The Energy Return on Invested of Biodiesel in Vermont

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Summary

High oil prices are driving renewed interest in biofuels, including biodiesel in the hope that it can substitute for petroleum-derived diesel. While many criteria must be used to determine whether these biofuels offer benefits over their fossil fuel-derived counterparts, the primary criteria must be that the biofuels are able to generate an energy surplus, defined as a positive energy return on energy invested (EROI). A literature review of biodiesel EROI yields estimates that vary widely, from those below the energy-break-even point of 1:1 to those up to 8:1. One hindrance in judging which EROI estimates to use is that methods for calculating them vary tremendously, and methods play a vital role in how life cycle system boundaries are drawn and thus which energy costs are counted and which are not. This paper reports on a life cycle assessment (LCA) on biodiesel produced from oilseed grown on five farms and from reclaimed vegetable oil in Vermont, using an expansive methodology that seeks to include all non-negligible energy costs. The resulting EROI estimates for Vermont biodiesel range from 2.6:1 up to 5.9:1, suggesting an unambiguously positive EROI for biodiesel in the state. Forecasts of EROI based on expected increases in production suggest potential EROI increases up to 3.9:1 to 8.1:1. These estimates compare favorably to those reported by the United States Department of Agriculture, and also compare favorably to estimates of EROI for diesel fuel produced by petroleum. Vermont producers appear able to deliver a viable biodiesel fuel with a positive EROI despite operating on relatively small scales.

1. Introduction

In the aftermath of the oil shocks of the 1970s, many governments, businesses and entrepreneurs searched for sources of liquid fuels not derived from petroleum (Körbitz, 1999). Rising petroleum prices after 2000, particularly the 2008 spike that lifted oil prices to nearly $150 per barrel, and concerns of fossil fuel depletion (see, for example, Deffeyes, 2010) have again renewed interest in alternative fuels, particularly biologically-derived fuels (Demirbas, 2007; Pradahan et al., 2009). One biofuel that is of growing interest is biodiesel, which is made most commonly from plant oils and animal fats through the chemical process of transesterification (Pradahan et al., 2009; Meher et al., 2006). Biodiesel readily substitutes for diesel fuel in most engines, and can be used as a substitute for heating oil as well. While current production of biodiesel is small relative to petroleum diesel, opportunities for expanding production exist in many regions.
A critical criterion that should be used to judge the potential of a biofuel—or any fuel—is the amount of energy it yields as a finished fuel relative to the energy required to produce it. This ratio of energy output relative to energy inputs is termed the energy return on invested ratio (EROI) (Mulder & Hagens, 2008). Calculated values of EROI range from zero to infinity, and the break-even point of 1:1 defines the point at which a fuel's energy yield exactly equals the energy required to produce it.

The economic and social ramifications of EROI are best explained within a societal context (Hall et al., 2009). A society's EROI is calculated as the weighted average EROI of all of the fuels that the society uses. If this weighted average is 1:1, it means that all of a society's energy output must be reinvested to generate tomorrow's energy. This "reinvested" energy constitutes the energy sector of the economy, and in a society with an EROI of 1:1 the energy sector of the economy is effectively the entire economy. When society's EROI rises above 1:1, surplus energy is generated that may be put to other uses besides further procurement of energy. With a societal EROI greater than 1:1, economic sectors outside of the energy sector may emerge such as art, information technologies, construction, etc. The higher society's EROI is above this 1:1 cutoff, the larger the non-energy sector of their economy can be. Figure 1 illustrates this with two energy flow diagrams, the one on the left showing the surplus versus reinvested energy for a society with high EROI and the one on the right showing the surplus versus reinvested energy for a lower EROI society. In order for societies to have functioning non-energy sector economies, the weighted average EROI for all of their fuels must be greater—and ideally substantially greater—than 1:1. Societies that cannot find a mix of fuels that yield surplus energy face economic and social decline. The higher the EROI of a society's fuel mix, the more substantial its non-energy sector can be.

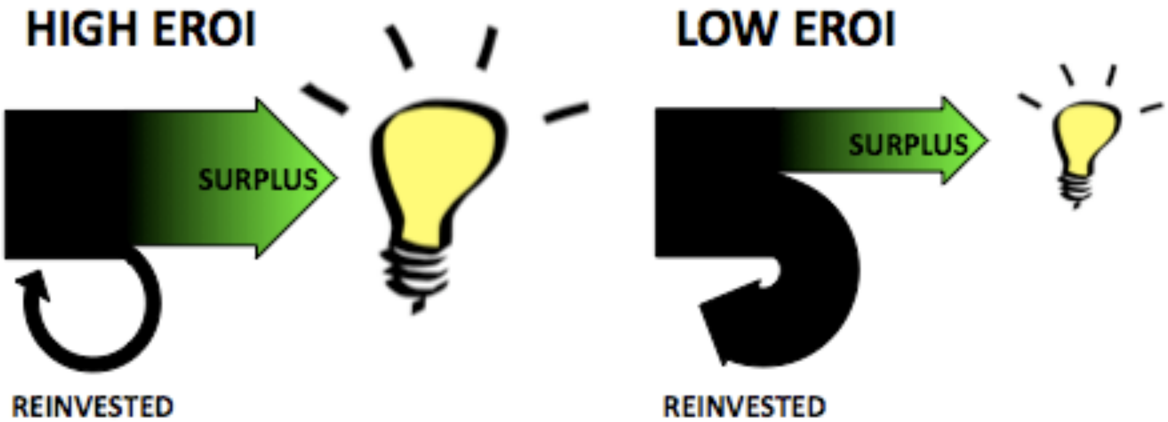

Figure 1. Two simplified energy flow diagrams. The one on the left compares surplus energy to that which is reinvested for a high EROI fuel, showing the high surplus delivered to the economy that allows for a large and thriving economy outside of the energy sector. The image on the right compares surplus energy to that which is reinvested for a lower EROI fuel, showing the smaller relative surplus and thus the smaller economy outside of the energy sector. Only surplus energy can contribute to economic productivity outside of the energy sector.

