards Organization (ISO) (*8*). Two of the research teams reported allocation improperly, confounding **wet-milling** and **dry-milling** coproducts as if they were interchangeable. Wet-milling and dry-milling are the two mature technologies for manufacturing ethanol; they are both commonly used in the industry but feature significantly different coproducts. Wet-milling is the more complex process and yields oil, corn gluten field (CGF), and corn gluten meal (CGM). Dry-milling is simpler and yields a single coproduct, either dried distiller's grains (DDG) or dried distiller's grains with solubles (DDGS). Both wet and dry mills may also choose to compress and market the carbon dioxide generated during the fermentation step, adding one more coproduct.

In Table 1, we identify underneath each study name whether we tabulated the study's data for dry-milling, wet-milling, or a mixture. Where possible, we attempted to extract the dry-milling results for consistency, and because dry-milling appears to be expanding in popularity (*4*, *9*). If a study's label in Table 1 indicates "mixed" we were unable to extract either dry- or wet-milling data alone, which can be interpreted as a signal that the study's treatment of allocation is likely to be inaccurate.

Of the studies reviewed here, those that compare dry- and wet-milling do not show them to require significantly different values of net energy input per liter of ethanol. Typically, wet-milling seems to require a slightly higher gross

TABLE 1. Results of Corn Ethanol Studies, Grouped by Common Process Steps and Normalized to HHV (Sums May Not Match Totals Due to Rounding Error)

	Marland & Turhollow 1991	Lorenz & Morris 1995	Graboski 2002	Shapouri et al. 2002	Pimentel & Patzek 2005	Kim & Dale 2005
milling technology:	wet	mixed	mixed	dry	dry	dry
	all values in MJ per liter ethanol unless otherwise noted					
	fuel and electricity					
agriculture						
fuel	2.0	0.7	2.2	2.7	2.0	0.8
electricity	0.2	2.0	0.5	0.6	0.5	0.1
feedstock transport		0.4	0.5	0.6	1.5	0.5
industrial process						
fuel	10.5	10.9	11.8	10.0	11.7	12.5
electricity	3.5	3.2	2.9	3.6	5.3	2.2
ethanol distribution			0.4	0.4		0.6
total fuel and electricity	16.1	17.1	18.4	17.9	21.0	16.8
	upstream energy					
agriculture						
fertilizer	4.2	3.6	2.6	2.3	4.7	2.0
biocides	0.3	0.3	0.2	0.4	1.3	0.4
other		0.9	0.3	0.1	3.1	0.1
other nonagriculture					0.1	
total upstream energy	4.5	4.9	3.2	2.8	9.2	2.5
	calculation of r_E					
gross energy input	20.6	22.0	21.6	20.7	30.1	19.3
coproduct energy input	(2.3)	(7.7)	(4.5)	(3.7)	(2.0)	(4.8)
net energy input	18.3	14.3	17.1	17.1	28.1	14.5
allocation factor (%)	89%	65%	79%	82%	93%	75%
r_E (unitless)	**1.29**	**1.65**	**1.38**	**1.38**	**0.84**	**1.62**
	reference data					
upstream fuel included?	yes	no	yes	yes	yes	yes
electricity heat rate	3.0	2.4	3.0	2.7	3.3	3.2–3.4
corn yield (Mg/ha)	7.5	7.5	8.8	7.7	8.7	9.0
ethanol yield (L/kg)	0.37	0.38	0.39	0.39	0.37	0.39
oil reduction (%)			94%	84%		
projected r_E (unitless)	1.67	2.51	1.40			1.91

energy input, but also allocates a slightly higher fraction of this input to the coproducts, thus balancing the difference. Dry mills have some potential to drop their gross energy input by offering an undried coproduct, though this is only economically viable if the coproduct does not need to be transported long distances.

Reference Data. Table 1 includes several reference data that affect how each study should be interpreted.

