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Review

Seeking to Understand the Reasons for Different Energy Return on Investment (EROI) Estimates for Biofuels

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Abstract: The authors of this paper have been involved in contentious discussion of the EROI of biomass-based ethanol. This contention has undermined, in the minds of some, the utility of EROI for assessing fuels. This paper seeks to understand the reasons for the divergent results.

Keywords: Ethanol; EROI; corn-based; cellulosic

1. Introduction

We are in a time of profound transition in how the world will be fueled and fed. The fossil energy resources (petroleum, coal and natural gas) that have powered the world's economy since the initiation of the industrial revolution are increasingly problematic in terms of their price (and price volatility), security of supply, declining energy return on investment (EROI) and environmental impacts [1]. These issues are well known and will not be discussed further here.

There is a less well known, but very important, positive correlation between the amount of energy that a society has at its disposal and the wealth of that society. Richer societies invariably have more energy available to them than do poorer societies [2-5] Energy consumption is a key factor associated with the greater wealth of richer societies, which makes sense if economic production is thought of as a work process, with more economic production requiring more energy. Billons of people have no access to modern energy services and they are almost invariably poor in economic terms. If fossil fuels are increasingly problematic in cost, availability and environmental impacts, what energy resources, if any, are available to help lift these billions of humankind from their poverty?

For these and other reasons, alternatives to fossil fuels, and especially alternatives to petroleum, are being explored worldwide. The poor often have substantial biological resources that might be mobilized for the kinds of fuels that are especially useful in generating wealth. Biofuels (liquid fuels made from plant matter) might be affordable alternatives to petroleum with a low carbon footprint and therefore appear to some investigators attractive as a petroleum alternative. One downside is that this organic matter might have other good functions, such as maintaining soil fertility or forest biodiversity. The only large scale petroleum alternatives currently available for liquid transportation fuels are biofuels, principally ethanol made from cane sugar or corn starch, and smaller amounts of biodiesel produced from oilseeds. At present corn-based ethanol provides for about 10% by volume of US motor “gasoline” [5], although this is clearly for gross energy and not net energy. The sustainable resource base could be expanded considerably if we were able to use cellulosic biomass as a feedstock (e.g., some portion of crop residues (although coauthor Pimentel believes that no portion of crop residues should be harvested [6], woody materials, grasses and herbaceous crops) in addition to starch and sugar feedstocks. The starches and sugars are much easier to ferment with present day technologies but the cellulosic resource base is considerably larger and appears to have many desirable environmental properties.

However, biofuels are controversial. Their environmental impacts, cost, potential scale and EROI have all been questioned. If we are to make informed and rational choices between our alternatives to petroleum, these questions must be addressed and resolved. This article focuses on the EROI for biofuels. The different results derived from different investigators (including, perhaps especially, ourselves) have caused some prominent analysts to disparage EROI as not being useful because of the highly divergent results of different investigators [7,8] We emphasize here corn ethanol, for which most of the EROI analyses have been done, and cellulosic ethanol, a possibly promising new alternative to petroleum gasoline. Indeed the controversy about EROI for corn-based ethanol, usually formulated as whether or not corn-based ethanol makes a positive energy gain relative to the fossil fuels used to produce them, is probably the issue by which most scientists and policy makers have encountered EROI.

It is important that we determine whether it is possible to get reliable estimates of EROI for a given fuel. The corn-based ethanol industry is mature and we can derive reasonable empirical results. A number of corn ethanol EROI (or “net energy”) studies have been performed) which are reported in metastudies by Farrell *et al*. [7], Hammerschlag (2005, [9]) and Chavas (2008, [10]). From among these studies, a large difference in values can be found by comparing the results of Kim and Dale [11], who give an EROI for corn-based ethanol of 1.73:1 and Pimentel and Patzek [12] (who give a value of 0.82:1).

In this paper we seek the reasons for these large differences, and explore whether they are due to the measured, verifiable process-related energy consumption for individual processes or instead primarily on boundary and/or other philosophical assumptions or, perhaps, something else. If the reason is the former then indeed there may be some basis for the criticisms leveled at EROI methodology, if the second then these issues are readily accommodated within the EROI protocol format put forth in this issue by Murphy *et al*. [13].

There are three basic reasons for the differences in EROIs as determined by different investigators: procedural/metric issues, philosophical and boundary issues and quality adjustment issues. We discuss each briefly.

1.1. Procedural/Supply Chain Issues

We use the term *supply chain* to refer to issues pertaining to the derivation of energy costs, measured per unit input, per unit product or per ha, associated with the various inputs to the production processes. For example if we know that to grow 60 kg (approximately 1 MJ) of maize requires, on average, about one kg of fertilizer, there are various studies that have been done that can give a fairly unambiguous and limited range of energy values associated with that production (Table 1). Similarly it is possible to derive straightforward estimates of the energy to run a tractor pulling a standard plow for one hour, and to derive the hours required per ha. It becomes more difficult to derive other factors that are not based on simple physical variables; for example, the energy that was used to make and maintain the tractor used, and even the building in which the tractor was produced. But while we do not have look up tables for the energy to make a kg or a unit of a certain tractor, we do have various estimates of energy used per dollar of product in various machinery production facilities, often gathered, when it is possible, from national aggregate statistics. Then that has to be prorated over the useful life of the tractor. We include some of these estimates and their ranges in Table 1 also.

1.2. Philosophical and Boundary Issues

A second issue relating to different energy costs among different authors pertains to *boundaries and philosophies of inclusion/exclusion*. It is nearly universally accepted that one should include direct (on site) energy use and basic indirect (e.g., energy used to make equipment used on site) energy inputs. However, the agreement tends to evaporate when considering whether or not to include other possible energy terms, for example; allocation to coproducts, energy for labor or finance and so on. We do not believe that there is a single acceptable boundary (although one should undertake a standard assessment for fuel alone and then clearly specify procedures for each additional analysis). However, comparative studies must use the same boundaries if they are to provide useful results. This issue is addressed in the protocol paper by Murphy *et al*. [13] in this volume. Good arguments for including all components associated with expenditures are found in [14].

If the different published EROIs for biofuel are due principally to such philosophical issues then this would not undermine the value of EROI as a key metric for analyzing energy systems, or at least not very much. In fact the different approaches can be viewed as a means of gaining greater flexibility and hence utility for EROI by specifying the conditions of the process under consideration, especially if a standard procedure is also done [13]. In addition the different investigations highlight the importance of clearly defining the assumptions made during the EROI analysis and how allocations are handled for multiproduct energy systems.

1.3. Quality Adjustment Issues

Not all energy is of the same quality, for example liquid fuels are normally thought of as higher quality than solid fuels (hence we transform corn to alcohol). Electricity is higher quality than fossil fuels, hence we burn some three heat units of fossil fuel to generate one heat unit of electricity. Gasoline has higher energy density than alcohol and so on.

