FINAL REPORT
Fall 2010

Emissions Life Cycle Analysis for Biodiesel and Glycerin Based Chemicals Derived from Rendered Animal Fats: Current Status and Improved Emission Control Strategies

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Project Start Date: July 1, 2009
Project End Date: Jun 30, 2010

Lay Overview of Project and Goals:

In the rendering industry, many have begun to think of animal fats as *chemical* feed stocks instead of animal feed products. Currently, the most economical conversion processes for animal fats to useable fuels or chemicals involves the formation of biodiesel and bioderived chemicals (e.g., glycerin, propane diol, etc.). In order to fully evaluate the environmental, economic, and energetic costs and benefits of biodiesel production from animal fats, a detailed life cycle analysis has been developed. Initial efforts of our group focused on an energy life cycle study. However, the focus of our current effort moved to collect additional emissions data and finalize all calculations and reporting related to the creation of a detailed emissions life cycle analysis report using accepted analysis methods. Further, the final journal article (attached) uses these results to suggest alternative methods for toxic emission control and waste stream abatement. The focus of the life cycle study was on the conversion of beef tallow, pork fat and chicken fat into biodiesel fuel for buses using efficiency information for state-of-the-art processing technologies and recent engine test results for large diesel engines. The final life cycle study report considers the chemical release profiles from the rendering plant forward. It does not include emission information for the synthesis of the animal fat (i.e., chemical releases associated with the growth of the animals) as these emissions and energy costs are likely to occur independent of the use of the final rendered fat products.

Significance to the rendering industry:

In order for rendering plants and government agencies to make effective decisions about the economic and environmental advantages of producing biodiesel and bioderived chemicals from animal fats, it is imperative that a detailed life cycle analysis (of emissions) study be completed. The final report generated from this project will help rendering companies make decisions about which technology should be used for the processing of animal fats and will also provide input to government regulatory agencies about likely emissions from the generation of biodiesel from animal fats and how those emissions compare to the production of diesel fuel from fossil fuels sources, such as crude oil.

Energy Life Cycle Assessment for the Production of Biodiesel from Rendered Lipids in the United States

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The energy life cycle assessment for the production of biodiesel from rendered lipids in the United States is presented in this study. Three different scenarios were found eligible for analysis: (I) conversion to biodiesel, (II) rendering and conversion, and (III) farming, rendering, and conversion. The amounts of energy required in farming, meat processing, and baseline conversion to biodiesel were reviewed from the literature. The thermal energy and electricity used in rendering were surveyed from the U.S. rendering industry. For animal fats, scenario III resulted in a net energy ratio (NER, ratio of energy outputs to energy inputs) much lower than 1. In contrast, the NERs for scenarios I and II were both found to be >1. For scenario I, the NER was found to be >3.6, larger than the value typically reported for soybean oil (SBO) biodiesel. As for the waste SBO grease, the NER was found to be >1 for both applicable scenarios (I and II). To a limited extent, sensitivity analysis was used to evaluate changes in assumptions with respect to the type of fuels employed in the generation of thermal energy as well as the method for biodiesel production.

1. Introduction

The increasing price of crude oil and concerns about global warming have provided motivation to utilize alternative clean-burning fuels. Biodiesel, a mixture of monoalkyl esters derived from a variety of lipids, is an alternative first-generation biofuel that has the potential to be used in existing diesel engines. As a result, the biodiesel industry in the United States has experienced vast expansion during the past few years. However, the procurement of starting materials for the synthesis of the fuel has become the major limitation for the sustainable growth of the industry.[1] The utilization of waste lipids and rendered products, such as yellow grease and animal fats, may help expand the portfolio of biodiesel feedstock materials. According to recent statistics (Table 1), the U.S. production of animal fats and greases reached nearly 4.5 billion kilograms in 2007.[2] For that same year, a survey that covered 70% of the U.S. biodiesel production volume (1.09 billion liters or GL) reported that only 31.4 million liters (ML) of biodiesel originated from animal fats and used oil feedstocks.[3] However, from these feedstocks, a potential 5.2 GL/year (1.37 billion gal/year) of biodiesel could be domestically synthesized, which would satisfy about 2.2% of the current U.S. diesel demand (238 GL/year).[4]

Slaughterhouse plants, also known as “abattoirs”, are the facilities where animals are slaughtered and processed into meat products for human consumption. In 2007, the U.S. meat sector produced nearly 56.7 billion kilograms (Tg) of meat derived from cattle, broilers, hogs, and turkeys.[5] As a result of meat production, large amounts of animal byproducts are continuously being generated for the most part in slaughterhouses, but also in farms (deaths during livestock production), meat processing facilities, and meat retail stores (e.g., trimmings and past sell-by-date products). Rendering has been a practical, economic, and green alternative for adding value to these perishable byproducts, which are currently collected and transported to the nearly 300 rendering plants existing in the United States. These plants are concentrated in the central, southeastern, and northeastern regions of the United States.[6] Rendering according to the USDA definition is “a process of heat-treating fat, bone, offal, and related material derived from carcasses of livestock, poultry, and fish, and used cooking fats and oils”. Figure 1 illustrates a simplified flow diagram for the rendering process. Initially, raw animal byproducts are conveyed into a crusher or grinder to obtain a consistently sized material. Then, the sized animal byproducts are heated inside a cooking chamber (cooker or evaporator) by means of indirect steam. García et al.[6] and Meeker[7] reported that the continuous dry rendering process is the predominant practice in the United States. Inside the cooker (or evaporator), the materials are sterilized, the fat is melted, and most of the moisture is removed. The cooking time, pressure, and temperature depend on the type of raw materials and the specifications of the final rendered products. Byproduct cooking temperatures may vary from 115 to 165 °C[6−11] but typically do not exceed 145 °C, with the goal of ensuring the innocuity of the final product. Typical cooking pressures are atmospheric pressure (in the United States)[12] and 3 bar (in Europe).[9,11,13] A considerable amount of cooking vapors (i.e., volatiles and water vapor) are produced in this step. These vapors are later condensed and treated to avoid odor and water contamination. After cooking, the fat is normally drained and pressed out of the meal cake by using a screw press. The pressed meal cake coproduct (containing a mixture of protein, ash, and fat) is further dried and ground to form protein meal. This meal is usually stored in silos and shipped in hopper truck trailers or rail cars. The rendered fat products are purified by centrifugation or filtration, stored in tanks, and finally shipped using tank trucks or rail cars to commodity scale end users.

Table 1. Production of Rendered Lipids in the United States during 2007[2]

type of lipid	production (Tg or teragram)
edible tallow	0.79
inedible tallow	1.67
lard	0.20
poultry fat	0.64
yellow grease	0.67
other grease	0.54
total	4.51

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10.1021/ie900884x

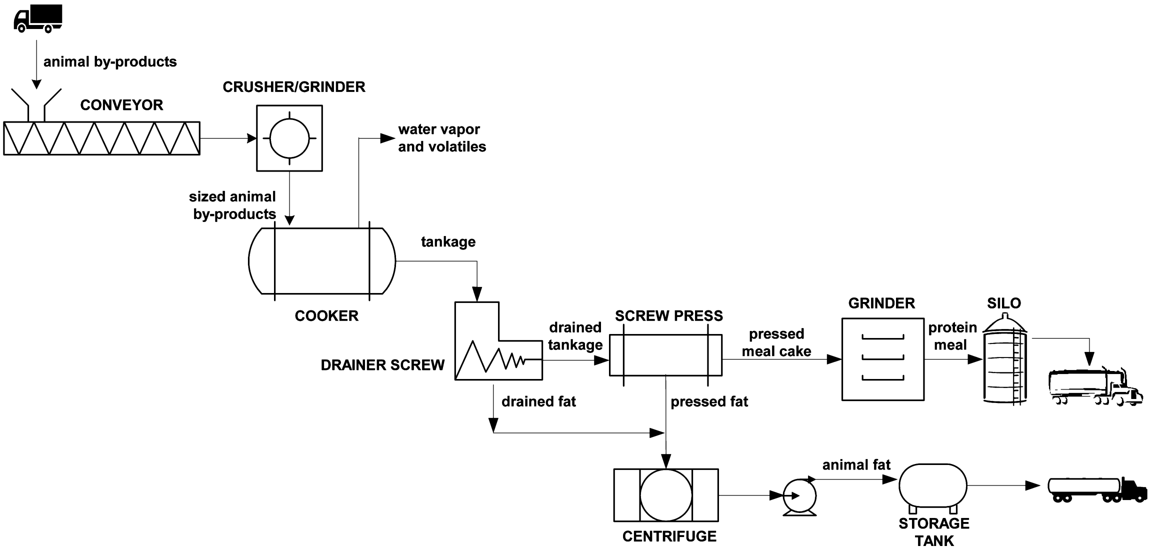

Figure 1. Simplified flow diagram for a typical rendering process.