An additional societal impact of EROI deals with economic growth. For a society's economy to grow over time, the production of goods and services must expand. For the production of goods and services to expand, capital investments must also expand and these capital investments require energy—to build the new machinery, transport the additional goods, etc. For a growing economy, the energy to power these new capital investments must come from existing energy surplus. Therefore, in order for a society's economy to grow it must have a large enough energy surplus that it can afford to invest some of its energy surplus into building additional capital to fuel growth. While a society can certainly persist at a steady-state with a low societal EROI, for it to grow its economy the society needs a higher EROI.

Fossil fuels, particularly petroleum, have historically delivered fuels with very high EROI. Analysts estimate that crude oil yielded an EROI of 100:1 in the 1930s (Murphy & Hall, 2010). Given crude oil's dominance as an energy source, this suggests that an oil-powered economy at this time would readily have the capacity to expand its non-energy sectors given its high EROI fuel mix. Since the 1930s however, the quality of crude oil resources has steadily declined and the infrastructural investments needed to extract a barrel of crude oil have increased, causing the EROI of crude oil to fall to approximately to 20:1 globally. These 100:1 and 20:1 figures equate to EROI of crude oil where crude oil flows from the well before it is delivered to a refinery and turned into finished products like gasoline, diesel, and kerosene. EROI estimates of finished fuels such as gasoline and diesel are typically much lower than these values due to the additional energy costs of transport and refining. Data presented in Sheehan et al. (1998), for instance, suggest that the EROI of diesel fuel was about 5:1 in the late 1990s, and as EROI of crude oil at the wellhead has fallen since then the EROI of diesel fuel has likely fallen as well.

Estimates of biodiesel EROI range widely (Table 1), from values below 1:1 as reported by Pimentel & Patzek (2005) for soybean and sunflower-derived biodiesel to the opposite extreme of Elsayed et al. (2003)'s estimated range of 4.85-5.88:1 based on the use of reclaimed vegetable oil as a feedstock and Bona et al. (1999)'s estimate of 8.7 from sunflower oil. The large range of EROI estimates stems from three main issues:

- No standard system boundaries are used in deciding which energy costs are to be included,
- No standard methods are applied to estimate energy costs,
- No standard methods are used to account for co-products, which are other valuable products generated incidentally during the process of making biodiesel.

These three issues beg a more thorough discussion.

Table 1. Energy return for biodiesel by feedstock and reference.

Feedstock, reference	Energy return
Reclaimed vegetable oil	
Elsayed, et al. (2003)	4.85-5.88
Soybean oil	
Pimentel & Patzek (2005)	0.78
Carraretto, et al. (2004)	2.090
Ahmed, et al. (1994)	2.5
Sheehan, et al. (1998)	3.215
Hill, et al. (2006)	3.67
Pradhan, et al. (2009)	4.56
Sunflower oil	
Pimentel & Patzek (2005)	0.76
Edwards, et al. (2006)	0.85-1.08
Bona, et al. (1999)	1.3-8.7
ADEME & DIREM (2002)	3.16
Kallivroussis et al. (2002)	4.5
Rapeseed oil	
Edwards, et al. (2006)	1.05-1.38
IEA (1999)	1.09-2.48
Elsayed, et al. (2003)	2.17-2.42
ADEME & DIREM (2002)	2.99
Richards (2000)	3.71

2. EROI Approaches and Controversies

Given the wide range of estimates listed, it comes as no surprise that the question of whether or not biodiesel is a viable fuel that yields an EROI greater than 1:1 remains controversial. One important reason for the variability seen in estimates is that there exists no consistent framework for assessing EROI (Mulder & Hagens, 2008). EROI can be studied at three levels: first order, second order and third order. First order EROI analysis is represented as:

$$EROI = \frac{E_O}{E_D} \qquad (1)$$

where E_O is the energy contained in a unit of fuel and E_D is the direct energy costs required to deliver that unit of fuel. Direct energy costs include all fuels consumed in the production process, including liquid fuels such as gasoline, diesel or biodiesel, heating fuels such as natural gas, propane or fuel oil, and electricity to power machinery. Appropriate efficiency factors may be applied to the quantities of each fuel to account for energy requirements of their own processing or transport (Pradhan et al., 2009) although this is not always done. E_O and E_D are customarily measured in joules, the International System's energy unit, making EROI a unitless ratio. First order EROI analysis is relatively straightforward, and direct energy costs can often be measured precisely or estimated with high precision leading to EROI estimates with high certainty.

Second order EROI analysis is represented as:

$$EROI = \frac{E_O}{E_D + E_I} \qquad (2)$$

where E_I is the indirect energy costs required to deliver a unit of fuel, which are also called embodied energy costs. Indirect or embodied energy costs include energy required to design, build and maintain structures, machinery, vehicles, and to produce other inputs such as chemical reagents, fertilizers and pesticides, etc. The energy costs of structures, machinery and vehicles are normally amortized over the expected amount of fuel they will produce over their expected lifetime. E_I is also measured in joules, so EROI remains unitless. Second order EROI analysis is much more expansive in its scope than first order EROI analysis, and there are no agreed upon methods stating which indirect energy costs must be included and how one should assess those costs. Further, indirect energy costs are challenging and tedious to estimate, and while their inclusion makes the final EROI estimate more reflective of the real energy costs of a fuel, they also increase the uncertainty in the final EROI estimate. Most analysts ignore this added uncertainty, and unfortunately report estimates of indirect energy costs and second order EROI as if the result was precisely known. A better approach would incorporate an analysis of uncertainty and report EROI estimates with associated standard deviations or confidence intervals.