We believe that these are the three main reasons that contribute to differences among different estimates of the EROI of the same fuel. The main objective of this paper is to take two very different estimates of EROI and dissect the reasons for the differences.

2. Methods

Our methods are very simple. We examine the importance of each of the above three factors quantitatively in Kim and Dale [11] and Pimentel and Patzek [12] by comparing each energy-related component in tabular form. Our main activity was to list energy consuming operations and to convert units, for example from Pimentel and Patzek's kilocalories to megajoules (MJ, multiply kilocalories by 4.186/1000). In all cases energy operations were given in, or converted to, estimates of MJ/L of alcohol generated.

The second main procedure was to examine the importance of the allocation (or not) of energy costs to co-products. The energy costs of producing corn ethanol can be partially offset by allocating the energy used to various products and by-products, such as the dry distillers grains (DDG) made from dry-milling of corn. From about 10 kg of corn feedstock, about 3.3 kg of DDG with 27% protein content can be harvested [15]. This DDG is suitable for feeding cattle that are ruminants, but has only limited value for feeding hogs and chickens. In practice, this DDG is generally used as a substitute for soybean meal that contains 49% protein [15]. This allocation issue is somewhat complex. Soybean production for livestock feed requires less energy per kg than does corn production, because little nitrogen fertilizer is needed for the production of the soybean. However considerable energy is required to remove oil from soybeans and thereby produce the soybean meal that is actually fed to animals. In practice 2.1 kg of soybean protein provides the equivalent nutrient value of 3.3 kg of DDG.

In the system expansion approach used in Kim and Dale [11], the system boundaries were expanded to include corn dry milling, corn wet milling, and soybean crushing systems. Simultaneous linear equations representing the displacement scenarios for co-products of each system were solved as recommended by the International Standards Organization [16]. The underlying assumption is that co-products that deliver an equivalent function (DDG as an animal feed, in this case) from different product systems displace each other. The fraction of energy allocated to co-products (26%) was then estimated through system expansion. Pimentel and Patzek [12], in contrast, assume that 7% of the overall energy inputs will be allocated to co-products. Consequently, we examined the effect of allocating zero, 7% (coauthor Pimentel's value) or 26% of the energy used (coauthor Dale's value) to produce ethanol to DDG (see the Results section).

3. Results

Since the methods and the results for the corn based ethanol EROI and the cellulosic ethanol EROI are quite different we give first the results for corn-based ethanol, then we include additional methods and new results for cellulosic ethanol.

3.1. Results for Corn-Based Ethanol

The two procedures gave a very different EROI for corn based ethanol, 1.73:1 from Kim and Dale [11] and 0.82:1 from Pimentel and Patzek [12]. Obviously Kim and Dale estimate that a positive energy balance can be generated by turning inputs into ethanol. Pimentel and Patzek [12] conclude that investing fossil energy to make ethanol from corn is senseless because the process of generating ethanol consumes more energy than is derived from the product ethanol.

The principal reason for the large difference between the EROIs derived from these two papers was the difference in the allocation approaches used for coproducts. Kim and Dale used the "system expansion" approach to estimate that only 74% of the total energy costs should be allocated to generating the ethanol and the remainder to the co-product, the protein rich DDG. In brief, the system expansion allocation employed by Kim and Dale assigned the energy "cost" of producing soy bean meal, the major commodity with which DDG competes in the market, to DDG. About a half (approximately, depending on assumption used) of the difference between the EROI given in the Pimentel and Patzek and the Kim and Dale papers was due to co-product allocation issues (*i.e.*, philosophical and boundary issues). About a third was due to differences in estimates of the energy intensity of the inputs (*i.e.*, supply chain issues), and about 15% was due to the greater inclusivity of costs by Pimentel and Patzek. These results are considered in greater detail next.

3.2. Supply Chain Issues: Energy per Unit Inputs

Table 1 gives the energy intensities per unit used in their analyses by the two sets of authors. The inputs are listed side by side in Table 1 so that they can be compared easily. The per unit values used in making subsequent calculations are almost universally within 10 or at most 20% of one another (Table 1). The values used by Pimentel and Patzek tend to be often, but not always, higher than those of Kim and Dale. For example, the former give diesel fuel as 42.6 and the latter 47.5 MJ/L. Since Pimentel and Patzek include the energy required to refine the fuels, which is about 10% of the output value [17], and Kim and Dale do not, this seems to be the reason for the difference. Exceptions to the general similarities are the energy costs per ton of potassium fertilizer, which differ by 30%, and transport energy which differ by 70%. Neither of these energy inputs is especially large, so we do not think that differing per unit energy costs are likely to contribute in any important way to the final results with the exception of items included by one study but not the other.

Table 1. Energy Costs Per Physical Unit or Per Dollar of Input to Agriculture or Biorefining.

Entity	Units	Energy Cost Kim & Dale (2005)	Energy Cost Pimentel & Patzek (2008)
Diesel	MJ/L	42.6	47.5
Electricity	MJ/kwhr	9.61	10.8
Natural Gas	MJ/L	0.04	Not determined
Fuel oil	MJ/L	43.2	Not determined
Coal	MJ/kg	23.1	Not determined
Gasoline	MJ/L	40.5	42.4
LPG	MJ/L	27.1	Not determined
Methanol	MJ/L	21.2	21.5
Steel	MG/kg	Not determined	96.4
Stainless Steel	MJ/kg	Not determined	230
Cement	MJ/kg	Not determined	202
Fertilizer Nitrogen	MJ/kg	63.7	67
Fertilizer Phosphorus	MJ/kg	18	17.4
Fertilizer Potassium	MJ/kg	8.22	13.7
Lime	MJ/kg	1.46	1.17
Irrigation	GJ/cm	Not determined	166
Pesticides	MJ/kg	426	419
Herbicides	MJ/kg	437	419
Machinery	GJ/$1000	Not determined	73.4
Transport	MJ/ton-km	Not determined	73.4

Since there was no consistent pattern of one or the other authors using higher or lower estimates the energy input estimates tend to "come out in the wash". The estimates of the total energy used to generate a liter of ethanol differ more because of the inclusion or not of different costs. Pimentel and Patzek include more categories of inputs and hence estimate the total energy input to generating a liter of ethanol as 28.1 MJ, while Kim and Dale estimate 16.7 MJ, which is 59% of Pimentel and Patzek's value. If one assigns additional energy costs (based on Pimentel and Patzek's numbers) for the factors used by Pimentel and Patzek but not by Kim and Dale the latter's energy costs would be 19.5 MG/L, 69% of the former's value.