Rendered lipids consist of a complex mixture of saturated and unsaturated glycerides (triglycerides, diglycerides, monoglycerides), glycerol, free fatty acids (FFAs), water, and other minor components. In animal fats, FFAs can be formed via enzymatic action after the animal has been slaughtered[14] and during rendering. For grease, FFAs are usually created while the oil is being repeatedly used for frying hydrated foods (the triglycerides undergo hydrolysis with the water contained in the foods). Deep frying cooking temperatures often range between 160 and 200 °C;[15] consequently, while water is continuously stripped off the fryer, the higher boiling FFAs accumulate in the grease.

Rendered lipids have been typically consumed as livestock feed, but they have also found some limited use in the chemical industry. However, financial gains could potentially exist for both renderers and biodiesel producers if these materials were used as biodiesel feedstock. Specifically, lipids are less costly than some traditional biodiesel feedstocks, and recent reports have shown that a large percentage (∼90%) of the cost of producing biodiesel derives from the cost of the virgin oil feedstock.[16] In addition, contrary to the production of dedicated energy crops, another benefit of employing rendered lipids as biodiesel feedstock is that their generation is not in direct competition with the production of food. For instance, the production of skinless and boneless poultry products, such as cut-up chicken and processed chicken, generates leftovers that can later be rendered to obtain poultry fat for biodiesel.[17] Likewise, the preparation of high-calorie foods via deep frying creates substantial amounts of waste cooking oil (WCO) that can be used later as low-price biodiesel feedstock.

Hill et al. pointed out that, for any biofuel to be a viable alternative to conventional fuels, it should have a positive energy evaluation (renewable), be environmentally beneficial, be economical, and have an impact without depleting food supplies.[18] The question of whether biodiesel is in fact a renewable fuel has been studied by comparing the amount of energy inputs to the energy outputs on the overall life cycle. There exist numerous studies dealing with life cycle analysis (LCA) for the production of biodiesel from bioenergy crops.[4,19−32] The stages that are normally considered in these LCAs are crop cultivation, oil extraction and refining, oil conversion, and transportation.[1,4,18,20,21,27,28,33] The reported values of the net energy ratio (NER, unitless ratio of energy outputs to energy inputs[34]) for soybean oil biodiesel have ranged from values lower than 1 (0.79)[33] to 3.21.[27] The inconsistency of the NER results was recently examined by Pradhan and co-workers.[32] Using a unified model and a mass coproduct allocation procedure, these authors found that the mean NER was 2.55 with a standard deviation of 0.38. Typically, energy balances for biodiesel obtained from bioenergy crops have resulted in a net energy gain as measured by means of NER. As a result, the use of bioenergy crops for biodiesel has been suggested to be an effective way to limit the consumption of nonrenewable resources and to combat climate change.

Fewer studies have dealt with LCAs for the production of biodiesel from rendered lipids.[30,35−38] For animal fats, comprehensive LCA system boundaries include animal growth and maintenance, animal byproduct rendering, fat conversion, and transportation.[36] Life cycle impact analyses (LCIAs) have suggested that tallow methyl esters have less negative environmental effects than diesel fuel and rapeseed oil methyl esters (under the assumption that the production of meat is entirely responsible for the environmental burdens of the livestock production stage).[35,38] Nelson and Schrock evaluated the energetic and economic feasibility of the production of beef tallow biodiesel in the United States.[36] In that energy analysis, three different allocation methods were considered: mass, market value, and replacement. When the energy inputs associated with the cattle production stage were solely ascribed to the meat product, the authors reported a satisfactory fossil energy ratio regardless of the allocation procedure employed. For waste cooking oil, the energy inputs associated with the stages prior to its transportation to the biodiesel conversion facility are normally neglected.[37,39] Using this assumption, it has been shown that the WCO integrated conversion process has a low exergy loss.[37]

2. Goal and Scope Definition

Energy calculations for biodiesel obtained from rendered lipids have been rarely reported. Nevertheless, there exists a great need for this type of sustainability evaluation to assist in the development of new products and in the process of public policy creation. The objective of this study was to evaluate an ISO-compliant (series ISO-14040) energy life cycle for the production of biodiesel from rendered lipids in the United States. The study comprises the following key issues: (i) compilation

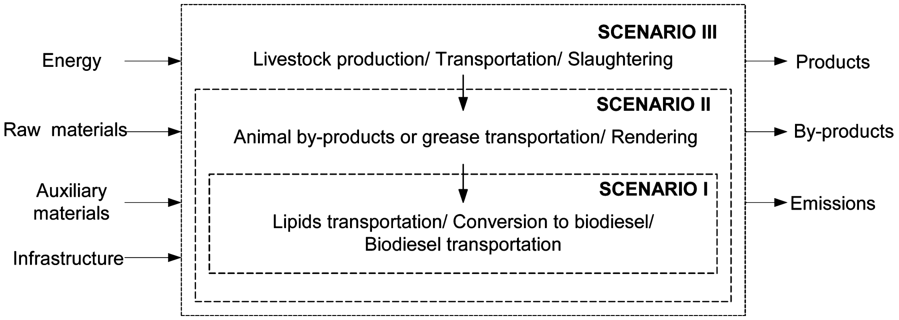

Figure 2. Possible ELCA system boundaries for the production of biodiesel from rendered lipids (adapted from ref 35).

of rendering industry data; (ii) calculation of mass and energy balances from agriculture to rendered-lipids-based biodiesel production (cradle-to-pump analysis); (iii) computation of the mass-allocated net energy ratio for biodiesel produced from three different types of rendered lipids, i.e., poultry fat, beef tallow, and yellow grease; (iv) assessment of net energy ratios using different system boundaries; (v) comparison of the energy life cycle assessment (ELCA) results obtained for soybean oil biodiesel and rendered lipids biodiesel; and (vi) evaluation of processing assumptions.

3. Life Cycle Inventory

Data gathering was one of the major challenges of this study. There exist very few reports on energy use for this type of agro-industry, possibly because this may not be considered energy intensive. Even when data are available, they will usually be in aggregated or allocated forms. Also, we found that vast differences exist among the practices of these agro-industrial sectors. Therefore, the ELCA data for the production of biodiesel from rendered lipids from different sources in the United States was analyzed and compared. These data primarily included published peer-reviewed literature (national and international), U.S. industry data, theoretical estimations, experimental measurements, personal communications with experts, and U.S. databases.

3.1. System Boundaries. Fossil energy may be consumed throughout the whole life cycle for the production of biodiesel from animal fats and greases. Scenario III in Figure 2 shows the complete life cycle for animal fat derived biodiesel, with system boundaries defined to include livestock production, slaughtering, rendering, conversion to biodiesel, and the transportation of materials. Because the objective of livestock farming is the production of meat for food and animal byproducts are jointly but unintentionally produced in this stage, one can assume that the agrarian energy consumption should be exclusively allocated to the meat product. Therefore, a system delimited as in scenario II (Figure 2) was also evaluated. Moreover, the rendering practice in the United States has traditionally offered a safe alternative for the disposal of perishable animal byproducts, deadstock, and waste grease. Large amounts of such potentially hazardous materials would otherwise be landfilled, composted, buried, incinerated, or simply improperly dumped, causing a great economic and environmental burden.[7] Thus, it can also be argued that the energy inputs ascribed to the first two stages (i.e., livestock/meat production and rendering) should both be disregarded. Consequently, a system that includes only the transportation of rendered lipids to the biodiesel plant, the lipid conversion to biodiesel, and the final transportation of biodiesel fuel to consumers was also considered eligible for analysis (scenario I in Figure 2).

Table 2. Lifetime Consumption of Feed Ingredients by a Single Head of Cattle and Broiler Chicken in the United States

type of feed	cattle[a] (kg)	broiler chicken[b] (kg)
corn	790	3.0
dry land grain sorghum	760	–
soybean meal	127	0.9
alfalfa	190	–
sorghum silage	1370	–
poultry meal	–	0.1
poultry fat	–	0.1
fish meal	–	0.1
salt and limestone	–	0.1
total	3237	4.3

[a] Data from ref 36, which corresponds to a beef cattle slaughter weight of 578 kg. [b] Data from ref 41, which corresponds to a broiler chicken slaughter weight of 2.26 kg.

When defining system boundaries for the ELCA involving waste vegetable greases, the processes prior to the generation of the waste grease (i.e., crop cultivation, oil extraction, oil refining, cooking, and transportation of materials) were excluded from the analysis. This was done because, analogous to animal byproducts, waste vegetable greases are the unintended result of a food production practice. Thus, only scenarios I and II were considered applicable to this type of biodiesel feedstock.

3.2. Functional Unit. The functional unit utilized in this study was 1 kg of produced biodiesel. Accordingly, the mass and energy balances calculated for the selected rendered lipids were normalized on a per kilogram of biodiesel (BD) basis.