1. Upstream fuel included? indicates whether the author accounted for fossil fuel used during extraction and processing of input fuel. Those that did reported that upstream processing increased the fuel's energy value by 10–30%, depending on the type of fuel. Studies that include the upstream energy cost will report a correspondingly lower value of r_E than those that do not.

2. Electricity heat rate states the number of units of nonrenewable heat energy required to generate one unit of electric energy. For instance, if the electricity heat rate is 3.0, then generating one MJ of electricity requires 3.0 MJ of nonrenewable HHV. Readers familiar with the electric industry will be more accustomed to heat rates reported in engineering units; for instance our example of 3.0 MJ/MJ is equivalent to about 10,200 Btu/kWh. The electricity heat rate is the inverse of electric generation efficiency: a heat rate of 3 means that $^1/_3 = 33\%$ of the fossil HHV is converted to electricity in the generation process.

Different authors' heat rates vary in part because the ethanol production is modeled in different parts of the country that experience different electricity heat rates. Also, authors that include upstream fuel accounting will report higher heat rates than those who do not, because the 10–30% additional energy needed to extract and process the raw fuels will be included in the number of units of heat energy required to generate one unit of electricity.

3. Corn yield is the number of metric tons (Mg) shelled corn produced per hectare (ha) of land in one crop cycle. Of course, yield varies tremendously with local soil and weather, so each author used a range or a weighted average; in all cases we report a weighted average for easy comparison. Where an author reported yield in volume units (e.g., bushels) we converted this to Mg assuming 15% moisture content shelled corn, the industry standard.

The value used by any author for corn yield can have a significant effect on the gross energy input. The agricultural inputs are typically measured per hectare, so a higher assumed yield lowers the agricultural inputs per Mg corn produced.

4. Ethanol yield is the number of liters (L) of ethanol produced from one kilogram (kg) of corn. This reflects the efficacy of the industrial process: the higher the ethanol yield, the better job the factory is doing at getting useful liquid fuel out of the raw feedstock.

5. Oil reduction is reported by a few of the authors. Recognizing that the principal purpose of fuel ethanol is gasoline displacement, these authors took the additional step of estimating the reduction in crude oil consumption