3.3. Sensitivity Analysis

Both Kim and Dale [11] and Pimentel and Patzek [12] allocate some energy costs to coproducts. For the Kim and Dale this is 26% (about 445 kcal or 1.86 MJ) per liter, while for Pimentel and Patzel it is 7% (about 120 kcal or 0.5 MJ) per liter. In the case of Pimentel and Patzek factoring this credit for a non-fuel source in the production of ethanol reduces the negative energy balance from 46% to 39% (See tables). For Kim and Dale it increases the positive value by about 18%. Some scientists, such as Shapouri *et al*. [18], would give an even larger credit for DDG of 4,400 kcal (18.4 MJ) / kg and thereby further increase the positive value of EROI relative to Kim and Dale. Shapouri's values are based on surveys of operating corn ethanol plants.

Table 2. Corn Ethanol: Comparing Different EROI Calculations.

Energy inputs (MJ/L of ethanol of fuel generated)		
	Input (MJ/L ethanol)	
	Kim & Dale 2005	**Pimentel & Patzek 2008**
Agriculture:		
Fuel	0.76	1.69
Machinery	Not determined	1.22
Electricity	Not determined	0.05
Fertilizer	2.29	3.69
Lime	Not determined	0.38
Irrigation:		
Pesticides/Herbicides	Not determined	1.08
Seeds	Not determined	0.62
Feedstock Transport	0.46	0.20
Total for Corn Production	**3.51**	**10.03**
(Estimate for Not Determined items)	2.65	(2.65)
Total including Not Determined	6.16	10.03
Biorefinery:		
Fuel	10.60	11.08
Electricity	1.54	4.23
Steel	0.31	1.08
Misc	Not determined	0.33
Total energy input	**12.45**	**16.72**
Ethanol Distribution	0.60	1.39
Total energy input	**16.56**	**28.14**
(Estimate for Not Determined items)	2.98	(2.98)
Total input incl all categories	19.54	28.14
Total Energy Output	21.20	21.479
Energy Return on Investment	**1.28**	**0.76**
EROI (with added ”Not Determined”)	1.10	0.76
Percentage allocated to ethanol	74	93
Input with correction for coproduct	12.25	26.17
EROI with coproduct	**1.73**	**0.82**

4. Discussion: Corn-Based Ethanol

4.1. Procedural/Metric Issues: Total Energy Costs

The estimated total energy costs to generate ethanol from corn derived by Kim and Dale are about 16.6 MJ/L, and about 28.1 MJ/L as derived by Pimentel and Patzek. Thus Pimentel and Patzek’s estimates are about 170% of those of Kim and Dale (2005). About 2.65 MJ/L of the 11.6 MJ/L difference between the two estimates, or 23%, is due to what might be considered boundary (or perhaps more accurately inclusionary) issues (*i.e.* Pimentel and Patzek include more categories, such as the energy cost of seeds), and the rest due to the frequently somewhat higher estimates of energy costs at each step by Pimentel and Patzek. For most of the items the estimates of energy costs are similar, again within 10-20%, although usually higher in Pimentel and Patzek’s work. The largest differences are for fuels used in the field for production and for fertilizer plus herbicides/pesticides. The difference of energy used for fuels is mostly Pimentel and Patzek's inclusion of the energy cost of refining in the cost of oil. Fertilizer energy inputs are also a significant source of difference, with Kim and Dale estimating fertilizer energy inputs at about 1.4 MJ/L ethanol less than Pimentel and Patzek, or about 8% (0.93/11.6) of the difference in total energy inputs between the two sets of authors.

4.2. Allocation Issues

Pimentel agrees with Dale that it may be appropriate under some circumstances to include adjustments for co-products. For example the energy and dollar costs of producing corn ethanol can be partially offset by allocating some of the energy used to generate by-products, like the DDG made from dry-milling of corn. From about 10 kg of corn feedstock, about 3.3 kg of DDG with a 27% protein content can be harvested [15]. This DDG is suitable for feeding ruminants, but has only limited value for feeding hogs and chickens. In practice, this DDG is generally used as a substitute for soybean feed that contains 49% protein [15]. However, soybean production for livestock feed is more energy efficient than corn production, because little or no nitrogen fertilizer is needed for the production of the soybean legume. In practice, only 2.1 kg of soybean protein provides the equivalent nutrient value of 3.3 kg of DDG. Thus, the credit of fossil energy per kg or liter of ethanol produced should be about 1.861 MJ/L. Factoring this credit for a non-fuel source in the production of ethanol reduces the negative energy balance from 46% to 39% (see Table 2). Some, like Shapouri *et al*. [19] give a credit for DDG of 4,400 kcal/kg DDG when reducing the energy cost of ethanol production. David Pimentel thinks this too high as the actual energy required to produce a kilogram of soy with the same nutrients is only 3,283 kcal [19,20].

Bruce Dale disagrees substantially with Pimentel's assessment mentioned above. In his opinion Pimentel and Patzek [12] underestimated the energy requirements necessary to produce soybean meal (and hence undervalues the energy allocation value from the DDG) because, in his opinion, they set the wrong system boundary. Pimentel and Patzek appear to have included just the agricultural energy used to produce soybeans but not the additional energy used to turn soybeans into the high protein soybean meal animal feed (*i.e.*, the DDG is ready to be fed to some animals). Soybeans are heated, flaked and then extracted with hexane to extract the oil, then the residual hexane is removed by heating and the oil and hexane separated in order to produce soybean meal. Bruce Dale believes that all these are energy-requiring steps that must be included in the energy cost of soybean meal and therefore must be included in the energy allocated to the production of that product. It is true that soybeans don't take much energy to produce, but we don't feed soybeans to animals, we feed high protein soybean meal that has been extensively processed using lots of energy. Thus Kim and Dale [12] included all the energy costs of producing soybean meal using ISO-approved allocation methods, and consequently calculated a much different energy allocation factor than Pimentel and Patzek (74 *vs.* 93% of the total energy of growing and processing corn to ethanol allocated to the ethanol produced). Dale notes that ISO recommends the systems expansion approach for allocation in multiproduct systems because it reduces subjectivity in allocation. Dale believes that the systems expansion approach also represents the actual world situation better in which products compete with each other, and net environmental impacts occur at the margin in which different products are substituted for each other.

5. Estimating EROI for Cellulosic Ethanol

5.1. Overview

Due to the inherent problems with corn ethanol, including as both Dale and Pimentel acknowledge its low or negative EROI and hence low profitability if and as subsidies are removed, there is a growing interest in using cellulosic biomass from non-food biological material to produce ethanol. However, such cellulosic biomass materials have fewer carbohydrates and more complex matrices of lignin and hemicellulose, thus complicating the ethanol conversion processes. In terms of biomass energy produced per hectare (not liquid fuel), switchgrass and willow are more productive and, of importance here, more efficient than corn in terms of fossil energy inputs versus biomass energy output [12]. The problem is that they are also more difficult to turn into liquid fuel. This analysis focuses on the potential of cellulosic biomass to serve as a liquid fuel.