Tertiary EROI analysis expands the scope of analysis even further, looking beyond merely energy inputs. For instance, a tertiary EROI analysis may inquire about non-energy inputs such as water (Mulder et al. 2010), or other ecosystem services, or may account for environmental externalities per energy unit of fuel output. While it is possible to attempt to translate these non-energy inputs into energy units, this introduces uncharacterizable uncertainty into the analysis and should be avoided. Carrying out a tertiary EROI analysis while leaving non-energy inputs in their native units requires a more expansive analytical process.

Perhaps one of the greatest challenges in assessing the EROI of individual fuels is that no two analysts include the same list of direct and indirect energy costs in their analysis. This yields the suite of biodiesel EROI estimates presented in Table 1 above, each with its own unique accounting framework and a final estimate that cannot readily be compared to other estimates due to differences in methodology. Beyond issues of methodological differences, analysts are not always clear on which direct and indirect energy costs they do include in their analyses. Some studies cited above, such as Elsayed et al. (2003) and Hill et al. (2006), take great pains to be transparent. Others, such as Bona et al. (1999), report results while giving virtually no information about their methodological approach. In an ideal world, analysts studying EROI would adopt a standardized way of delineating, or at the very least reporting on, their study boundaries (Mulder & Hagens, 2008). Such a standardized approach would make EROI analyses more useful, if only because the resulting numbers would be more believable and analysts would be better able to compare EROI estimates from study to study.

Other types of energy analyses can be expressed in ratios that appear similar to EROI, but they measure a very different set of processes or inputs and should not be compared to a standard first or second order EROI estimate. If boundaries are drawn strategically and embodied energy estimated carelessly or left out entirely, even a dismal biofuel can be made to appear as though it yields a high EROI.

Another important factor in previous studies of biofuel EROI is how data is gathered. All studies cited in Table 1 gathered highly aggregated data from regional or national datasets and by borrowing some assumptions on indirect energy costs from other, unrelated studies. This divorces the final estimate of EROI from any ecological context, thereby ignoring differences in oilseed yield, fertilizer and pesticide requirements, or other important inputs, as they vary as a function of physical geography and climate. A superior approach would study EROI on an individual farm, acknowledging the specific growing conditions and specific production process. Not only would this provide a more accurate appraisal of EROI, it would also allow the analyst—and the grower—to study how to improve the EROI of the biofuel produced. Kim & Dale (2005) focus on a more local area (Scott County, Iowa) in one study, although they do not narrow their study to a specific farm and its specific agricultural practices, nor do they publish an estimate of energy return for their biodiesel on its own (the study models the production of biodiesel and ethanol as dual biofuel products on land grown with corn and soybeans in rotation). It is necessary to study agricultural systems at a finer resolution to understand how the production process interacts with both production scale and geography to deliver, or fail to deliver, a positive energy balance for biodiesel. Producer-specific studies of energy return that actually measure direct energy inputs and that estimate indirect energy inputs specific to a supply chain represent an ideal to be strived for, as only these studies allow researchers and producers to observe the impacts of different elements of the production process on the fuel's energy balance. Producers can change their production process to make it more profitable, from an energy perspective, but only if they understand where the energy costs and potential for greater efficiencies lie.

3. Purpose

The purpose of this work is to gain a better understanding of the EROI for biodiesel produced in small-scale, distributed facilities in Vermont, USA. In particular, this work will calculate EROI for biodiesel produced from oilseed grown on five farms, and for one processor who uses reclaimed fryer oil to make biodiesel. A full accounting of direct and indirect energy costs for each producer will be presented using an expansive second order EROI analysis to assess the value of biodiesel as a fuel.

4. Data and Methods

4.1. System Boundaries

Direct energy costs tabulated in the analysis include all liquid transport fuels used to move oilseed around or to power farm machinery, all fuels used to provide space or process heat for buildings and equipment, all electricity used to power machinery, and an estimate of the direct energy input associated with human labor. Transport fuels included diesel and biodiesel, while fuels used for space heat included biodiesel. Figure 2 illustrates the process of growing oilseed and processing this into biodiesel. Energy costs are apportioned between biodiesel and other co-products by mass similar to Pradhan et al., (2009). I assume the energy content of diesel fuel is 136 MJ/gallon, the energy content of biodiesel is 126 MJ/gallon, and assume that 1 kWh of electricity equates to 3.6 MJ. The lower heating value for diesel fuel was adjusted by an efficiency factor of 0.84 to account for the life cycle energy costs of production (Pradhan et al. 2009). An efficiency factor of 0.31 was applied to electricity estimates to account for generation and transmission losses (Pradhan et al. 2009). The producer who uses reclaimed fryer oil used some of their biodiesel as an input into their production process, so their EROI was converted to an efficiency factor of 0.75 to account for the life cycle energy costs of producing this biodiesel. I assume that the direct energy input of human labor equates to a power output of 300 W (Smil, 2008). In reality, human power output varies as a function of the type of labor being done (heavy lifting versus driving a vehicle, for instance), but in practice the direct energy value of human labor is negligible relative to other direct and indirect energy inputs so investing substantial effort further delineating types of labor is unnecessary. Surveys were used to collect data from biodiesel growers and producers on direct energy costs and labor inputs. All estimates of direct energy inputs are translated to energy input per gallon of biodiesel produced.