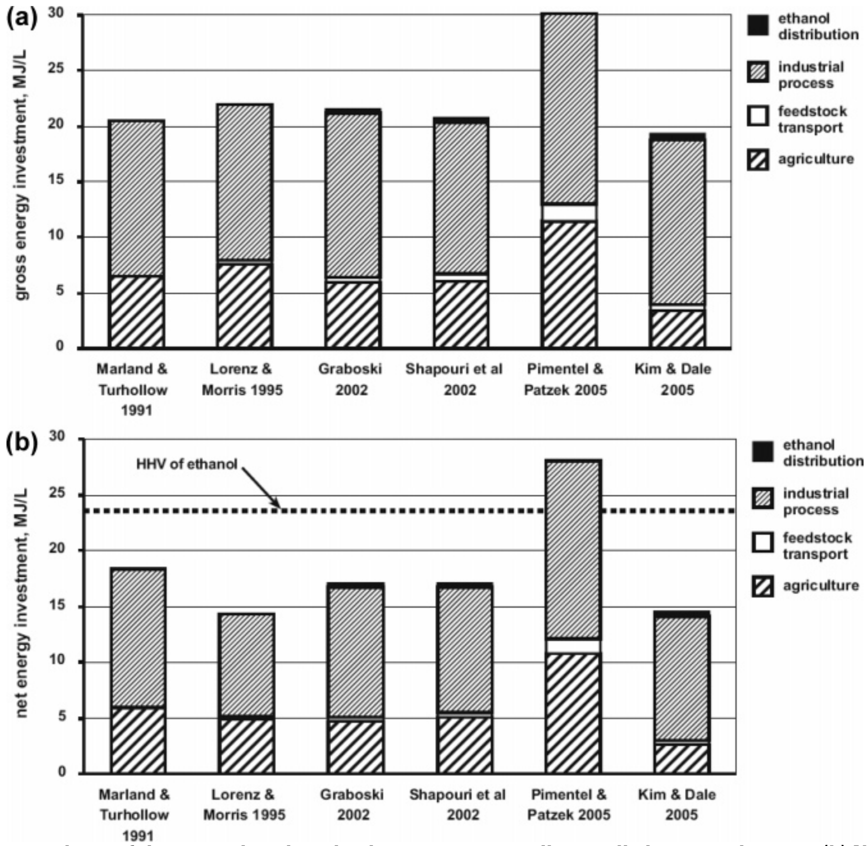

FIGURE 1. (a) Gross energy input of the corn ethanol production process according to all six research teams. (b) Net energy input of the corn ethanol production process according to all six research teams. This figure scales each bar in Figure 1a so that only the portion of the production that is responsible for generating ethanol (and not for generating coproducts) is included. The HHV of one liter of ethanol is indicated by the horizontal dotted line.

achieved by driving the same distance with ethanol vs with gasoline. This calculation, when reported, ignores the consumption of other fossil fuels, which typically increases because ethanol production utilizes coal, natural gas, and electricity, while gasoline production uses little of these.

The higher the value of oil reduction, the more effective ethanol is in displacing oil use. For instance, a reported oil reduction of 94% means that a car driving on ethanol causes only 6% the crude oil use that its gasoline counterpart does.

6. Projected r_E is reported by a few of the authors who attempted to predict future improvements in corn cultivation and ethanol manufacture. Projected r_E represents the reporting research team's opinion of future, achievable energy return on investment, and is less rigorous than the carefully normalized values of contemporary r_E tabulated in the main body of the table.

Discussion. Figure 1a and b summarize the gross and net energy input from Table 1.

All research teams over the past 15 years, with the exception of Pimentel & Patzek, have reported similar inputs to the agricultural, transport, industrial, and distribution components of the process.

Lorenz & Morris' work features an unusually generous allocation of gross process energy to the coproducts, in part because the wet- and dry-milling processes are confounded. However, generous estimates of agricultural and industrial energies mean that the resulting net energy inputs still fall in line with those of most of the other researchers.

The large energy inputs reported by Pimentel & Patzek are due not to any single factor, but rather a collection of conservative assumptions regarding efficiency, the inclusion of a few upstream energy burdens not accounted by other analysts, and a very small energy allocation to coproducts. Conservative assumptions regarding efficiency include high energy demands for nitrogen fertilizer manufacture, high upstream energy costs of seed production, and an electricity-intensive industrial process. Upstream energy burdens not included by other research teams are personal energy consumption of the laborers and energy costs of manufacturing capital equipment. Less than 7% of the production energy is allocated to the dry-milling coproduct, while the other two teams that separately examined dry-milling coproducts allocated 18−25% of the production energy to them.

The unusually low agricultural energy input in Kim & Dale's study is due to their choice to examine no-till corn agriculture in particular.

Excepting Pimentel & Patzek, the values of r_E range from 1.29 to 1.65 for current technology, indicating that corn ethanol is returning at least some renewable energy on its fossil energy investment. Pimentel & Patzek's result of $r_E < 1$ is an exception, implying that there is no renewable energy return on the fossil fuel investment.

The values for oil reduction calculated by two of the teams are intriguing. In both cases, the studies presume that ethanol displaces gasoline on a MJ-for-MJ basis, meaning that a driver who burns 1 L of ethanol would otherwise have burned about 0.65 L of gasoline, since gasoline has a higher heating value per liter. Because only a small fraction of the fossil energy used to manufacture ethanol is petroleum, even with this volume tradeoff corn ethanol consumes much less petroleum in the same amount of driving. Of course, this is offset by increased consumption of the other fossil fuels.