3.3. Material Balances. 3.3.1. Livestock Production and Slaughtering. Livestock production supply chains are usually complex as a result of their interconnections with other industrial activities, such as crop, feed, and fertilizer production. Refsgaard et al. showed a general conceptual model for the material and energy flows in a livestock farm.[40] The provision of feed is normally responsible for most of the energy burden in raising and maintaining farm animals.[36,41] Typical feed formulation and consumption for a single head of cattle and broiler chicken in the United States are provided in Table 2. Notice that the broiler diet currently includes poultry ingredients; however, if poultry fat is to be used as biodiesel feedstock, then this ingredient is likely to be substituted from the poultry ration. Therefore, in order to be consistent with the analysis and to avoid a circular reference in the calculations (looped flow diagram is provided elsewhere[41]), we employed the following feed formulation for the estimation of the life cycle energy balance: 70 wt % corn, 25 wt % soy meal, 2.5 wt % soybean oil, and 2.5 wt % salt and limestone. Note that this substitution acknowledges the energy costs of redirecting the rendered lipid stream from feed to biofuel.

Upon reaching adequate growth and weight, animals are transported to slaughterhouses. Detailed flow diagrams of meat processing in slaughterhouses have been reported elsewhere.[42,43]

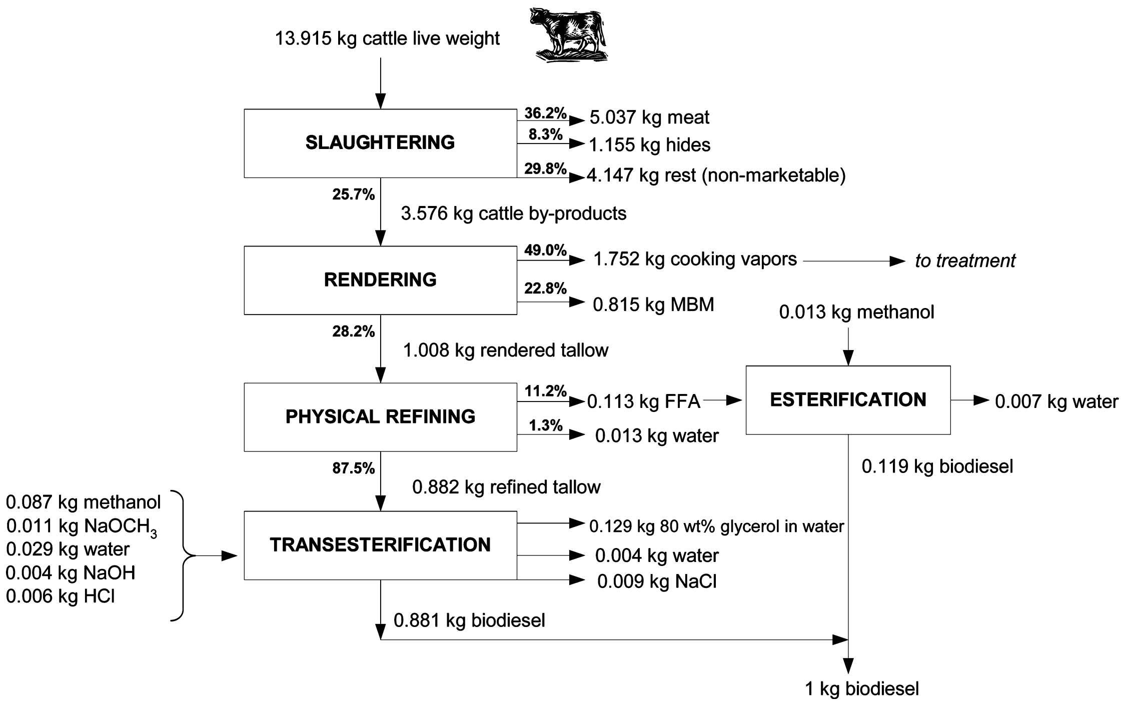

Figure 3. Mass balance for the production of 1 kg of biodiesel from tallow.

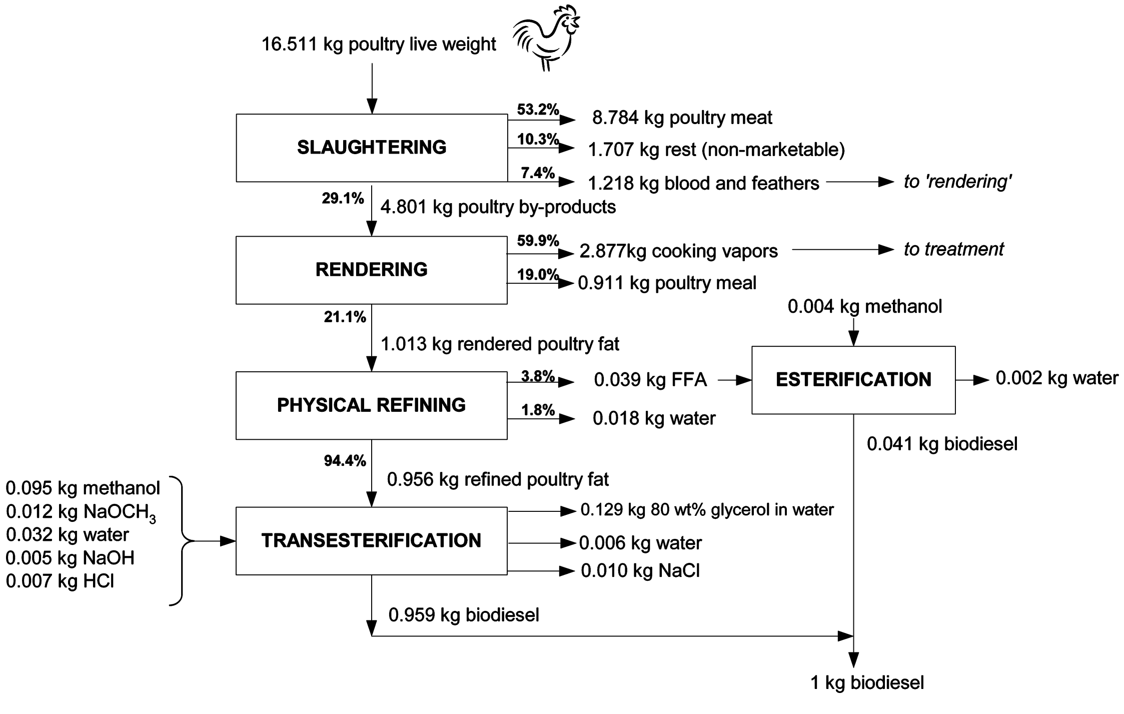

Figure 4. Mass balance for the production of 1 kg of biodiesel from poultry fat.

For cattle, the typical process comprises reception in holding pens, stunning/desensitization, sticking and bleeding, dressing, evisceration, splitting, chilling, cutting, cold packaging, and storage. For poultry meat production, birds are first received and manually loaded upside down on a conveyor belt. This process is normally followed by stunning/desensitization, sticking and bleeding, scalding, defeathering, evisceration, washing of carcasses, chilling, cutting, cold-packaging, and storage.[44,45]

The simplified material balances from slaughtering to the production of 1 kg of biodiesel are provided in Figures 3 (tallow) and Figure 4 (poultry fat). The cattle and poultry (broilers) product yields were obtained from the studies by Niederl et al.[35] and Somsen et al.,[46] respectively. The amount of animal byproducts to be rendered per head of cattle and broiler were calculated to be 149 and 0.7 kg, respectively. As shown in Figure 3, in order to synthesize 1 kg of tallow biodiesel, approximately 14 kg of cattle live weight is needed. This translates to 41.6 kg of tallow biodiesel per cattle head, by taking a cattle live weight of 578 kg.[36] By contrast, 16.5 kg of poultry live weight is required to synthesize 1 kg of poultry fat biodiesel (see Figure 4). In other words, seven broilers with an average slaughter weight of 2.26 kg[41] are needed to obtain about 1 kg of rendered poultry fat biodiesel. Using the material balances and the information provided in Table 2, the cattle and poultry