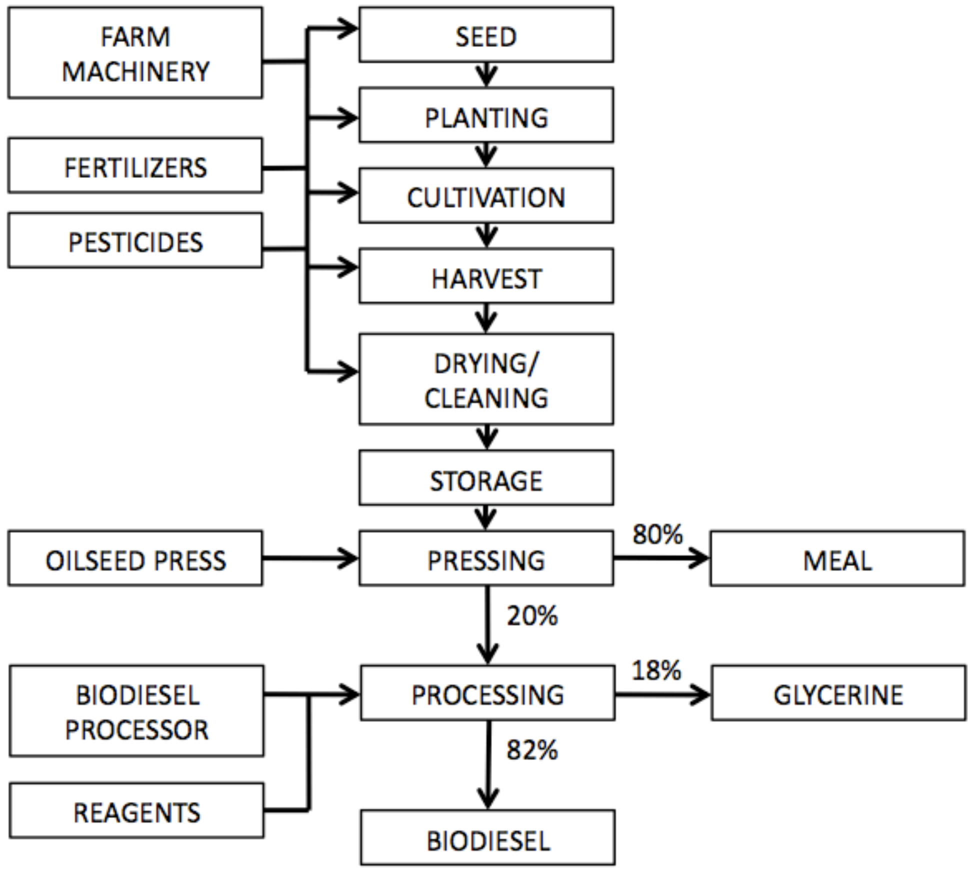

Figure 2. The process of growing oilseed and processing it into biodiesel. All inputs and machinery (at left) have both direct and indirect energy costs and labor costs associated with their use. All non-biodiesel outputs that have value (at right) are apportioned some of energy costs as a function of mass (Pradhan et al., 2009).

Resources and data are never available to carry out a complete accounting of indirect energy costs, forcing researchers to draw an inevitably arbitrary boundary line between that which is counted and that which is not. Indirect energy costs accounted for in this study included the embodied energy of all buildings, farm and processing machinery, fertilizer and other chemical agricultural inputs, seed, used vegetable oil, chemical reagents required for transesterification, and the indirect energy costs of human labor. Surveys collected data on the purchase price and purchase date of all farm machinery and implements, and these data were translated to embodied energy costs using the Carnegie-Mellon Economic Input-Output Life Cycle Assessment (EIOLCA) tool (Carnegie Mellon Green Design Institute, 2008). This model equates the purchaser price of a product to the amount of energy required to produce it by attempting to trace energy costs in different sectors as a function of monetary flows. This method is not as accurate or precise as assessing the physical make-up of all agricultural inputs and mechanical equipment, but offers a less resource- and time-intensive means of estimating embodied energy costs and was used in this case due to resource limitations. The consumer price index for years 1970-2010 was used to adjust purchase price estimates to 2002 dollars for input into the EIOLCA model.

The EIOLCA estimates embodied energy for products from particular economic sectors, acknowledging that products from some economic sectors are more energy intensive to produce than those of other sectors. Embodied energy of all farm machinery and implements were estimated using the EIOLCA sector 'machinery and engines—farm machinery and equipment manufacturing'. Embodied energy of biodiesel processing equipment was estimated using the EIOLCA sector 'petroleum and basic chemical—petroleum refineries' if the processing unit was purchased, and using the sector 'food, beverage and tobacco—breweries' if the processing unit was hand built. Embodied energy of vehicles was estimated using the sector 'vehicles and other transportation equipment—light truck and utility vehicle manufacturing'. Embodied energy of buildings was estimated using the sectors 'construction—other residential structures' or 'construction—nonresidential manufacturing structures'. The EIOLCA documentation acknowledges that there is an unknown amount of uncertainty associated with estimates of embodied energy generated by its model. To attempt to account for at least some of this uncertainty, I assumed the EIOLCA model output represents a mean value and assumed a standard deviation of 25% of the mean for all estimates taken from the model.

Aside from using the EIOLCA model to estimate embodied energy of farm implements, buildings and processing equipment, I use values from the USDA report to translate fertilizer, pesticide, seed, an reagent masses into energy values. These include 23.3 MJ/lb N, 4.1 MJ/lb P, and 2.7 MJ/lb K for fertilizer inputs; and 148 MJ/lb of pesticides (Pradhan et al., 2009). As with the EIOLCA model, there is unacknowledged uncertainty in these estimates, and to attempt to capture it I assume that these values represent a mean and that the standard deviation around the mean is 25 percent of the mean. The embodied energy of manure was assumed to be 30 percent that of synthetic fertilizer per hectare (Wiens et al., 2008). The embodied energy of chemical reagents are assumed to be 11.2 MJ/gal of biodiesel for methanol, and 1.1 MJ/gallon of biodiesel for other reagents (Pradhan et al., 2009). Other estimates of embodied energy for these components are available (see Elsayed et al., 2003; Nelson & Schrock, 2006 for examples), some higher and some lower, but estimates from Pradhan et al. 2009 were used to facilitate comparison of final EROI estimates to those put forward by the USDA. To estimate the embodied energy of human labor, I divided total energy use in Vermont in 2008 by the population of Vermont in 2008 estimate per capita energy consumption, divided this number by the number of hours per year to yield an estimate of per capita energy consumption per hour, and allotted this value as embodied energy as a function of the hours of labor embodied in each gallon of biodiesel (EIA, 2008; US Census Bureau, 2008). All indirect energy inputs are translated to energy inputs per gallon biodiesel produced.