The displaced gasoline also has upstream energy costs. Graboski's publication provides sufficient data to calculate an energy return on investment for gasoline, yielding $r_E = 0.76$. This provides an interesting perspective on Pimentel & Patzek's otherwise discouraging value for ethanol $r_E = 0.84$. Even if their low value is correct, ethanol still appears to

TABLE 2. Results of Cellulosic Ethanol Studies, Grouped by Common Process Steps and Normalized to HHV (Sums May Not Match Totals Due to Rounding Error)

	Tyson et al. 1993	Lynd & Wang 2004	Sheehan et al. 2004	Pimentel & Patzek 2005
fuel:	various	poplar	corn stover	switchgrass
	all values in MJ/L unless otherwise noted			
	fuel and electricity			
agriculture				
fuel	0.8	1.1	0.8	1.1
electricity				
feedstock transport	0.4	1.3	0.5	1.4
industrial process				
fuel	0.2	2.9		20.1
electricity	0.1		0.3	8.9
ethanol distribution	1.4			
total fuel and electricity	2.9	5.4	1.5	31.5
	upstream energy			
agriculture				
fertilizer	1.1	0.1	4.0	0.9
biocides		0.0		0.3
other				0.8
other nonagriculture	0.5	0.4	0.3	0.5
total upstream energy	1.5	0.5	4.3	2.5
	calculation of r_E			
gross energy input	4.4	5.9	5.8	34.0
surplus electricity	5.4	3.3	1.9	
gross energy output	29.0	26.9	25.5	23.6
r_E (unitless)	**6.61**	**4.55**	**4.40**	**0.69**
	reference data			
upstream fuel included?	yes	?	yes	yes
nominal electric multiplier	3.3	2.7	3.0	3.3
feedstock yield (Mg/ha-yr)	11.2–33.6		8.2	10.0
ethanol yield (L/kg)	0.37–0.41	0.34	0.34	0.40
oil reduction (%)			95%	

provide an improvement in fossil fuel consumption when it is used to displace gasoline on a MJ-for-MJ basis.

Cellulosic Ethanol Studies

We reviewed four studies (*6, 10–12*) published since 1990 that report r_E or a similar variant of energy return on investment for the manufacture of cellulosic ethanol. As with corn ethanol, we tabulated only the single, most representative work of each U.S. research team that has treated the topic in depth. The four teams' results are summarized in Table 2. As in Table 1, the energy intensities listed under "fuel and electricity" and "upstream energy" are directly derived from the original authors' values, but the values of r_E are all calculated by our own, uniform methodology (described below) to create values that are meaningful when compared to each other.

Surplus Electricity and Allocation. The tabulation of cellulosic ethanol studies resembles that of the corn ethanol studies with one important exception. The cellulosic ethanol manufacturing processes modeled in these studies do not include commodity coproducts because the manufacturing processes consume the entire plant, including cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are eventually fermented to ethanol, while lignin is combusted to fuel the industrial process that supports fermentation. In most process models the heat released by lignin combustion exceeds the heat required by the industrial process, and the excess is used to generate surplus, salable electricity.

The surplus electricity can, technically speaking, be treated as a commodity coproduct and subjected to an allocation procedure. However, since electricity is also an energy product like fuel ethanol, it is more transparent and rational to combine the energy values of the two products in E_{out} for the purpose of calculating a justifiable value of r_E. Hence, Table 2 presents no coproduct energy inputs or associated allocation factors. Instead, r_E is calculated by summing the surplus electricity value with the HHV of ethanol (23.6 MJ/L), and dividing the resulting total by the gross energy input.

Commodity coproducts to cellulosic ethanol production may be introduced in the future (*13*). When and if this occurs the effect will most likely be to increase cellulosic ethanol's values for r_E.

Feedstock Yield. In contrast with corn ethanol, each cellulosic ethanol team modeled a different crop. Tyson et al modeled a complex combination of crops adapted to local soils and climates, so a range of feedstock yields is indicated.