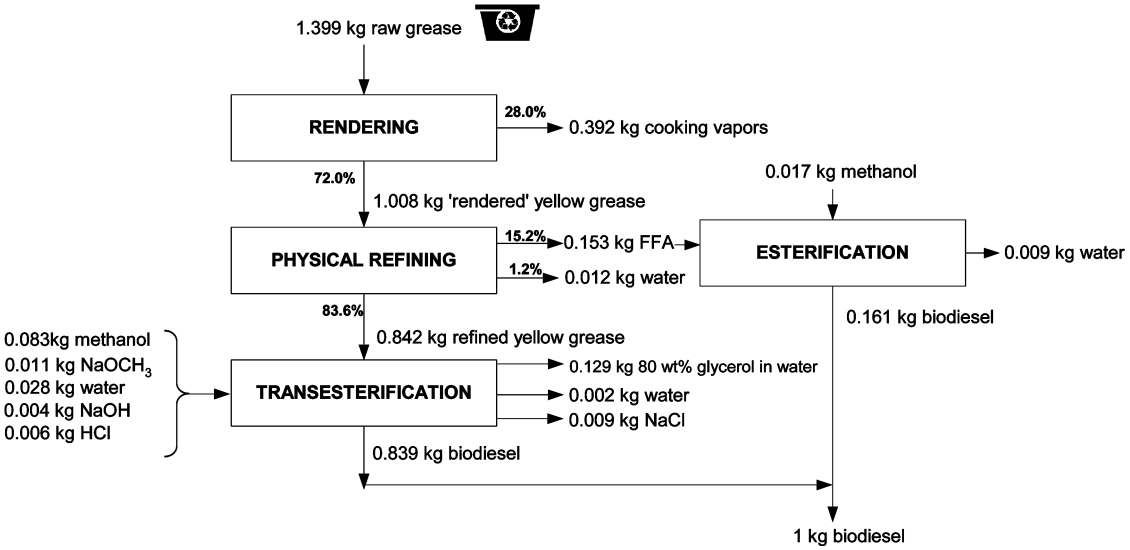

Figure 5. Mass balance for the production of 1 kg of biodiesel from soybean oil grease.

protein production efficiencies were estimated to be 15.4 and 3.6 kg of feed/kg of meat, respectively. These values are comparable to European protein production efficiencies.[42]

Figure 5 provides a simplified material balance for the production of 1 kg of biodiesel from a typical soybean oil grease containing 15 wt % FFAs.

3.3.2. Rendering. Scientific literature regarding energy use in the rendering industry is scarce and limited. Therefore, as an attempt to obtain accurate and updated energy-use data, the rendering industry was surveyed with the assistance of the National Renderers Association, Inc. (NRA, Alexandria, VA). The source of the information was kept confidential by NRA. Some surveys were also directly received by Clemson researchers. Thus, it could be inferred that most of the information regarding rendering of poultry byproducts came from the larger poultry producer states.[47] Data concerning characterization of raw materials, electricity requirements (from monthly electricity consumption bills), process fuel requirements (as to avoid thermal efficiency conversions), emissions to air and water, characterization of final rendered products, and transportation of materials were requested on the survey (see Supporting Information). We tried to reach all U.S. registered rendering firms. Nevertheless, the questionnaire was answered only for 26 different rendering plants, which corresponds to a sample size of approximately 10%. Since not all returned surveys were completely answered, we have indicated in the text the number of surveys a statistical value is based on by using the variable *n*. With rare exceptions, all data provided on the surveys were considered. Examples of unutilized data included values with no units and percentages not adding up to 100%.

Only one out of the 26 surveyed renderers was a packer−renderer. The other 25 were independent renderers, meaning that their operation was not integrated with the meat-packing process. As shown in Figure 6, a wide variety of animal byproducts and greases were processed in the surveyed rendering plants. They also reported processing up to five different types of raw materials. Given that more than 50% of these renderers processed grease, poultry, and cattle byproducts, the energy life cycles that integrated these materials were selected for the assessment.

For cattle byproducts, the average amount of water removed was found to be 49.0 ± 6.4 wt % (from seven survey responses, $n = 7$). For this material, the yields of fat and protein meal were estimated to be 28.2 ± 3.6 and 22.8 ± 6.2 wt %, respectively ($n = 7$). The reported concentration of FFAs in tallow was broad, i.e., it ranged from 2 to 25 wt %; therefore, an average value of 11.2 wt % ($n = 9$) was employed for calculation purposes. The concentration of water and other impurities in rendered tallow were typically <2 wt %. For poultry byproducts, the water content was found to be higher than that for cattle byproducts, 59.9 ± 4.2 wt % ($n = 13$). The fat and protein meal yields were on average 21.1 and 19.0 wt %, respectively ($n = 13$). For poultry offal, typical yields for water, poultry fat, and poultry meal are known to be 62.7, 16.7, and 20.6 wt %, respectively.[48] The concentrations of FFAs and water in rendered poultry fat were estimated to be 3.8 ± 0.6 ($n = 12$) and 1.8 ± 0.6 wt % ($n = 13$), respectively. The survey results also indicated that the initial water content in the collected restaurant grease was 28.0 ± 8.5 wt % ($n = 9$). After "rendering", the water content was reduced to 1.2 ± 0.8 wt % ($n = 7$). The concentration of free fatty acids (FFAs) in "rendered" grease was estimated to be 15.2 ± 6.2 wt % ($n = 7$). Other impurities in the "rendered" grease were typically <2 wt %. Our estimates reflect typical yields and compositions; however, these varied considerably among rendering facilities.

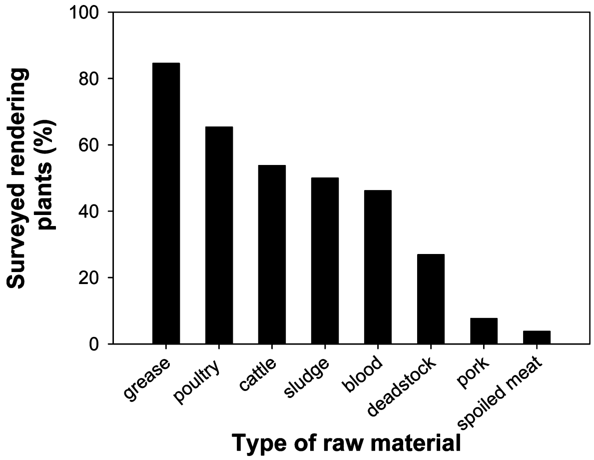

Figure 6. Type of raw materials processed by the surveyed rendering plants. The category "poultry" includes both broilers and turkey.

3.3.3. Conversion of Rendered Lipids into Biodiesel. As described in the previous section, rendered lipids typically contain significant amounts of FFAs and water. This fact makes

Table 3. Average Fatty Acid Composition of Beef Tallow, Poultry Fat, and Soybean Oil Grease

fatty acid	beef tallow	poultry fat	soybean oil grease
$C_{14:0}$ (wt %)	3.1 ± 0.6	1.1 ± 0.6	0.12
$C_{16:0}$ (wt %)	25.2 ± 1.7	22.9 ± 2.2	11.4
$C_{16:1}$ (wt %)	3.7 ± 1.6	7.8 ± 1.2	0.14
$C_{18:0}$ (wt %)	18.5 ± 5.2	5.4 ± 0.5	5.3
$C_{18:1}$ (wt %)	44.5 ± 4.7	41.5 ± 1.0	35.4
$C_{18:2}$ (wt %)	3.0 ± 0.8	18.2 ± 2.3	39.7
$C_{18:3}$ (wt %)	0.7 ± 0.3	0.9 ± 0.3	5.4
others (wt %)	1.3	2.2	2.54
$C_{18:2}/C_{18:1}$	0.1	0.4	1.1
unsatd/satd[a]	1.1	2.3	4.8
references	7, 62−66	7, 17, 62−64, 91[b,c]	this study[c]

[a] The mass ratio of unsaturated fatty acids to saturated fatty acids is based on a composition ≥97.5 wt %. [b] The average poultry fat composition also includes the composition determined in this study. [c] See Supporting Information.

rendered lipids unsuitable for direct alkali catalyzed transesterification;[49] however, there exist methodologies to separate, convert, and neutralize free fatty acids before conventional transesterification. These may include alkali refining (which generates a soapstock side stream), distillation (also known as steam refining),[50−54] acid catalyzed esterification,[49,55−60] and solvent extraction.[14,61] In this study, we chose to employ physical refining as the baseline pretreatment methodology because it is a well-established technology and it can be easily retrofitted as an upstream process in existing U.S. biodiesel plants that primarily use low FFA vegetable oil feedstocks. Thus, as shown in Figures 3−5, the conversion of rendered lipids into biodiesel comprised three major operations: steam (physical) refining, solid acid catalyzed esterification, and homogeneous alkali catalyzed transesterification.

In order to calculate an appropriate material balance for the conversion of rendered lipids into biodiesel, the fatty acid composition of tallow, poultry fat, and yellow grease was reviewed from the literature (Table 3). We found that the fatty acid composition for grease may vary significantly depending on the nature of the original oil (or fat) and the conditions of use (e.g., cooking temperature, extent of usage, and food type). For this reason, the composition of a particular soybean oil grease was experimentally determined in this study (Supporting Information). Also, the composition of a refined poultry fat was determined for comparison; this fat was kindly provided by Fieldale Farms Corporation (Baldwin, GA) (see Supporting Information). According to the literature and our results, the most abundant fatty acid in tallow and poultry fat is oleic acid ($C_{18:1}$).[7,62−66] On the other hand, the most abundant fatty acids in the tested soybean oil grease were found to be linoleic acid ($C_{18:2} = 39.7$ wt %) and oleic acid ($C_{18:1} = 35.4$ wt %). Thus, for homogeneity of the analysis, all material balances employed triolein (MW = 885.43 g/mol) and oleic acid (MW = 282.46 g/mol) to represent an average component for triglycerides (TGs) and FFAs, respectively.