4.2. Accounting for Uncertainty

Monte Carlo simulation was used to estimate final EROI for each producer while accounting for uncertainty. The Monte Carlo process begins with the generation of a random number with a normal distribution between 0 and 1 for each direct or indirect energy input that has uncertainty associated with it. This random number is used to generate a normal random value of that energy input based on its estimated mean and standard deviation. EROI is then calculated as in equation 2 by dividing the energy content of a gallon of biodiesel by the sum of the normal random values of all indirect and direct energy costs. This process is repeated 1000 times, generating 1000 unique estimates of EROI based on the means and standard deviations of all direct and indirect energy costs. The mean EROI estimate for each producer is calculated from these 1000 runs, along with the standard deviation of the mean.

4.3. Projections

Because many of the producers included in this study are in the process of scaling up their operations, biodiesel production forecasts were used to project how their estimated EROI will change in the future. Table 2 presents biodiesel production forecasts for the processor who uses reclaimed fryer oil and the five growers. These forecasts are based on planned increases in oilseed planting using current equipment and current or foreseeable land acquisition, and do not assume additional equipment purchase. Labor, energy, agricultural input and reagent costs are assumed to rise proportionately to biodiesel production, while the embodied energy costs of existing machinery and buildings are assumed to remain constant.

Table 2. Processors and production forecasts, specifying years 2011 (oilseed grown in the 2010 growing season), 2014, and 2016. Projections assume that biodiesel production will remain constant from 2016-2020. Producer 1 operates a non-farm facility that uses reclaimed fryer oil as a feedstock, while producers 2-6 use vegetable oil pressed from oilseed grown on-farm.

Producer	2011	2014	2016
1	16,000	36,000	50,000
2	10,000	20,000	26,000
3	3,000	4,000	5,000
4	1,000	2,700	6,700
5	1,500	10,000	25,000
6	550	1,000	1,000

5. EROI of Vermont Biodiesel

Table 3. shows the mean EROI for the production of biodiesel at each of the five farms and one reclaimed fryer oil processing center, along with estimates or forecasts of their total biodiesel production from oilseed grown in 2010. Mean estimates of EROI for Vermont-produced biodiesel range from a low of 2.63:1 to a high of 5.89:1. The weighted average for Vermont is 4.04:1, which is unambiguously above 1:1. For the small-scale growers studied here, direct energy costs represented 3-23 percent of total energy costs, while indirect energy costs represented 77-97 percent of total energy costs. Energy surplus ranges from 61-83 percent for all Vermont producers.

Table 3. Feedstock, mean second order EROI ± one standard deviation, and 2010 biodiesel production for six producers in Vermont.

Processor	Feedstock	EROI	Energy surplus (%)	Production (gal/yr)
1	Reclaimed oil	3.60 ± 0.38	72	16,000
2	Soybean oil	4.24 ± 0.44	76	10,000
3	Sunflower oil	3.61 ± 0.39	72	3,000
4	Sunflower oil	2.63 ± 0.41	61	1,000
5	Sunflower oil	5.89 ± 0.73	83	1,500
6	Sunflower oil	5.12 ± 0.56	81	550

Figure 3 shows the energy costs associated with biodiesel production for the five growers and one used oil processor studied, as well as equivalent energy costs from the USDA study (Pradhan et al., 2009). These energy costs are normalized to each gallon of biodiesel produced. Figure 4 shows these same energy costs and energy surplus as a percentage of the lower heating value of a gallon of biodiesel, clearly delineating energy costs from the energy surplus delivered by produced biodiesel. The numbers assigned to each grower correspond to those in Tables 2 and 3. The embodied energy of reagents, particularly methanol, is consistently a large component of all growers' and producers' energy costs, including that of industrial growers studied by Prahan et al. (2009). For the relatively small-scale growers studied here, the embodied energy costs of their processor can also be substantial, particularly in the case of grower 4 who purchased a sophisticated processor and who produces only 1,000 gallons of biodiesel, preventing him from apportioning the embodied energy costs of this processor over a larger amount of finished product. The direct energy costs of liquid fuels, primarily diesel or biodiesel, are important for some Vermont growers and producers, as is the embodied energy costs of fertilizers and pesticides. Tables showing itemized energy costs for all growers and producers studied in Vermont are provided in the appendix.