Discussion. Figure 2 summarize the gross energy inputs from Table 2.

Pimentel & Patzek's results stand out, at nearly an order of magnitude larger values for nonrenewable energy inputs than the other three studies. The reason for the difference is that Pimentel & Patzek assume that industrial process energy is generated by fossil fuel combustion and electricity, rather than by lignin combustion. All well-developed models of cellulosic production generate industrial energy with lignin combustion. The other three research teams, all of whom

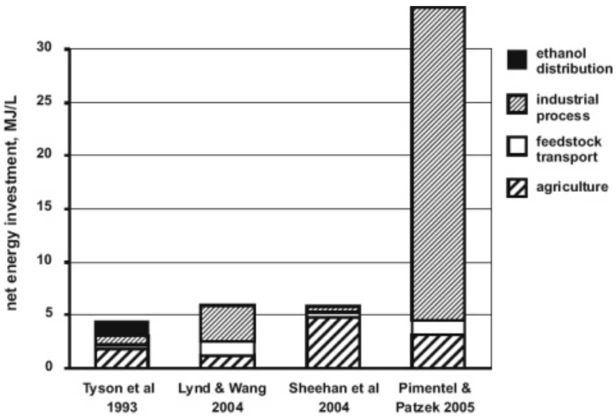

FIGURE 2. Gross energy inputs to the cellulosic ethanol production process according to four research teams.

assume this, are highly credible: the report by Tyson et al, supported by the U.S. Department of Energy, is one of the most thorough and transparent analyses of ethanol production ever conducted; the first author of Lynd & Wang has a 15-year history of work with cellulosic ethanol including a groundbreaking, 1991 *Science* paper (*14*), and Sheehan et al.'s paper is supported by a detailed model of the cellulosic ethanol industrial process developed at the National Renewable Energy Laboratory and widely reviewed by industry (*15*).

Even discounting Pimentel & Patzek, the other three studies show more widely varying distributions of energy input than the corn ethanol studies. This is consistent with the developing nature of cellulosic ethanol technology, and with the wider variety of feedstocks available. Regardless, the fossil energy inputs consistently stack up to be far less than the energy value of the ethanol and surplus electricity delivered, producing values of r_E ranging from 4.40 to 6.61 and indicating an excellent return of renewable energy on nonrenewable energy investment. These analyses are based on the present understanding of cellulosic ethanol manufacture. Because it is a developing industry, there is potential for mature processes to deliver ethanol with considerably greater r_E; some analysts believe that r_E for a mature cellulosic ethanol industry could exceed 10 (*16*).

Policy Discussion

Ethanol Policy Should Follow Impact-Based Metrics. r_E has a quick appeal to scientists because it is based on a measurable and meaningful physical property (energy), and a quick appeal to policymakers because it provides a simple *go/no go* decision based on a numeric threshold: 1 in the case of r_E as we defined it in this report.

However, choosing whether to pursue ethanol manufacture in the next decade or two must be viewed in the context of the environmental, social, and economic goals of the same time period. Those goals are likely to include greenhouse gas reduction, wise land use, and independence from foreign oil sources. r_E has more or less relationship to each of these goals, and where it has less it must be supplemented with impact-based metrics that relate more strongly to the goals.

Relationship of r_E to Greenhouse Gas Reduction. The CO_2 intensities (CO_2 emissions per unit energy) of fossil fuels vary within a limited range, so the quantity of CO_2 emitted when any combination of fossil fuels is burned is roughly proportional to the energy content of the fuels. This means that a value of r_E greater than about 0.76 (the value of r_E for gasoline) indicates that the manufacture of ethanol, when used to displace gasoline, will result in a net reduction of CO_2 emissions.