It should also be pointed out that an advantage of using biodiesel derived from rendered lipids is that it may present better oxidation stability than soybean oil biodiesel.[62,67] This fuel characteristic derives from the fact that the constituent fatty acids chains are highly saturated. Figure 7 shows a graphical comparison of the level of saturation among rendered lipids, soybean oil (SBO), and SBO grease. Tallow and lard showed the highest levels of saturation, while poultry fat was less saturated than the former two but more saturated than SBO and SBO grease. We observed a slight increase in saturation for SBO after frying, in agreement with the literature.[68] This is also reflected in the ratio of linoleic to oleic acid ($C_{18:2}/C_{18:1}$), which initially had a value of 2.5, but after 6 days of oil use had decreased to 1.1 (see Supporting Information). In order to improve the cloud point and low temperature performance resulting from the higher saturation of rendered lipid methyl esters, it is possible to blend them with petrodiesel, biodiesel from other feedstocks (with higher iodine value),[62,69] and alcohols.[62]

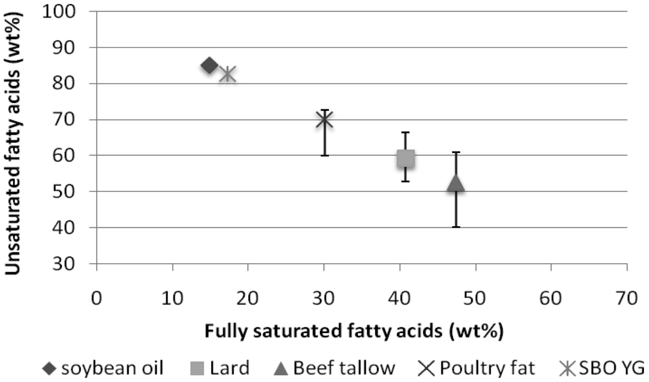

Figure 7. Typical level of fatty acid saturation for different biodiesel feedstock materials. *x* values should be adjusted accordingly with *y*-error bars.

Other inventory materials for the lipid conversion process included methanol, sodium methoxide, NaOH, and HCl. As for the solid acid catalyst employed during esterification, it can be expected that it is suitable for continuous regeneration and reuse. Consequently, the fossil energy spent on its preparation should have a low impact on the ELCA and was not included in the assessment.

4. Energy Life Cycle Assessment

Shrestha et al. recently reviewed some of the most relevant studies regarding the energy life cycle for the production of biodiesel from soybean oil in the United States.[70] According to these authors, there had been variations in the definition and calculation of the net energy ratio among these studies. They proposed the following definitions for a more consistent evaluation of the biodiesel energy life cycle:

$$\text{net energy ratio (NER)} = \frac{\text{calorific value of biodiesel}}{\sum_{i=1}^{m} E_i f_i} \tag{1}$$

where E stands for the energy inputs at the ith stage, f denotes the mass fraction of biodiesel after the ith stage, and m is the number of processing stages. These authors also provided the following definition for the renewability factor (RF):

$$\text{RF} = \frac{\text{calorific value of biodiesel}}{\text{nonrenewable energy input}} \tag{2}$$

This definition of the renewability factor has also been employed in the literature to designate fossil energy ratio. For instance, Nelson and Schrock defined the fossil energy ratio as "the thermal energy of the fuel divided by the fossil-based thermal energy required in the conversion".[36] Notice that if all energy inputs in the life cycle are fossil based (i.e., petroleum, natural gas, and coal), then the value of the net energy ratio (NER) would be the same as that of the renewability factor (RF). In

Table 4. Net and Gross Calorific Values of Rendered Lipid Methyl and Ethyl Esters Predicted Using Mendeleev's Formula

	beef tallow		poultry fat		SBO yellow grease	
property	methyl ester	ethyl ester	methyl ester	ethyl ester	methyl ester	ethyl ester
ACF[a]	$C_{18.3}H_{35.4}O_2$	$C_{19.3}H_{37.4}O_2$	$C_{18.3}H_{34.8}O_2$	$C_{19.3}H_{36.8}O_2$	$C_{18.8}H_{34.8}O_2$	$C_{19.8}H_{36.8}O_2$
mass (%)						
C	76.4	76.9	76.6	77.1	77.1	77.4
H	12.4	12.5	12.2	12.3	12.0	12.1
O	11.1	10.6	11.1	10.6	10.9	10.4
Q_n^M (kJ/kg)	37 499	37 794	37 358	37 659	37 292	37 591
Q_g (kJ/kg)	40 136	40 450	39 952	40 275	39 839	40 161

[a] Average chemical formula.

Table 5. Energy Requirements in the Production of Rendered Lipids Biodiesel (BD)[a]

processing stage	tallow (MJ/ kg BD)	poultry fat (MJ/ kg BD)	yellow grease (MJ/ kg BD)
livestock production			
animal feed and feedlot energy	388.0	163.1	N/A
animal transportation to slaughterhouse	49.2	2.9	N/A
slaughtering	17.9	68.6	N/A
rendering			
transportation of byproducts to rendering plant	0.6	1.1	0.3
rendering	11.2	18.0	3.4
conversion of rendered lipids into biodiesel			
transportation of rendered lipids to biodiesel plant	0.3	0.3	0.3
physical refining of rendered lipids	1.0	1.0	1.0
esterification of free fatty acids	3.7	3.7	3.7
transesterification of refined rendered lipids	2.7	2.7	2.7
production of chemicals for trans/esterification	3.8	3.9	3.8
transportation of biodiesel to consumer blender pump	0.1	0.1	0.1

[a] Energy includes both primary (fuel and electricity) and LCI fossil energy.

contrast, if both renewable and nonrenewable sources are employed, the value of RF would be higher than that of NER.

4.1. Calorific Value of Rendered Lipids Biodiesel. The net calorific value (Q_n) also known as "net energy" or "lower heating value" is the energy released upon combustion of a fuel at constant pressure, with all combustion products in the gas form. The gross calorific value (Q_g) also known as "gross energy" or "higher heating value" is the energy released at constant volume with water condensing to the liquid state. Since we considered that biodiesel would be mainly used as a transportation fuel burned in compression ignition engines (where no energy is recovered from the condensation of water vapor), then, the numerator in eqs 1 and 2 would be best described by Q_n. The net calorific value of biodiesel can be predicted using Mendeleev's formula (Q_n^M):[71,72]

$$Q_n^M\ (\text{kJ/kg}) = 339C + 1030H - 109(O - S) - 25.2W \tag{3}$$

where C, H, O, S, and W are the fuel weight percentages of carbon, hydrogen, oxygen, sulfur, and water, respectively. For a biodiesel fuel with negligible concentrations of sulfur and water, Q_n^M values can be calculated using C, H, and O values provided in Table 4. The average chemical formula (ACF) in Table 4 was determined using the average fatty acid compositions given in Table 3. Using these predicted net calorific values, the gross calorific values were estimated using the following general correlation:[73]

$$Q_g\ (\text{kJ/kg}) = Q_n^M\ (\text{kJ/kg}) + 212.2H\ (\text{wt }\%) \tag{4}$$

The predicted net and gross calorific values of rendered lipids biodiesel (methyl and ethyl esters) are provided in Table 4. These values were found to be in good agreement with literature experimental calorific value results. For example, the gross calorific value of tallow methyl esters has been reported to be 39 949 kJ/kg,[62] which is similar to the predicted value of 40 136 kJ/kg. Among net calorific values for "animal fats methyl esters" reported in the literature are 36 649 kJ/kg (115 720 BTU/gal)[74] and 37 200 kJ/kg,[75] which are similar to the values estimated here. In order to further corroborate the reliability of Mendeleev's correlation, the net calorific value of a poultry fat methyl ester sample prepared in our laboratories was obtained experimentally via the standard test method ASTM D240-02 (heat of combustion of liquid hydrocarbon fuels by bomb calorimeter). The test was performed at an external laboratory (Core Laboratories, Houston, TX). By this means, the experimental gross calorific value for poultry fat methyl esters was found to be 39 729 kJ/kg (17 073 BTU/lb) (see Supporting Information), which is in good agreement with the predicted value of 39 913 kJ/kg.