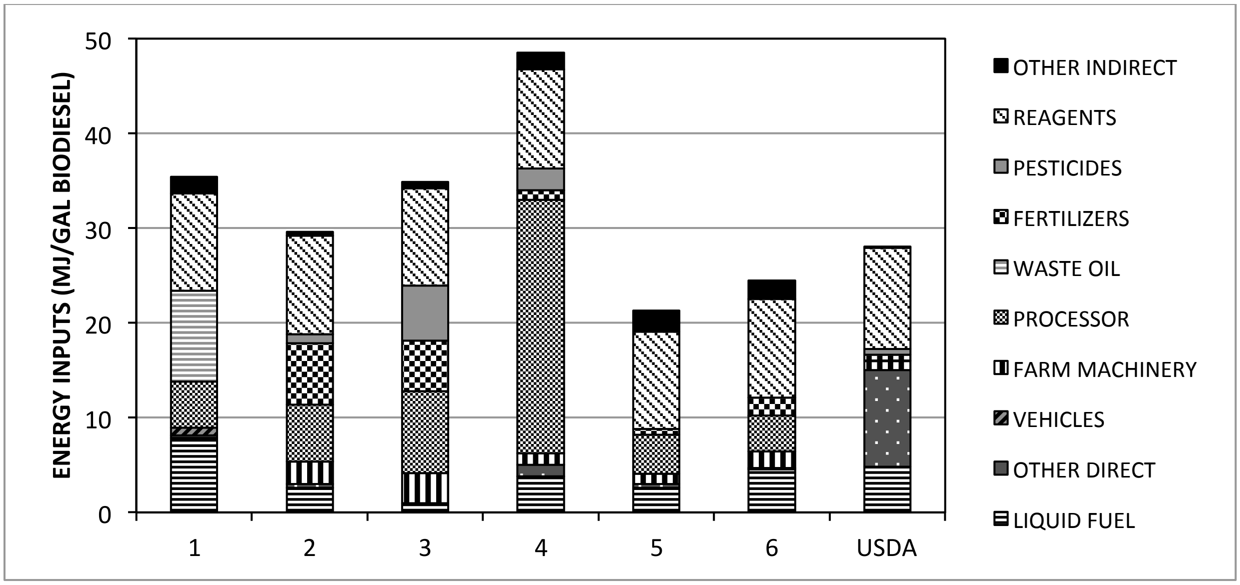

Figure 3. Energy costs for producing biodiesel for all producers in Vermont presented next to energy costs reported by USDA (Pradhan et al. 2009). "Liquid fuel" includes gasoline, diesel and biodiesel fuel, "Other Direct" includes electricity, natural gas, propane, and human labor. "Other Indirect" includes the embodied energy of buildings, vehicles, oilseed presses, seed, and human labor, except for the USDA analysis which does not include the embodied energy of human labor. "Reagents" is dominated by the embodied energy of methanol, but includes all reagents involved in transesterification.

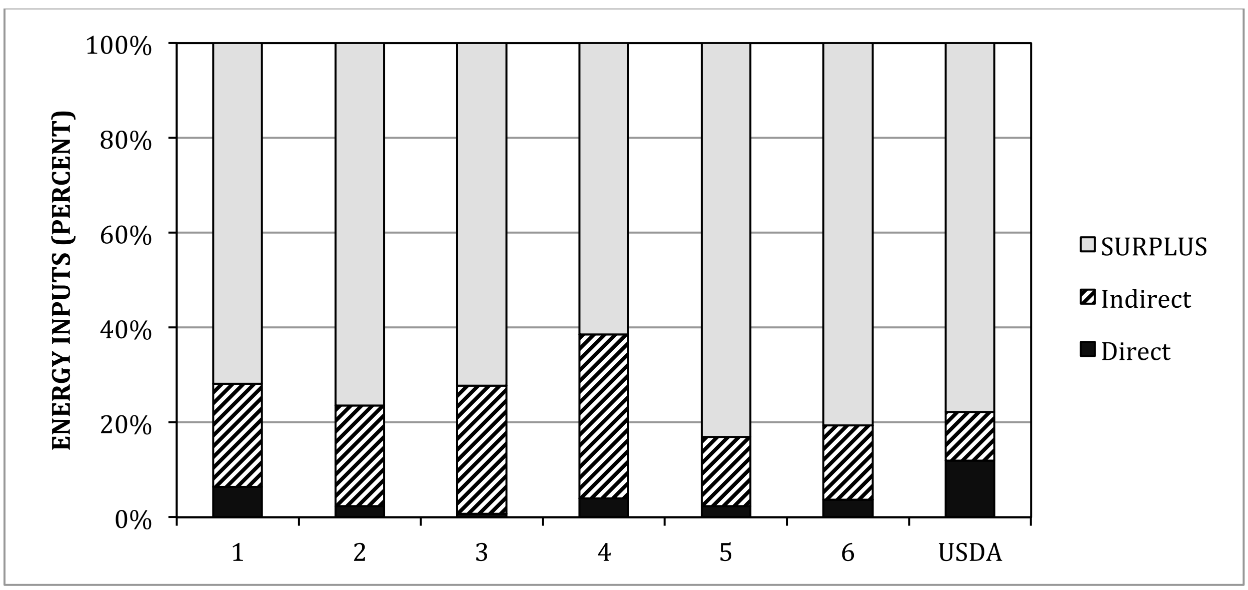

Figure 4. Energy costs and energy surplus from 6 Vermont biodiesel producers normalized to the lower heating value of biodiesel. "Indirect" includes all indirect energy costs, "Direct" includes all direct energy costs.

The impacts of projected biodiesel production increases on the EROI of the six producers studied are shown in Figure 5. Producer 4, who has the lowest EROI and currently produces 1000 gallons of biodiesel per year, is projected to see the largest increase in EROI as his production scale increases. This is largely due to his ability to apportion the energy costs of his biodiesel processor over a larger number of gallons of finished biodiesel product. Producer 5, an organic grower with the highest EROI for the 2010 growing season, is projected to reach an EROI of roughly 8:1 if he reaches his production targets without requiring additional equipment.

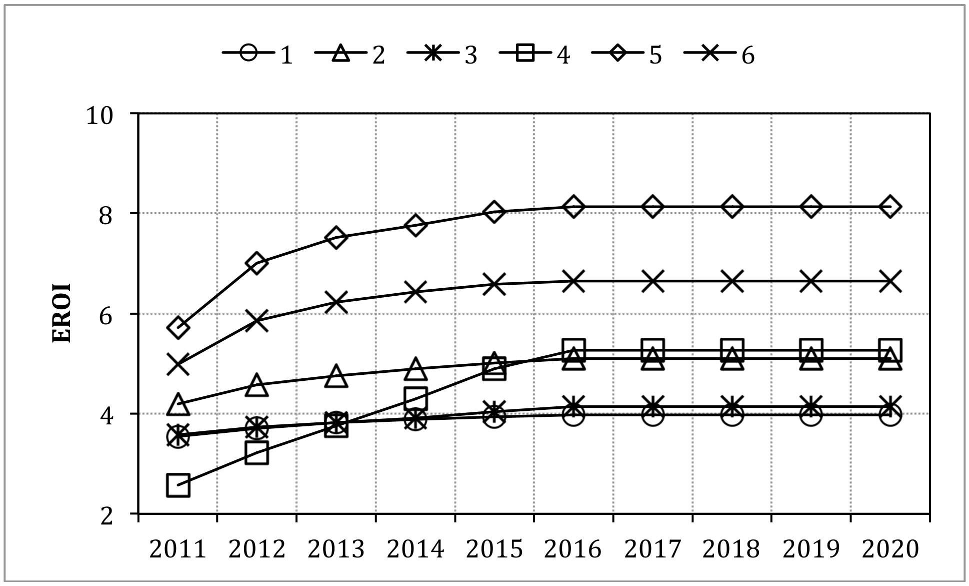

Figure 5. Projected EROIs for the six biodiesel producers based on expected increases of biodiesel processing, as noted in Table 2.