The corn ethanol industry is quite mature, and the EROI values are not likely to change much without a significant change in technology, or a significant change in raw materials (e.g., providing process heat by burning biomass rather than coal or natural gas). In contrast, the cellulosic ethanol industry is just beginning to emerge and no large scale plants are available from which to extract performance data to calculate EROI values. Thus we are limited to "paper" studies. We can do this in two general ways: use existing data that is as close to possible to what we think a mature cellulosic industry might look like or make assumptions about how technologies will change by the time the industry is operational.

The cellulosic ethanol system as defined for these calculations consists of the biomass production (or "agricultural" or "field" phase) and the processing or "biorefinery" phase. These are considered separately, and then the results from each phase are combined to estimate the overall system EROI. Both Pimentel and Patzek [12] and Dale (this paper) have used the energy cost of field operations based on field studies done by others on switchgrass, a productive perennial grass.

5.2. Estimates of Field Energy Costs

It is important to note here that there are some large differences in the assumptions made by Dale and Pimentel for the methods used here. These differences are brought out in the discussion between them.

Method 1. (David Pimentel). In Pimentel's opinion and that of his coauthor Tad Patzek the best information on actual field production of switchgrass is by Sampson and his coworkers [21,22]. Sampson's research is based on more than 15 years of actual operation including the production (using fossil fuels) of switchgrass pellets. The data are summarized in Table 3 of the Results section.

Method 2. (Bruce Dale) Dale used energy input data from two large scale field trials for cellulosic biomass production: switchgrass [23] and willow [24]. The Schmer *et al.* paper also used literature information to estimate the energy costs and energy outputs from a cellulosic ethanol plant based on switchgrass. The Heller *et al*. paper assumes the production of solid (wood) fuel products. The Schmer *et al.* data are compared with those from Pimentel and Patzek in Tables 3. Since both papers (Schmer *et al*. and Heller, Keolian and Volk) are important to subsequent analysis in this paper, their approach and findings are reviewed briefly here.

5.3. Cellulosic Ethanol from Switchgrass: Schmer et al. *2008*

(Bruce Dale) The Schmer *et al.* paper relied on extensive field studies to determine energy inputs and yields for the production of switchgrass, a deep rooted perennial grass native to the American Great Plains. These five year field studies (3–9 ha plots during 2000-2005) were conducted on marginal croplands on ten different farms in the midcontinental U.S. and represented a wide precipitation and temperature gradient. Diesel fuel for field operations and biomass transport to the biorefinergy as well as fertilizer nitrogen were found to be by far the dominant energy inputs for switchgrass production, representing about 93% of direct energy inputs. Fertilizer alone accounts for almost half of direct energy inputs.

5.4. Willow for cellulose: Heller et al. *2003*

(Bruce Dale) Heller's study used strict life cycle analysis methodologies to evaluate the environmental and energetic performance of willow biomass crop production in the state of New York for electricity generation. The base case analysis was founded on field data from establishment of a 65 ha willow plantation in western NY under current (as of 2000) silvicultural practices in that state. Overall the system produced 55 units of biomass energy output (raw wood) per unit of fossil energy input over a 23 year lifetime of the willow plantation, or an EROI of 55:1 at the farm gate. As with the Schmer *et al.* study described above, fertilizer nitrogen and diesel fuel for farm operations were the largest single energy inputs for willow production according to Heller *et al*. (37% and 46%, respectively of total direct energy inputs, see Figure 3 of their paper) for willow production. EROI for liquid fuel production was not calculated by Heller *et al*.

5.5. Estimates of Energy Costs of Processing Cellulosic Biomass

(Bruce Dale) Cellulosic biomass consists of three major components, cellulose, hemicellulose and lignin, in a roughly 40:30:20 mass ratio, depending on the species, plus a host of other components such as ash, protein, etc. Cellulose and hemicellulose are structural carbohydrates composed of sugars that can be fermented to ethanol, at least potentially. The lignin is a complex aromatic polymer and cannot be fermented using current technology. In practice, not all the sugars in cellulose and hemicellulose are fermented. So at the end of the fermentation the residual material contains the lignin plus the residual carbohydrates that were not successfully fermented. It is often assumed that this residual material will be burned to provide all the electricity and steam required to run the processing facility.

In contrast, Pimentel and Patzek believe that at this time the technology to generate cellulosic ethanol at a commercial scale is quite unproven, and even speculative. They assume that if the cellulosic ethanol technology can be made to scale (which they think is very speculative) then all the energy needed for distillation steam will have to come from fossil fuels [25].

Bruce Dale bases his EROI estimates for cellulosic ethanol from switchgrass on the work of Schmer *et al.*, who, in addition to estimates of the energy used in the field to grow switchgrass, used modeling to explore the crop conversion (biorefining) portion of the system. Schmer's calculations were based on models for the biorefinery and the overall system derived by the Energy and Resources Group Biofuel Analysis Meta-Model (EBAMM, University of California-Berkeley). EBAMM assumes that all energy used by the biorefinery will come from residual biomass (*i.e.*, that portion not converted to ethanol). This residue is burned to produced electricity and to generate steam to run the biorefinery, *i.e.*, to distill the alcohol from the mash. EBAMM also estimates an electricity export of 4.79 MJ/L of ethanol produced in the biorefinery. Thus Schmer estimates that the overall energy output is 21.2 MJ/L of ethanol plus (3 (a factor for the quality of electricity) × 4.79 equals 14.4) MJ of electricity for a total of 35.8 MJ/L of ethanol.

To check the EBAMM model, Dale used the Schmer data to calculate the energy used for the agricultural system and the Laser *et al*. [26] modeling information (see Figure 1 in the Laser paper) to describe the conversion (biorefinery) part of the system. Assuming the only energy input to the biorefinery is the energy contained in the biomass, he multiplied the EROI of the agricultural system by the overall thermal energy efficiency of the biorefinery (correcting for electricity quality) and then subtracted the energy costs of biomass transport to the biorefinery to get the system EROI. Figure 1 from the Laser *et al.* paper provides an estimate of 43.3% overall thermal efficiency of conversion of feedstock cellulosic biomass (39.5% ethanol and 3.8% surplus electricity) for mature cellulosic ethanol based on biochemical conversion to ethanol combined with electricity generation. (In effect, this means that 43.3 MJ of useful energy products are derived from 100 MJ of feedstock energy delivered to the biorefinery.) Transport energy was estimated from the Heller *et al* paper as 0.1 kJ per MJ of delivered biomass over a 96 km average transport distance. Using these data, an EROI for cellulosic ethanol from switchgrass is estimated to be 18.1:1, similar to the value of 17.8:1 calculated in Table 3.