For a pure methyl oleate fuel ($C_{19}H_{36}O_2$), the predicted net and gross heating values are 37 521 and 40 118 kJ/kg, respectively. Note that these values are not significantly different from the predicted calorific values of tallow, poultry fat, and grease derived methyl esters. This means that the utilization of methyl oleate as a biodiesel model component would not introduce significant error into the net energy ratio calculations. In practice, the composition of rendered-lipids-based biodiesel may vary considerably; however, if the fatty acid composition is known, the use of Mendeleev's formula becomes a convenient and sufficiently accurate way to predict net calorific values.

4.2. Energy Life Cycle Assessment. The following sections deal with the description of the energy requirements on each stage of the production of biodiesel from rendered lipids. The summarized breakdown of energy inputs for producing biodiesel from beef tallow, poultry fat, and soybean oil grease is provided in Table 5.

4.2.1. Energy Requirements for Animal Growth and Maintenance. Nelson and Schrock recently reported the energy requirements for the production of beef cattle in Kansas (one of the largest cattle production states in the United States).[36] The total energy for livestock production was calculated by

Table 6. Unallocated Life Cycle Inventory Energy Required for the Production of Broiler Feed Ingredients

type of ingredient	energy (MJ/kg ingredient)	ref
corn[a]	2.6	41
soybean meal[a]	5.5	41
soybean oil[a]	21.9	41
salt[b]	2.2	92
limestone[b]	0.1	92

[a] Cradle to mill gate energy. [b] Includes process energy only.

Table 7. Energy of Fuels and Chemicals

substance	energy	ref
fuels/ energy		
diesel[a]	1.201 MJ/MJ	27
natural gas[a]	1.083 MJ/MJ	93
electricity[a,b]	2.910 MJ/MJ	94
chemicals[c]		
methanol	32.4 MJ/kg	27
sodium methoxide (25 wt %)	31.7 MJ/kg	27
sodium hydroxide	15.8 MJ/kg	27
hydrogen chloride	16.6 MJ/kg	27

[a] Includes direct and embodied energy. [b] Average U.S. nonrenewable energy consumption per 1 MJ of electricity produced (equivalent to 34.4% generation efficiency). [c] Includes only the embodied fossil energy (calculated from Sheehan et al.[27]).

adding the energy used in the agricultural production of feed rations, feedlot operation, and transportation of feed and cattle. The energy for the production of feed (most demanding contributor) comprised the energy consumed in farm machinery manufacture and repair, irrigation systems, application of fertilizers and pesticides, and the embodied energy of fertilizers, pesticides, and fuel/lubricants for tillage, planting, and harvesting. The mass-allocated total energy for the growth and maintenance of beef cattle was reported to be 44.4 MJ/L tallow.[36] Because the mass coproduct share of tallow employed in that study was 17.5%, the unallocated total energy was equivalent to 253.7 MJ/L tallow (44.4 MJ/L tallow divided by 0.175). With a tallow density of 0.88 kg/L and a tallow yield of 63 kg/head of cattle,[36] this translates to 18 163 MJ/head of cattle (253.7/0.88 × 63). Also, according to that study,[36] animal transport accounted for 11.3% of the total energy; therefore, the transportation energy can be calculated to be 2045 MJ/head of cattle (18 163 MJ/head of cattle × 0.113).

Analogous to the production of beef cattle, the most relevant energy requirements in the production of broiler poultry consist of the energy for the production and preparation of feed, feedlot energy (on-farm inputs), and transportation of feed and broilers. The life cycle inventory (LCI) energy for broiler diet ingredients is summarized in Table 6. Using a poultry slaughter weight of 2.26 kg, an economic feed conversion ratio of 1.9 kg of feed/kg of bird produced (Table 2),[41] and the feed composition provided in section 3.3.1, the LCI energy for poultry feed production was estimated to be 16.3 MJ/bird. Feed was assumed to be transported a 15.5-mi distance from the mill to the farm[41] using 22-ton (ton or short ton equals 907.2 kg) capacity diesel trucks, with a fuel efficiency of 2.5 km/L (5.8 mi/gal). With the direct and embodied energy for petroleum diesel fuel equaling 1.2007 MJ/MJ (Table 7), the total energy for the transportation of feed was estimated to be 0.06 MJ/bird. On-farm energy inputs have been reported to be 6.0 MJ/bird.[41] Broiler transportation was assumed to be carried out using diesel powered trucks (6200 birds/truck) traveling an average distance of 100 mi. Therefore, the total energy for the transportation of broilers from the farm to the slaughterhouse is 0.41 MJ/bird. Accordingly, the total energy for poultry farming in the United States was calculated to be 22.8 MJ/bird (11 086 MJ/ton poultry), which is comparable to the energy required for poultry farming in the United Kingdom (11 998 MJ/ton poultry[76]). The energy spent in hatcheries and the energy credit derived from the utilization of poultry manure as fertilizer substituent have been shown to be just minor contributors to the cradle-to-farm gate poultry energy life cycle.[41] Therefore, these two were not included in our analysis.

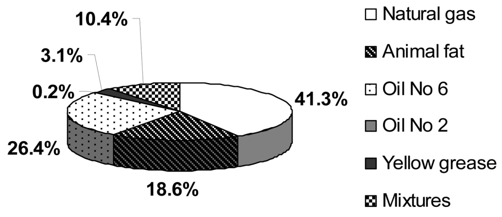

Figure 8. Fuels for the generation of thermal energy in the rendering process (data from $n = 23$ U.S. rendering plants).

4.2.2. Energy Requirements at the Slaughterhouse Plant. In meat processing, fossil fuels are mainly employed in the generation of process heat. Electricity is primarily used in cooling operations.[42] The consumption of both types of energy has continued to increase not only as a result of higher processing standards (health and environmental) but also because of the higher demand for processed meat products (e.g., cut-up, deboned, frozen). Beef and poultry meat production require 1.532 and 3.413 MJ/kg of dress carcass weight, respectively.[42] Another study reported that typical meat processing energy requirements range from 1.323 to 5.291 MJ/kg of standard hot carcass weight.[77] For the energy balance calculation, we assumed that 85% of the total energy required was fuels for boilers (e.g., natural gas), whereas the remaining 15% was electricity from the grid.[77]

4.2.3. Energy Requirements in the Rendering Process. In rendering, process steam is generated in boilers fueled by natural gas (NG), oil No. 2, oil No. 6, grease, or animal fat (from 25 survey responses, $n = 25$). For calculation purposes, the energy contents assigned to NG (at 0 °C and 101.325 kPa), oil No. 2, and oil No. 6 were 38.3, 32 052, and 34 561 kJ/L, respectively. Animal fat for boilers was assumed to be a poultry fat with a density of 0.91 g/mL (7.6 lb/gal)[64] and a calorific value of 39 541 kJ/kg (survey data). The energy provided by yellow grease burned in boilers was already given in units of therms/month by the renderers. As shown in Figure 8, at least 68% of the thermal energy generated in boilers was derived from fossil fuels (NG, oil No. 6, and oil No. 2). The category “mixtures” corresponds to an unspecified mixture of fossil and nonfossil fuels. Therefore, it could be inferred that at least 21.7% of the steam generated at the surveyed rendering plants originated from burning self-integrated rendered lipids. Normally, the use of a given fuel would depend on the boiler design, fuel availability, and fuel cost.

The monthly utilization of fuels and electricity data was averaged to calculate an annualized energy consumption (2007). This energy was correlated with the estimated total amount of rendered products (RP) manufactured by each surveyed rendering plant in 2007. About 90% of the energy consumed in rendering is thermal energy generated by combustion of fuels in on-site boilers (Figure 9a). The correlation for fuels was found to be 5.589 MJ/kg RP. This correlation corresponds to an average water removal of 57.2% ($n = 23$). Using the correlation, the fuel-for-boilers demand for processing cattle (originally containing an average of 49.0 wt % water) and poultry (originally containing 59.9 wt % water) byproducts was

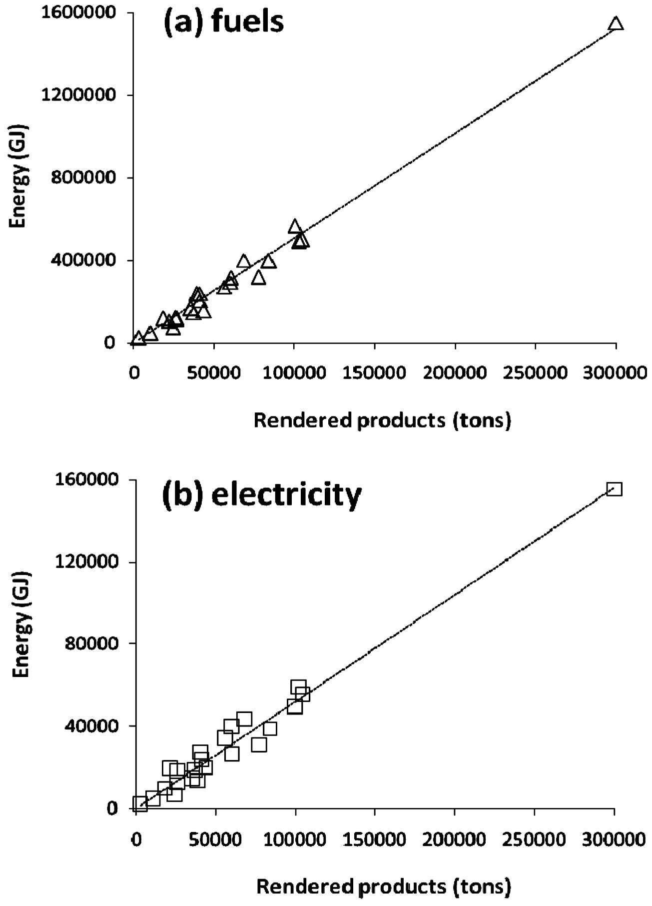

Figure 9. Energy consumed by the surveyed rendering facilities in 2007: (a) fuels and (b) electricity. Note: 1 ton = 2000 lb.