6. Considerations

EROI estimates from this study are comparable to those noted in Table 1, although one must be cautious comparing EROI numbers from different studies due to methodological differences. Notably, even the smallest-scale grower studied in Vermont, who produces 550 gallons of biodiesel per year, shows an EROI well above those calculated by Pimentel & Patzek (2005).

One important benefit of studying biofuel production at the level of individual grower and individual supply chain is that it affords the researcher and other stakeholders the opportunity to compare the influences of alternative growing practices and alternative production practices on final estimates of EROI. Some of the energy costs cataloged are effectively fixed energy costs and cannot be reduced relative to the energy benefit of a gallon of finished biodiesel. The energy costs of chemical reagents are the perfect example of this, as methanol and other reagents must be used at a standard ratio when reacting vegetable oil to produce biodiesel. These fixed energy costs impose an upper limit of roughly 20:1 on the EROI that can be achieved when transesterification is used to convert vegetable oil to biodiesel. In practice, other variable energy costs, such as those associated with transporting feedstock, powering machinery, and preparing, fertilizing and cultivating land, can be reduced but can never be reduced to zero. Other chemical processes are being investigated for their ability to yield quality biodiesel products (Körbitz, 1999; Meher et al., 2006), but they will certainly also require reagents so care must be taken to assess the energy costs of alternatives before producers make substantial investments to switch production processes.

While acknowledging this maximum is important, it is also important to realize that all of the producers outlined in this report can improve their operations and deliver a fuel with a higher second order EROI than that measured by this study. Direct energy costs are made up primarily of liquid fuels used for transporting feedstocks and to power agricultural machinery. While it may not be cost effective to purchase new machinery that is more energy efficient to reduce liquid fuel use, a mixture of behavioral shifts and more strategic decision-making when scheduling on-farm or off-farm tasks will likely allow for the reduction of liquid fuel use. The degree to which these direct energy costs can be reduced will vary from farm to farm, but the potential is certainly there and in many cases may allow for modest EROI gains.

Direct energy requirements represent a small proportion of the total energy requirements to produce a gallon of finished biodiesel in Vermont. Besides reagents, which account for roughly 20 percent of the energy value of the finished fuel, all other indirect energy costs are variable and subject to change based on the grower and processor's strategic decision-making. The embodied energy of farm machinery, seed presses and the biodiesel reaction apparatus generally represent a small component of the total indirect energy, but this energy input can still be reduced. By reducing the use of machinery, sharing machinery among growers and producers, or more thoroughly using existing machinery for a wider variety of purposes, the proportion of the embodied energy attributable to a single gallon of finished biodiesel can be reduced. Scaling up biodiesel production without adding new equipment, as investigated in the projections shown in Figure 4, is one means of doing this and allows producers and growers to spread the embodied energy costs of equipment over a larger amount of finished product. Additionally, if other production practices allowed for higher yields of oilseed and thus biodiesel, the embodied energy of machinery could be spread among more finished gallons of fuel, reducing it further. Among the growers, there are farmers who use less fertilizer than others and one that replaces synthetic fertilizer with manure, lowering energy costs. Some growers also do not use pesticides, lowering their energy costs. More experimentation with the level of fertilization and pesticide application, combined with programs of crop rotation to reduce pest infestations could allow for modest increases in biodiesel EROI.

No other state in the United States or the world is currently studying its biofuel producers with the rigor that the state of Vermont currently is, creating the opportunity for Vermont to emerge as a global leader in acknowledging and using EROI as a criteria in judging the viability of its biofuel enterprises. But EROI should not be the single criteria used to judge biofuel viability, which prompts a return to third order EROI analysis noted above. In addition to requiring energy inputs to generate a gallon of finished biodiesel, a variety of other inputs are required. One vitally important input is cash flow. Other work is underway to estimate the monetary costs associated with producing a gallon of biodiesel, and while monetary cost accounting is not typically thought of as EROI analysis, it fits in perfectly with Mulder & Hagens' notion of third order EROI analysis. Second order EROI analysis asks what we get back in terms of energy relative to what we invest, or E_O/E_I based on the notation used above. A third order EROI that studies monetary cost inputs might estimate the energy return on money invested (EROMI) as $E_O/\$_I$. Knowing that E_O generally represents the energy content of a gallon of fuel (or other set volume), EROMI is effectively the reciprocal of cost per gallon of fuel. Other inputs or impacts can be accommodated in EROI analysis using a generalized ratio of E_O/X as well, where X might be the mass of carbon released or sequestered by the production process, the amount of water required to produce a gallon of fuel, the amount of nitrogen or phosphorus lost from farm fields due to runoff, the mass of soil lost from fields due to erosion, or any number of relevant social, economic or environmental variables. While the basic second order EROI analysis that accounts for energy inputs and outputs is a vital element of biofuel viability over the short to moderate term, third order EROI analysis that broadens the scope of assessment is necessary to determine biofuel sustainability over the long term.

7. Conclusions

The totality of evidence suggests that biodiesel can be produced in Vermont with a positive EROI, and that modest changes in production practices would improve EROI on most farms. When compared, using similar methods, to studies that survey national oilseed datasets, Vermont farmers appear to be better able to efficiently grow and turn oilseed into finished biodiesel, despite their small production capacity.