Some no-till agricultural processes can sequester additional carbon in soil. However, all agriculture can induce both methane (CH_4) and nitrous oxide (N_2O) emissions, both of which are potent greenhouse gases. Hence, r_E must be supplemented with an inventory of all three gases (CO_2, CH_4, and N_2O) under two fuel scenarios: one gasoline-based and the other including ethanol substitution of gasoline. Still, the values of r_E do provide a good preview of how emissions of one of the three gases will change.

Relationship of r_E to Land Use. Arguably the greatest environmental impact of ethanol production will be land use. In the very long term, presumably much of the fuel energy needed to support ethanol manufacture will be ethanol itself (along with other renewable fuels). Even though r_E is based on nonrenewable fuel input, on a qualitative level large values of r_E hint that a future, self-powered ethanol industry may need only a small amount of extra land to fuel itself, while values of r_E only slightly larger than 1 indicate that the industry may need a great deal of extra land to fuel itself.

Unfortunately, r_E tells us little about whether large-scale ethanol production would benefit or harm the U.S. agricultural economy, landscape, or ecosystems. Impact-related metrics, such as land area per liter-year of ethanol, would be much more useful for comparing the impacts of technologies proposed for manufacturing ethanol. Pimentel & Patzek point out that large-scale ethanol production can compete with food production for land area, an especially substantive issue in countries more densely populated than the United States. Evaluation of this environmental−social interaction requires significantly more sophisticated analysis than can be represented with a simple, scalar metric like r_E.

Relationship of r_E to Foreign Oil Dependence. Comparing the values of r_E to the separately calculated oil reduction values in Tables 1 and 2 demonstrates that r_E has little relationship to oil reduction. Fortunately, several authors did calculate the values listed in Tables 1 and 2, which taken together imply that most ethanol production scenarios can significantly reduce oil consumption, regardless of their associated r_E.

In the case of corn ethanol (but not cellulosic ethanol) significant reductions in oil consumption are partially offset by increases in coal and natural gas consumption. As the North American supply of natural gas depletes over the coming two decades, the gas industry will become increasingly reliant on imported, liquefied natural gas (LNG). The global distribution of natural gas resources is similar to that of oil, so decreased dependence on foreign oil may be tempered by an increased dependence on foreign natural gas. Again, if the impact of concern is oil dependence, it would be unwise to depend on the energy balance studies alone to make a policy decision.

It is Safe to Say that Corn Ethanol Reduces Fossil Fuel Use. Even the most pessimistic estimate of corn ethanol's r_E (Pimentel & Patzek at $r_E = 0.84$) is higher than the r_E for gasoline, so it seems safe to say that corn ethanol reduces fossil fuel consumption when used to displace gasoline. It is also safe to say that corn ethanol substantially reduces oil consumption when used to displace gasoline, though with attending increases in other types of fossil fuels.

Cellulosic Ethanol can Displace More Nonrenewable Energy than Corn Ethanol. Comparing the r_E values reported in Table 2 to those in Table 1 indicates that cellulosic ethanol displaces profoundly more nonrenewable energy than corn ethanol. The effect on greenhouse gas emissions will probably be even more pronounced, since the agricultural practices tied to cellulosic ethanol are typically less likely to produce CH_4 and N_2O. Examination of a proper land-use indicator will probably also show cellulosic ethanol to beat corn ethanol, because the whole-plant approach can take advantage of greater per-hectare yields than are possible for shelled corn. Last, the substantial oil displacement of both corn and cellulosic ethanol is not offset by increases in other fossil fuels when the ethanol is cellulosic.

Regardless, policymakers should be careful not to categorically dismiss corn (or other starch) ethanol. Starch ethanol might be energetically and economically efficient when manufactured in conjunction with processes that utilize the lignocellulosic portions of the starch crop. An example could be ethanol produced from the entire corn plant, from kernels to stover.

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Supporting Information Available

Notes and a calculation spreadsheet. This material is available free of charge via the Internet at http://pubs.acs.org.

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