There is obviously a substantial difference in the EROI of cellulosic biofuels between Pimentel and Patzek (0.78:1) and Dale (this work) (17.8:1). There are various reasons for this difference. Most importantly, Pimentel and Patzek use 25.5 MJ/L of energy derived from fossil or other outside fuel sources to distill the ethanol from the fermentation residue while Dale assumes that this energy can be derived from the fermentation residue itself. This accounts for 90% (25.5/27.7) of the difference in energy costs and correspondingly most of the difference in the EROIs. The second largest difference is that Dale estimates that there will be 4.79 MJ/L of surplus electricity derived from the process. This is based on the assumption that the residual biomass will be enough to not only distill the ethanol but also to generate some residual electricity. This electricity is weighted by a factor of three representing its quality. Thus Dale's overall energy output is 21.2 MJ/L of ethanol plus 14.4 MJ of electricity for a total of 35.6 MJ/L of ethanol. These data for energy inputs and outputs for switchgrass ethanol are summarized in Table 3.

Table 3. Comparing Different EROI Calculations for Switchgrass.

Input (MJ/L ethanol)	Dale (this work)	Pimentel & Patzek
Agriculture		
Fuel	0.19	0.42
Machinery	Not determined	1.22
Fertilizer	0.94	4.18
Pesticides/Herbicides	0.15	0.71
Seeds	Not determined	0.54
Feedstock Transport	0.63	1.07
Estimate for Not Determined items	1.76	0.00
Total including Not Determined	3.77	8.14
Biorefinery		
Water	Not determined	0.23
Fuel	0.00	
Steam	0.00	18.40
Electricity	0.00	7.13
Steel	Not determined	1.08
Misc	Not determined	1.45
Ethanol distribution	0.00	1.39
Total Energy Input to Ethanol	2.01	29.70
Total Energy Output	35.80	21.40
Energy Return on Investment	**17.8:1**	**0.72:1**

6. Discussion: Cellulosic Ethanol

6.1. Discussion: Yield of Ethanol per Ton of Biomass

Pimentel believes that since cellulosic biomass, like straw and wood, clearly have very few of the simple starches found in corn, this means that 2 to 3 times more cellulosic material must be produced and processed to obtain a similar amount of cellulosic ethanol as corn (Patzek [27]). Dale responds that corn grain has about 80% carbohydrate (starch), and it is the starch that is converted to ethanol. Switchgrass has about 70% carbohydrate (almost all cellulose and hemicellulose, but very little starch), and these are the carbohydrates that are converted to ethanol. Dale believes that it is incorrect to assert that 2 to 3 times more cellulosic material must be processed to make a similar amount of ethanol. Current ethanol yields from corn grain are about 2.7 gallons per bushel, or approximately 470 L per MG dry grain. Depending on the species used for biomass and conversion technology, current ethanol yields from cellulosic biomass are about 240–350 L per dry MG of biomass ([28-30], with a rough upper limit at about 400 L per dry MG as the technology improves. The upper limit of the current ethanol yield range quoted above (350 L/MG) was obtained by DDCE, LLC (DuPont Danisco Cellulosic Ethanol, LLC) at their 250,000 gallon per year cellulosic ethanol demonstration plant in Vonore, Tennessee [30].

At the yields obtained by DDCE, LLC Dale estimates that it takes about 1.3 tons of cellulosic biomass to provide the same amount of ethanol as a ton of grain, not 2 to 3 times as much, as Pimentel suggests and that eventually it may take only about 10% more cellulosic biomass to provide the same amount of ethanol. Actually, since the residual (unfermented) biomass will be burned to produce electricity, for the sake of a higher EROI we may not want to push the ethanol yield any higher than it is right now. The 3 to 1 multiplier for the quality of the electricity generated from the biomass residual above that required for distillation will push the EROI higher than it would be if more of the carbohydrate were converted to ethanol. The key seems to be getting the right balance of ethanol and electricity to meet our society's needs for both liquid fuels and electricity at sufficiently high EROI.

6.2. Discussion: Potential Scale of Cellulosic Ethanol Industry

While David Pimentel certainly hopes that the proposal to convert cellulosic biomass into liquid fuel will achieve the goal of generating a significant amount of net energy, he is not optimistic that even if this were possible it could make a sufficient difference. Green plants collect and convert less than 0.1% of the incident sunlight into plant matter [12,31,32]. In the United States all green plants collectively produce biomass equivalent to about 53 exajoules of energy per year from sunlight, only about half of our total fossil energy use. Hence even if we were able to use all agricultural, forest , grassland and aquatic plants, with no production of food or fibre, at an impossible 100% efficiency this would be barely enough energy to displace oil. Photovoltaics at 15% efficiency collect 150 times the solar energy per square meter than green plants do per year and would be, in his opinion, a better use of the land.

Bruce Dale responds that the biofuel industry is not trying to replace all energy used in the United States, but only a portion of our liquid fuel, most of which is currently derived from petroleum. He does agree that a high EROI by itself is not sufficient to give us a useful alternative to petroleum—scale also matters. The latest Department of Energy study indicates that around 1.3 billion metric tons of cellulosic biomass can be sustainably produced each year in the U.S. (http://www1.eere.energy.gov/biomass/pdfs/billion_ton_update.pdf). This much biomass is equivalent to about 20 exajoules (or 20 quadrillion BTUs, or 20 × 10 to the 15th power BTUs), roughly 20% of total U.S. energy consumption). Even if only half of the energy content of biomass can be converted to liquid fuel that would still give us a lot of energy. Relatively simple agricultural changes such as double cropping (growing a winter annual grass following corn) could increase the amount of biofuel produced still further [33] as could increasing the yield of energy crops such as switchgrass and willow.

David Pimentel believes that the DOE claim that 1.3 billion tons of cellulosic biomass can be harvested sustainably cannot possibly be true based on data that he and his graduate students have gathered. This would mean harvesting 72% of total U.S. biomass production per year including all food, grass, and forests. Food crops and grass alone total 92%.

6.3. Discussion: Estimates of Energy Cost of Cellulosic Feedstock Production (Schmer vs. *Sampson)*

While David Pimentel believes that Schmer's data on costs and gains of switchgrass production are generally believable, he points out that there have been several criticisms of that report [21,22,31,32]. He prefers the assessment of Roger Samson who has more than 15 years of field experience with switchgrass and has a business producing pelletized switchgrass. Samson *et al*. [21] report that they were able to produce nearly 15 kcal of switchgrass output per 1 kcal of fossil energy input . The main problem David Pimentel has with Schmer *et al.'s* report is their statement that "Switchgrass produced 540% more renewable energy than nonrenewable energy consumed". They achieve this projection by using an extraordinary high estimated yield of ethanol from switchgrass processing of 0.38 L/kg (or 380 L per ton). This is the same yield of ethanol produced from 1 kg of corn grain, a much more fermentable feedstock. Pimentel believes that no one else in the world has achieved even a small portion of the return reported by Schmer *et al*. from switchgrass. Bruce Dale responds that, on the contrary, the current yield of ethanol from corn grain is about 0.47 L/kg of dry corn grain and that many laboratories and commercial operations have already gotten yields approaching 0.35 L/kg of cellulosic biomass, as referenced above. Coauthor Hall wishes to remain neutral in this and other discussions but believe that his coauthors are setting up some very researchable questions for a more mature biofuels industry.