calculated to be 4.144 and 6.081 MJ/kg RP, respectively. On the other hand, electricity expenditures represent on average only 9.4% of the total primary energy consumption. The correlation for electricity was estimated to be 0.1607 kWh/kg RP, which translates to 0.573 MJ/kg RP (Figure 9b). Our survey results included small, medium, and large renderers. This means that, on a production volume basis, these energy correlations are likely to be representative of the entire rendering industry. Obviously, variations in the extent of heat integration at a given processing facility could cause the amount of required energy to differ.

Mindful of the fact that in rendering the largest energy cost is the generation of cooker steam, one can also approximate the process thermal energy demand by using typical equipment specifications. The Dupps Company (Germantown, OH), a leading manufacturer of rendering equipment, has found the following empirical rules for the consumption of steam in continuous Dupps cookers:[78]

1. In processing animal byproducts, it takes 0.75 lb of steam to process 1 lb of raw material. One pound of raw material will have about 0.5 lb of water (to be evaporated), 0.25 lb of protein, and 0.25 lb of fat.

2. In processing recycled cooking oil, it takes 1.5 lb of steam to evaporate 1 lb of water.

According to the first rule, the energy demand for processing typical animal byproducts (50 wt % water, 25 wt % protein, and 25 wt % fat) using indirect saturated steam at 125 psi[78] (Δh = 2.771 MJ/kg) would be 4.156 MJ/kg RP, in excellent agreement with the value derived from the survey data (4.143 MJ/kg RP). Using the Dupps second rule, the steam energy requirement for processing raw grease containing 28 wt % moisture can be estimated to be 1.616 MJ/kg RP, lower than the one for processing animal byproducts.

In the rendering process, besides primary energy use (fuels and electricity), there also exists an indirect energy consumption in the form of chemicals. According to the survey information, stabilizers (e.g., antioxidants) and enrichment ingredients (e.g., flavoring agents) may be added to rendered lipids and protein meals. Also, additional chemicals are used in odor and wastewater treatments. In the survey, however, insufficient information was gathered regarding the specific type and consumption of these chemicals. Therefore, due to lack of data, the energy associated with the production and transportation of these materials was not considered in the analysis. This may introduce a small error in our estimates as energy consumption arising from the use of such chemicals is likely to be only a minor contributor to the overall energy balance.

Raw grease and animal byproducts are normally transported to the rendering plants using trucks of capacity ranging from 9 to 24 tons ($n = 26$). In general, these trucks utilize petroleum diesel as fuel ($n = 26$). The average fuel efficiency of these trucks was 2.47 ± 0.38 km/L (5.8 ± 0.9 mi/gal, $n = 25$). The distance between the origin of the byproducts and the rendering plant was found to be 155.8 km (96.8 mi) with a standard deviation of 36.7 km (22.8 mi, $n = 19$).

After rendering, the protein meal and rendered lipids are shipped by either rail or truck, and both means of transportation generally utilize petroleum diesel as fuel ($n = 26$). The rendered product trucks ranged in capacity from 23 to 25 tons ($n = 26$) and had an average fuel efficiency similar to that of byproduct trucks, 2.3 ± 0.17 km/L (5.5 ± 0.4 mi/gal, $n = 23$). The average distance traveled by the trucks transporting rendered products was found to be about twice that traveled by byproduct trucks, 289.0 ± 131.5 km (179.6 ± 81.7 mi, $n = 21$), which indicates that the rendering plants are usually located closer to the byproduct generation facilities. Currently in the United States, most rendered lipids are utilized as an animal feed ingredient. To a lesser extent, these lipids are used as boiler fuel or biodiesel feedstock (<15% according to the survey statistics, $n = 23$). Therefore, the distance of 289.0 km (179.6 mi) is more representative of the average distance traveled from the rendering plant to the animal feed milling plant (or port). However, as a first approximation, this distance was employed in the energy assessment for travel distances from rendering plants to biodiesel production facilities. If rendered lipids are intended to be used as biodiesel feedstocks, the site of the biodiesel facility should be strategically planned so that the location of the rendering plant and the destination of the biodiesel fuel are both evaluated.

4.2.4. Energy Requirements for the Conversion of Rendered Lipids into Biodiesel.

In our baseline process, FFAs and glycerides are first separated by means of physical refining. Steam (or nitrogen) stripping and diluting agents are used to separate the higher volatility FFAs from the lower volatility glyceride mixture. The process is typically carried out at reduced pressures.[52,54] The fuel energy and electricity requirements per 1000 lb (453.6 kg) of acid feedstock (to achieve a FFA reduction from 5 wt % to ≤0.03 wt %) have been reported to be 380 000 BTU (401 MJ) and 1.5 kWh, respectively.[54] After physical refining, the FFA-rich distillate can be converted to biodiesel using a reactive distillation process. The thermal energy and electricity requirements for producing 1200 kg/h biodiesel (from oleic acid and methanol via solid acid catalyzed reactive distillation) have been reported to be 368 and 290 kW, respectively. On the other hand, the low FFA lipids resulting from physical refining can be transesterified using the conventional homogeneous alkali catalyzed process. A contemporary model for such a process has been reported by Haas et al.[16] In that study, the homogeneous alkali catalyzed transesterification consisted of a continuous operation where triolein was reacted with methanol using two sequential steam-heated reactors operating at 60 °C. After each reaction step, the glycerol phase was separated from the biodiesel phase via centrifugation. The resulting biodiesel was washed using acidulated water (HCl, pH 4.5) and later separated from this acidic aqueous phase by centrifugation. Finally, the washed biodiesel was vacuum-dried to meet the ASTM D 6751 water content standard. The glycerol stream (containing residual sodium methoxide catalyst, sodium hydroxide, and water impurities) was neutralized with HCl and refined to reduce the water content, yielding a product stream containing a minimum of 80 wt % glycerol in water. For an annual production of 10 million gal of biodiesel (37.9 ML/year), these authors reported a direct energy expense of 66 980 MCF of natural gas and 1 008 000 kWh of electricity (revised from the literature[79]). The thermal energy requirements were based on the Aspen process simulation results for the distillation column reboilers, the vacuum steam ejector, and other miscellaneous steam needs, such as heat tracing, general heating, etc.[79] Electricity was calculated from the power needs of all electrical drivers in the facility.[79] In addition to these primary energy requirements, the fossil energy embodied in the chemicals (e.g., sodium methoxide and methanol) employed to convert rendered lipids into biodiesel was found to be significant and was included in the energy assessment (see Table 7).

According to recent U.S. reports, the final biodiesel product is most commonly shipped via railcar, with lesser quantities shipped via truck and barge.[80] For that reason, it was assumed that the biodiesel would be shipped via railcar, with an energy intensity of 243 kJ/metric ton·km (337 BTU/ton·mi),[81] where energy intensity is defined as the heat value of the engine fuel divided by both the fuel economy of the locomotive and the total weight of material transported. Biodiesel plants are typically small (<50 million gal/year) and are distributed across the United States; therefore, and average distribution distance of 483 km (300 mi) was assumed reasonable.

5. Allocation

Relevant process energy inputs are typically ascribed only to valuable end products and coproducts. Allocation percentages may be assigned according to mass, energy content, market value, displacement, or percentage of energy consumed by each product.[22] The selection of the allocation method can significantly alter the outcome of the assessment. Therefore, in order to ensure better usability of the data provided in our energy life cycle assessment, until this point we have tried to provide only unallocated data to facilitate conversions using any allocation procedure.

The use of market value as the energy burden allocation method is believed to better reflect the sustainability of a manufacturing process. However, this approach was not employed here because it tends to be largely affected by variations in market values, which have undergone significant changes in recent years. Instead, the more traditional mass allocation approach was employed, which allowed comparing the results of this study with other relevant ELCAs. Table 8 provides the mass allocation percentages for each valuable product at a given processing stage for the different biodiesel feedstocks.