8. References

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9. Appendices

The following tables show energy costs estimated at all growers and producers included in this study, including their current production rate and feedstock type. All energy costs are normalized per gallon of finished biodiesel.

Table A1. Energy costs of Producer 1. Numbers after the ± are 1 standard deviation of the mean.

Feedstock	Reclaimed oil
Production (gal/yr)	16,000

Energy cost	MJ/gallon
Biodiesel	7.87 ± 0.47
Electricity	0.22 ± 0.02
Labor, direct	0.06 ± 0.01
Vehicles	0.75 ± 0.19
Processor	4.90 ± 1.23
Building	0.02 ± 0.00
Used vegetable oil	9.58 ± 2.39
Methanol	9.13 ± 2.28
Other reagents	1.14 ± 0.28
Labor, indirect	1.74 ± 0.44

Table A2. Energy costs of Producer 2. Numbers after the ± are 1 standard deviation of the mean.

Feedstock	Soybean oil
Production (gal/yr)	10,000
Energy cost	MJ/gallon
Diesel	2.61 ± 0.26
Electricity	0.35 ± 0.04
Labor, direct	0.01 ± 0.00
Tractor	0.46 ± 0.11
Tractor	0.09 ± 0.02
Tractor	0.20 ± 0.05
Tractor	0.36 ± 0.09
Combine	0.65 ± 0.16
Plow	0.14 ± 0.03
Land finisher	0.16 ± 0.04
Planter	0.30 ± 0.07
Roller	0.06 ± 0.01
Seed cleaner	<0.01
Press	0.06 ± 0.02
Processor	6.01 ± 1.50
Building	0.17 ± 0.04
Seed	0.43 ± 0.11
Nitrogen	4.99 ± 1.25
Phosphorus	0.89 ± 0.22
Potassium	0.57 ± 0.14
Pesticides	0.96 ± 0.24
Methanol	9.13 ± 2.28
Other reagents	1.14 ± 0.28
Labor, indirect	0.18 ± 0.04

Table A3. Energy costs of Producer 3. Numbers after the ± are 1 standard deviation of the mean.

Feedstock	Sunflower oil
Production (gal/yr)	3,000
Energy cost	**MJ/gallon**
Diesel	0.93 ± 0.23
Electricity	0.07 ± 0.02
Labor, direct	<0.01
Tractor	0.06 ± 0.02
Combine	2.81 ± 0.70
Harrows	0.22 ± 0.05
Planter	0.04 ± 0.01
Press	0.09 ± 0.02
Processor	8.68 ± 2.17
Building	0.24 ± 0.06
Seed	0.44 ± 0.11
Nitrogen	4.38 ± 1.09
Phosphorus	0.31 ± 0.08
Potassium	0.61 ± 0.15
Pesticides	5.83 ± 1.46
Methanol	9.14 ± 2.28
Other reagents	1.15 ± 0.29
Labor, indirect	0.36 ± 0.09

Table A4. Energy costs of Producer 4. Numbers after the ± are 1 standard deviation of the mean.

Feedstock	Sunflower oil
Production (gal/yr)	1,000
Energy cost	MJ/gallon
Diesel	3.82 ± 0.38
Electricity	1.19 ± 0.12
Labor, direct	0.01 ± 0.00
Tractor	0.36 ± 0.09
Tractor	0.04 ± 0.01
Combine	0.12 ± 0.03
Planter	0.04 ± 0.01
Sprayer	0.01 ± 0.00
Dump wagon	0.03 ± 0.01
Dryer	0.63 ± 0.16
Press	0.35 ± 0.09
Processor	26.73 ± 6.68
Building	1.12 ± 0.28
Seed	0.44 ± 0.11
Nitrogen	0.66 ± 0.16
Phosphorus	0.23 ± 0.06
Potassium	0.15 ± 0.04
Pesticides	2.32 ± 0.58
Methanol	9.27 ± 2.32
Other reagents	1.15 ± 0.29
Labor, indirect	0.32 ± 0.08

Table A5. Energy costs of Producer 5. Numbers after the ± are 1 standard deviation of the mean.

Feedstock	Soybean oil
Production (gal/yr)	1,500
Energy cost	MJ/gallon
Diesel	2.62 ± 0.26
Electricity	0.36 ± 0.04
Labor, direct	0.01 ± 0.00
Tractor	0.48 ± 0.12
Combine	0.03 ± 0.01
Cultivator	0.07 ± 0.02
Planter	0.03 ± 0.01
Seed cleaner	0.21 ± 0.05
Seed dryer	0.29 ± 0.07
Press	0.36 ± 0.09
Processor	4.13 ± 1.03
Building	1.63 ± 0.41
Seed	0.44 ± 0.11
Manure	0.57 ± 0.14
Methanol	9.17 ± 2.29
Other reagents	1.13 ± 0.28
Labor, indirect	0.21 ± 0.05

Table A6. Energy costs of Producer 6. Numbers after the ± are 1 standard deviation of the mean.

Feedstock	Sunflower oil
Production (gal/yr)	550

Energy cost	MJ/gallon
Diesel	4.54 ± 0.45
Electricity	0.15 ± 0.01
Labor, direct	0.01 ± 0.00
Tractor	0.14 ± 0.04
Combine	0.39 ± 0.10
Cultivator	0.08 ± 0.02
Tine weeder	0.01 ± 0.00
Planter	0.36 ± 0.09
Plow	0.01 ± 0.00
Dryer	0.79 ± 0.20
Press	0.32 ± 0.08
Processor	3.79 ± 0.95
Building	1.47 ± 0.37
Seed	0.44 ± 0.11
Nitrogen	1.52 ± 0.38
Phosphorus	0.22 ± 0.05
Potassium	0.11 ± 0.03
Methanol	9.25 ± 2.31
Other reagents	1.15 ± 0.29
Labor, indirect	0.16 ± 0.04