David Pimentel and his collaborator Tad Patzek give several additional arguments about the, in their view, inadvisability of large scale production of fuel from switchgrass in addition to their calculation that it was likely to have an EROI of less than one for one. Patzek in 2010 reported that even if the entire total 140 million hectares of U.S. cropland were planted to switchgrass and converted to ethanol, the gross yield would be only 20% of U.S. gasoline consumption. Also, Smith [34] reported that the cost of producing a liter of ethanol from cellulosic feedstock is ¢54/L ($3.09/gal). Bruce Dale responds that the values of switchgrass productivity and ethanol yield assumed by Patzek are unjustifiably low, since we are already able to produce about 10% (by volume) of our gasoline consumption from about one third of our corn grain, which is about one sixth of the total mass of corn grain and corn residue produced on about 36 million hectares of cropland.

Bruce Dale agrees that the Sampson and Schmer data are not that different in terms of the farm level operations. Sampson's data gives an EROI of about 23:1 for solid biomass delivered to the farm gate while the corresponding farm gate EROI for Schmer is about 38:1. (Interestingly, the Heller *et al*. data give an EROI of 55:1 at the farm gate, but that is for wood from trees.) These differences can be reasonably attributed to the different yields and agronomic practices employed in the Sampson study (eastern Canada) versus the Schmer study (midwestern US). As with Schmer, Sampson shows that the energy inputs from the fertilizer and the harvesting operations represent the greatest farm level energy inputs, 58% and 29%, respectively, of the overall energy required to grow, harvest and transport switchgrass to the fuel production facility.

Where Dale and Pimentel disagree strongly is on the ethanol yield from switchgrass. Dale notes that, in fact, DDCE and other firms have already achieved ethanol yields similar to or greater than those used by Schmer. Dale notes that over 100 years ago the Germans developed a wood to ethanol process based on sulfuric acid that achieved about 0.21 L/kg. During World War II, the US used this process to produce cellulosic ethanol for conversion to butadiene to produce synthetic rubber. The Vulcan Copper and Supply Company was contracted to construct and operate a plant to convert sawdust into ethanol. This plant achieved an ethanol yield of about 0.21 L/kg over several years but was not profitable in an era of cheap oil and was closed after the war [35]. Bruce Dale notes that there are a number of smaller (e.g., Mascoma, Gevo, KL Energy, Coskata) and larger (e.g., Shell, BP, DuPont, Chevron, ConocoPhillips) firms that are actively developing cellulosic ethanol and other biofuels from different materials including corn stover, wheat straw, mixed hardwood chips, sugar cane bagasse, *etc*. [36]. Although process data are generally confidential, these firms are working to increase these yields and seem to be making real progress. Some of them are already operating large demonstration plants. For example, DDCE, a cellulosic ethanol firm owned by DuPont, publicly states that they are achieving 85 gallons per ton (350 L per dry MG or 0.35 L/kg) at their demonstration plant in Vonore, Tennessee [30].

6.4. Discussion: Large Differences in Distillation Energy

Finally, there is a clear difference in opinion on whether or not we will be able to use residuals for fuel for distillation, and this is the main reason that the EROI estimates are so different. Of course because the technology is barely operational at a commercial scale we cannot check which assumption is correct.

Coauthor Dale believes that many different estimates by the National Renewable Energy Laboratory (NREL) and others have shown that more than enough energy is contained in the biomass to run the biorefinery and even have enough left over to export surplus electricity [26,37,38]. The NREL calculations in particular have been extensively vetted by industry and the latest NREL report is coauthored by six practicing engineers from the Harris Group, a large, diversified engineering services and design firm [39]. Also, if the residuals are not burned to provide process heat and electricity, they will have to be disposed of in some way, probably by landfilling. It does not seem reasonable to suppose that industry will not use the ready source of fuel available but will instead opt to pay for its disposal. Furthermore, the Kraft pulp and paper industry is powered largely by its biomass residuals and newer sugar cane to sugar-ethanol-electricity system is completely powered by its residue, sugar cane bagasse, while exporting surplus electricity [40]. Both of these are highly developed, well-established industries. So we have the example of two very large scale industries that show that it is indeed possible to use biomass residuals to provide most or all of the energy needed for biofuel production, presumably including cellulosic biomass.

Pimentel, on the other hand, believes that only some of the residual can be burned. Much of the lignin cannot be extracted and burned. According to the website Lignoworks [41] "Most schemes propose to use the separated lignin as a fuel to run the plant. However, a process that converts all of the input biomass to fuel is unlikely to be economically feasible". Further support for the statement that only a small portion of the lignin can supply energy comes from specialists in paper production in Alabama [42]. They stated that separating the lignin from the water was too costly in terms of both energy and dollars. What they do is spray the water-lignin mixture into the boilers. They claim only a little net energy from this. The same would be true for cellulosic ethanol production.

Coauthor David Pimentel further states that **"**There is no evidence that the suggested potential improvements in cellulosic ethanol are possible. Examine the multi-billion dollars that have been spent for the past 5 years with no result." [43,44]). He also believes that the GREET model is very optimistic, and generates high yield estimates that have not been verified in the field.

6.5. The Possibility for Improved Technology and Increased EROI for Cellulosic Ethanol

The following calculations are intended to illustrate the potential for improvements in cellulosic ethanol's EROI. These calculations assume that the Schmer *et al.* [23] and Heller *et al*. [24] papers are essentially correct in their estimates of the crop production phase energy inputs and that Dale's coauthored paper [26] provides reasonable estimates of the overall energy efficiency of converting biomass to ethanol and electricity, given different conversion technologies.

Dale develops his argument as: "As we have seen from several different sources, by far the dominant energy inputs to agricultural production for both corn and cellulosic biomass are in the nitrogen fertilizer applied and also the diesel fuel used for transport and field operations. Reducing these inputs would therefore increase the EROI for biofuels. Better fertilization practices (slow release fertilizer, precision agriculture), use of leguminous (nitrogen fixing) crops, breeding and genetic modification to reduce fertilizer nitrogen requirements and application of biosolids from waste water treatment instead of synthetic nitrogen fertilizer are all methods by which fertilizer nitrogen inputs might be reduced over time for bioenergy crops such as switchgrass and willow".

Assuming that a future cellulosic ethanol industry is supplied with both switchgrass and willow feedstocks in equal amounts, and that the nitrogen fertilizer inputs for these two materials would be reduced by half from the values given in Table 3, the total nitrogen input would be about 0.33 MJ/L of ethanol. Also, bioenergy crops such as switchgrass and willow are in the very early stages of breeding to increase yields with lower inputs per unit of yield, as has been done so successfully for corn and other crops For example, fertilizer nitrogen use per bushel of corn has decreased by about one third from 1970 through 2005 [45,46].

Dale believes that significant yield gains and more favorable nitrogen use efficiency can also be expected for cellulosic biomass crops. For example, in 2002 in the Midwestern US, switchgrass required about 120 kg of nitrogen (N) per ha to produce 10.2–12.6 Mg of dry biomass per ha [47]. This is roughly equivalent to 35 MJ of switchgrass produced per MJ of fertilizer N applied (assuming 18 MJ per kg of switchgrass (lower heating value) and 48.2 MJ required to produce 1 kg of N (also lower heating value). The energy requirements of N fertilizer production are based on recent data from the GREET model maintained by Argonne National Laboratory (GREET 1.8d).

In contrast, in 2009, in eastern Tennessee 67 kg of N were required to yield between 15.6–22.9 MG of dry switchgrass per ha on moderately to well drained soils, or around 108 MJ switchgrass produced per MJ of fertilizer N, an increase of about 3 fold versus the earlier Midwestern results of Schmer, *et al* [23]. Obviously, soil type, cultivar and climate all play a role in yield and nitrogen use efficiency, but the point is that very favorable yields and nitrogen use efficiencies leading to potentially high EROI values have already been shown for cellulosic biomass crops. Other increases in efficiency appear possible in agricultural fuel use [49] (and also in the operation of a biorefinery [26]. Table 4 gives Dale's estimates for the improvements in yield and reductions in energy costs for producing switchgrass. If all of these improvements in efficiency are realizable, as Dale thinks possible, then EROI for cellulosic ethanol from switchgrass might be doubled from 17:1 to 35:1. If the thermal efficiency of the biorefinery is increased (e.g., by ethanol and more net electricity produced in a gas turbine combined cycle (GTCC) system [26], then further increases in cellulosic ethanol EROI can be expected.

Table 4. Potential EROI for Advanced Cellulosic Ethanol.

Input (MJ/L ethanol)	Value
Agriculture: Fuel	0.19
Agriculture: Electricity	0.00
Feedstock Transport	0.29
Biorefinery: Fuel	none required
Biorefinery: Electricity	none required
Ethanol Distribution	negligible
Fertilizer	0.33
Pesticides/Herbicides	0.10
Less: Coproduct Energy Input	none
Allocated to Ethanol: Percent	100
Total Energy Input to Ethanol	0.91
Indirect Energy Inputs	0.13
Total Direct + Indirect Inputs	1.04
Total Energy Output	37.10
Energy Return on Investment	**35.70**

7. Conclusions and Summary

An important objective of this paper has been realized. The coauthors agree that the EROI concept is valuable and can provide important insights about the desirability of particular energy systems. The reasons for the published differences between coauthors Dale and Pimentel with regard to corn ethanol's EROI have been dissected and are shown to be primarily due to allocation issues, not to inherent problems with the underlying concept of EROI. These results highlight the importance of performing EROI using transparent methodologies and allocation approaches, clearly defined system boundaries, and using the best data possible. Lack of crucial data for operating cellulosic ethanol systems makes these EROI calculations inherently more speculative than those for corn ethanol. However, farm level EROI's are relatively high for cellulosic biomass production (ranging from 10:1 to about 50:1 in this analysis). Therefore it is the efficiency of energy conversion in the biorefinery, in particular the practicality of using residual biomass to power the biorefinery, which will determine whether cellulosic ethanol systems can reach the very attractive EROIs that seem possible.

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Conflict of Interest

The authors declare no conflict of interest.

References and Notes

1. US Energy Information Agency. International Energy Outlook. www.eia.doe.gov/oiaf/ieo/index.html (accessed on 2 December 2011).
2. Oh, W.; Lee, K. Causal relationship between energy consumption and GDP revisited: The case of Korea 1970- 1999. *Energy Econ*. **2004**, *26*, 51-59.
3. Skov, A.M. National health, wealth and energy use. *J. Pet. Technol.* **1999**, *51*, 48-60.
4. Hall, C.A.S.; Klitgaard, K.A. *Energy and the Wealth of Nations: Understanding the Biophysical Economy*; Springer: New York, NY, USA, 2011.
5. US Energy Information Agency. *Short Term Energy Outlook*; US Energy Information Agency: Washington, DC, USA, 2011.
6. Lal, R.; Pimentel, D. Soil erosion: A carbon sink or source? *Science* **2008**, *318*, 1040-1042.
7. Farrell, A.E.; Plevin, R.J.; Turner, B.T.; Jones, A.D.; O'Hare, M.; Kammen, D.M. Ethanol can contribute to energy and environmental goals. *Science* **2006**, *311*, 506-508.
8. Patzek, T. Thermodynamics of the corn-ethanol biofuel cycle. *Crit. Rev. Plant Sci*. **2004**, *23*, 519-567.
9. The conclusions of some of these papers on corn ethanol's EROI have been subject to debate (e.g., see responses to that article in Science **2006**, 312:1746). Kammen, an important contributor to the basically positive view given in Farrell *et al*., seems to have become less positive as seen in an article in Time magazine (7 June 2007).
10. Hammerschlag, R. Ethanol's energy return on investment: A survey of the literature 1990–present. *Environ. Sci. Technol.* **2006**, *40*, 1744-1750.
11. Kim, S.; Dale, B.E. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. *Biomass Bioenergy* **2005**, *29*, 426-439.
12. Pimentel, D.; Patzek, T. Ethanol production using corn, switchgrass and wood; biodiesel production using soybean. In *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks*; Pimentel, D., Ed.; Springer Science+Business Media B.V.: Dordrecht, the Netherlands, 2008; pp. 357-394.
13. Murphy, D.J.; Hall, C.A.S.; Dale, M.; Cleveland, C. Order from chaos: A preliminary protocol for determining the EROI of fuels. *Sustainability* **2011**, *3*, 1888-1190.
14. Henshaw, P.; King, C.; Zarnikau, J. System Energy Assessment (SEA), defining a standard measure of EROI for energy businesses as whole systems. *Sustainability* **2011**, *3*, 1908-1943.
15. Stanton, T.L. Feed composition for cattle and sheep. Colorado State University. Cooperative Extension. 1999, Report No. 1.615. 7 pages.
16. International Organization for Standardization (ISO). *International Organization for Standardization 14041: Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis*; ISO: Geneva, Switzerland, 1998.
17. Szklo, A.; Schaeffer, R. Fuel specification, energy consumption and CO_2 emission in oil refineries. *Energy* **2007**, *32*, 1075-1092.
18. Shapouri, H.; Duffield, J.A.; Wang, M. The energy balance of corn ethanol: An update. Agricultural Economic Report 813, US Department of Agriculture: Washington, DC, USA. 2002.
19. Patzek, T.W. Thermodynamics of the corn-energy biofuel cycle. *Crit. Rev. Plant Sci*. **2004**, *23*, 519-567.

20. Hermans, J.; Reinemann, D. Integrating bio-fuel production with Wisconsin dairy feed requirements. *ASABE J.* 2006, Paper number 066036.
21. Samson, R.; Duxbury, P.; Drisdale, M.; Lapointe, C. Assessment of pelletized Biofuels. PERD Program, Natural Resources Canada, 2000, Contract 23348-8-3145/001SQ.
22. Samson, R.; Duxbury, P.; Mulkins, L. Research and development of fibre crops in cool season regions of Canada. Resource Efficient Agricultural Production-Canada. Box 125, Sainte Anne de Bellevue, Quebec H9X 3V9, Canada, 2004.
23. Schmer, M.R.; Vogel, K.P.; Mitchell, R.B.; Perrin, R.K. Net energy of cellulosic ethanol from switchgrass. *Proc. Natl. Acad. Sci. U. S. A.* **2008**, *105*, 464-469.
24. Heller, M.C.; Keolian, G.A.; Volk, T.A. Life cycle assessment of a willow bioenergy cropping system. *Biomass Bioenergy* **2003**, *25*, 147-165.
25. Arkenol. Our technology. Concentrated acid hydrolysis. http//:www.arkenol.com/ Arkenolpercent20Increch01.html (accessed on 2 August 2004).
26. Laser, M.; Larson, E.; Dale, B.; Wang, M.; Greene, N.; Lynd, L.R. Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios. *Biofuels Bioprod. Biorefin*. **2009**, *3*, 247-270.
27. Patzek, T.W. A probabilistic analysis of the switchgrass ethanol cycle. *Sustainability* **2010**, *2*, 3158-3194.
28. Lau, M.W.; Dale, B. Cellulosic ethanol production from AFEX-treated corn stover using Saccharomyces cerevisiae 424A(LNH-ST). *Proc. Natl. Acad. Sci. U. S. A.* **2009**, *6*, 1368-1373.
29. Kazi, F.K.; Fortman, J.A.; Anex, R.P.; Hsu, D.D.; Aden, A.; Dutta, A.; Kothandaraman, G. Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. *Fuel* **2010**, *89*, 520-528.
30. Provine, W. DDCE, Inc. Personal communication, 2011.
31. Pimentel, D.; Patzek, T. Editorial: Green plants, fossil fuels, and now biofuels. *Bioscience* **2006**, *56*, 875.
32. Pimentel, D.; Trager, J.; Palmer, S.; Zhang, J.; Greenfield, B.; Nash, E.; Hartman, K.; Kirshenblatt, D.; Kroeger, A. Energy production from corn, cellulosic, and algae biomass. In *Global Economic and Environmental Aspects of Biofuels*; Pimentel, D., Ed.; Taylor & Francis: Boca Raton, FL, USA, 2012.
33. Dale, B.; Bals, B.; Kim, S.; Eranki, P. Biofuels done right: Land efficient animal feeds enable large environmental and energy benefits. *Environ. Sci. Technol.* **2010**, *44*, 8385-8389.
34. Smith, C.H. When long cycles and depletions interest. 2008. Available online: http//:www.oftwominds.com/blogmay08/cycle-depletion.html (accessed on 17 August 2011).
35. Katzen, R.; Schell, D.J. Lignocellulosic feedstock Biorefinery: History and plant development for biomass hydrolysis. In *Biorefineries—Industrial processes and Products*; Kamm, B., Gruber, P.R., Kamm, M., Eds.; Wiley-VCH: Weinheim, Germany, 2006; Volume 1, pp. 129-138.
36. Sims, R.E.H.; Mabee, W.; Saddler, J.N.; Taylor, M. An overview of second generation biofuel technologies. *Bioresour. Technol.* **2010**, *101*, 1570-1580.
37. Laser, M.; Jin, H.; Jayawardhana, K.; Dale, B.E.; Lynd, L.R. Projected mature technology scenarios for conversion of cellulosic biomass to ethanol with coproduction of thermochemical fuels, power, and/or animal feed protein. *Biofuels Bioprod. Biorefin*. **2009**, *3*, 231-246.

38. National Renewable Energy Laboratory (NREL). *Enzymatic Hydrolysis: Current and Futuristic Scenarios*; NREL: Golden, CO, USA, 1999; Report NREL/TP-580-26157.
39. Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.; *et al*. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover, 2011. Technical Report NREL/TP-5100-47764.
40. Leal, M.R.L.V. Tecnological evolution of sugarcane processing for ethanol and electric power generation. In *Sugarcase Bioethanol: R&D for Productivity and Sustainability*; Cortez, L.A.B., Ed.; Editora Edgard Blucher Ltda.: São Paulo, SP, Brazil, 2010; pp. 561-582.
41. Lignoworks. What is Lignin? 2011. Available online: www.lignoworks.ca/content/what-lignin (accessed 2 September 2011).
42. Eden, M.R. *et al.* Auburn University. Personal communication, 21 October 2006.
43. Abelard Organization. http://www.abelard.org/briefings/biofuels.php (accessed on December 2, 2011).
44. Ratliff, E. One Molecule Could Cure Our Addiction to Oil. *Wired Magazine* **2009**, 15. Available online: www.wired.com/science/planetearth/magazine/15-10/ff_plant? (accessed on December 2 2011).
45. Wang, M. Greet 1.5a–Transportation fuel-cycle model. Argonne National Laboratory, IL, USA. 2000.
46. University of Nebraska-Lincoln. http://cropwatch.unl.edu/web/cropwatch/archive?articleID=4585476 (accessed on 2 December 2011).
47. Vogel, K.P.; Brejda, J.J.; Walters, D.T.; Buxton, D.R. Switchgrass biomass production in the Midwest USA: Harvest and nitrogen management. *Agron. J.* **2002**, *94*, 413-420.
48. Mooney, D.F.; Roberts, R.K.; English, B.C.; Tyler, D.D.; Larson, J.A. Yield and breakeven price of 'Alamo' switchgrass for biofuels in Tennessee. *Agron. J.* **2009**, *101*, 1234-1242.
49. Cook, D.; Shinners, K. 227 Agricultural Engineering Building, University of Wisconsin-Madison, 460 Henry Mall Madison, WI 53706, USA. Personal communication, 2011.