Table 8. Mass Allocated Coproduct Shares for the Different Stages of Biodiesel Production from Rendered Lipids

fat type	process stage	output[a]	mass allocation (%)
beef tallow	slaughtering	meat	51.6
		hides	11.8
		render products	36.6
	rendering	meat bone meal (MBM)	44.7
		tallow	55.3
	conversion to biodiesel	biodiesel	88.5
		glycerol (80 wt %)	11.5
poultry fat	slaughtering	meat[b]	59.3
		render products[c]	40.7
	rendering	poultry meal[d]	53.7
		poultry fat	46.3
	conversion to biodiesel	biodiesel	88.5
		glycerol (80 wt %)	11.5
SBO grease	rendering	yellow grease	100
	conversion to biodiesel	biodiesel	88.5
		glycerol (80 wt %)	11.5

[a] Mass allocation is only burdened on valuable (marketable) coproducts. [b] Meat includes legs, fillets, and wings.[46] [c] Render products include giblets, upper back, lower back, feet, breast skin, neck, etc.[46] [d] Poultry meal includes poultry bone meal, blood meal, and feather meal.

6. Interpretation of the ELCA

6.1. Analysis and Discussion. In this study, we investigated the production of biodiesel from typical U.S. rendered lipids using a single category: energy use. This category is particularly important because it allows for assessing the renewability of the fuel. Also, there exists a direct relationship between energy consumption and other environmental impact categories, such as greenhouse gas emissions and carbon footprint. In addition, from an economic standpoint, addressing energy efficiency is critical to the sustainability of any biofuel industry.

The energy requirements and net energy ratios (NERs) for the different scenarios considered in this study are provided in Table 9. For this calculation, it is important to note that 100% of the required thermal energy was assumed to be fossil based. The net energy ratios for scenario III (NER_{III}) were found to be much lower than 1 (0.20 and 0.33 for tallow and poultry fat, respectively). This means that more fossil energy is required in the elaboration of the fuel compared to the energy in the final biodiesel fuel. Therefore, from an energetic standpoint, no animal should be raised and processed with the sole purpose of producing biodiesel. In contrast, if no energy is allocated to livestock production and meat processing, the output/input energy ratios (NER_{II}) for tallow and poultry fat biodiesel are 2.22 and 1.94, respectively. For all three rendered lipids considered in this study, the net energy ratio for scenario I was found to be >3.6. A graphical comparison of the energy contributors for the complete ELCA is illustrated in Figure 10. Clearly, the most energy intensive process associated with the production of biodiesel from animal fats is farming and meat processing (~80%), and as previously discussed, the major energy sink at that stage is the provision of feed. For SBO grease, energy is mainly consumed in the conversion to biodiesel (72.5%), while the rendering process and transportation contributed 24.6% and 2.8%, respectively.

6.2. Comparison with Previous ELCA Studies. To the best of our knowledge, the study by Nelson and Schrock[36] is the only previous energetic investigation addressing the production of biodiesel from beef tallow in the United States. Using a mass-coproduct allocation method, these authors obtained NERs of 0.81, 3.49, and 5.90 for our equivalent scenarios III, II, and I, respectively. Although those results led them to similar conclusions, these values are significantly different from the NERs

Table 9. Mass-Allocated Fossil Energy Demand and Net Energy Ratio for Biodiesel Produced from Rendered Lipids Using Different System Boundaries

	tallow biodiesel^a	poultry fat biodiesel^a	SBO YG biodiesel^a
scenario I			
fossil energy consumed in the conversion of rendered lipids to BD (MJ/kg BD)	11.5	11.5	11.4
glycerol coproduct credit^b (MJ/kg BD)	−1.3	−1.3	−1.3
mass-allocated fossil energy for conversion of rendered lipids to BD (MJ/kg BD)	10.2	10.2	10.1
transportation of biodiesel to pump (MJ/kg BD)	0.1	0.1	0.1
mass-allocated fossil energy consumed in scenario I (MJ/kg BD)	10.3	10.3	10.3
NER$_{\mathrm{I}}$	3.64	3.61	3.63
scenario II			
fossil energy consumed in rendering of byproducts^c (MJ/kg BD)	11.9	19.1	3.7
meal coproduct credit (MJ/kg BD)	−5.3	−10.3	0
mass-allocated fossil energy consumed in rendering of byproducts (MJ/kg BD)	6.6	8.9	3.7
mass-allocated fossil energy consumed in scenario II (MJ/kg BD)	16.9	19.2	13.9
NER$_{\mathrm{II}}$	2.22	1.94	2.67
scenario III			
fossil energy consumed in livestock and meat production^d (MJ/kg BD)	455.2	234.6	N/A
coproducts credit (MJ/kg BD)	−288.5	−139.2	N/A
mass-allocated fossil energy consumed in livestock and meat production (MJ/kg BD)	166.6	95.4	N/A
mass-allocated fossil energy consumed in scenario III (MJ/kg BD)	183.6	114.6	N/A
NER$_{\mathrm{III}}$	0.20	0.33	N/A

[a] NER was calculated using the net calorific value of the respective methyl ester biodiesel (Table 4). [b] Partially purified glycerol (80 wt % glycerol in water). [c] Includes transportation of byproducts to the rendering plant. [d] Includes livestock transportation.

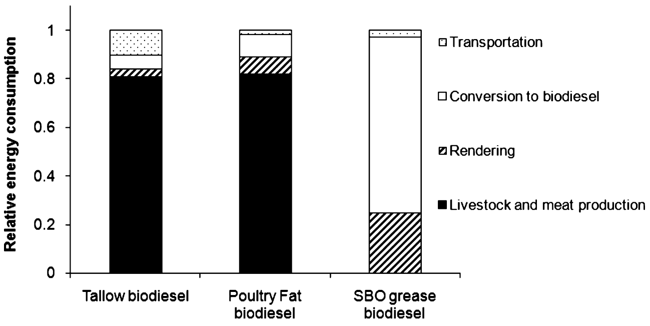

Figure 10. Relative mass-allocated energy requirement at different stages for producing biodiesel from rendered lipids.

found in this study. The following arguments may explain some of these discrepancies:

(1) For scenario III, the value of 5.90 was obtained considering only the energy necessary to carry out the conventional transesterification process. However, beef tallow may contain a considerable amount of FFAs and water, which under conventional transesterification conditions may cause catalyst neutralization (saponification), incomplete reaction, and inefficient reaction rate. For this reason, we considered more processing stages (physical refinining and esterification). Doing so added an extra energy penalty on the conversion to biodiesel resulting in a lower NER (3.64).

(2) In this study, the energy for rendering was found to be higher than the ones previously reported. Nelson and Schrock[36] reported a cumulative mass-allocated rendering energy of 4138 kJ/L biodiesel. Using a methyl tallowate specific gravity of 0.8772 (at 15.5 °C), this energy would be equivalent to 4717 kJ/kg biodiesel, whereas the mass-allocated rendering energy found in this study was somewhat higher, 6567 kJ/kg biodiesel.

In this study, the total primary energy for rendering cattle byproducts (fuels + electricity) was calculated to be 4.74 MJ/kg RP (2.40 MJ/kg raw material processed), which is again somewhat higher than European rendering reports of 1.80 MJ/kg raw material processed.[42] This could be expected given the method employed here to estimate the rendering energy. Contributions such as electricity for buildings, fuel for forklifts, etc. may have been the source of the higher estimate.

(3) Nelson and Schrock neglected the abattoir energy, maybe because U.S. animal slaughtering energy data are difficult to find. Only for this process we had to employ European data, and this energy was included in the analysis. However, this expenditure was found to be only a small contributor to the overall energy balance.

(4) The tallow yield used by Nelson and Schrock was 63.1 kg of tallow/head of cattle, while in this study a more conservative estimate of 41.9 kg of tallow/head of cattle was employed.

It is also interesting to compare the ELCA of rendered lipids biodiesel to those reported for soybean oil biodiesel. Although there have been significant differences among soybean oil biodiesel ELCAs, Shrestha and co-workers recently reviewed these studies and proposed a unified model that employed the same system boundaries, allocation, and NER definition.[70] Their analysis included the energy required in soybean agriculture and transport, soy oil extraction and transport, transesterification, and SBO biodiesel transport. Using this reconciled approach, they found an NER of 2.55 ± 0.38, which is similar to the one found for SBO biodiesel under Canadian conditions (NER range = 2.12−2.41).[4] Mindful of the fact that soybeans may be considered a dedicated bioenergy crop (i.e., soybeans are grown with the intention of manufacturing fuel and feed), it is reasonable to compare those results to the NERs of scenarios I and II. For the examined cases, it can be stated that, from an energetic standpoint, producing biodiesel from rendered lipids is as good as or better than producing SBO biodiesel.

6.3. Perspectives. A preliminary evaluation of processing assumptions showed that changes in the type of fuels employed (to generate process heat) and biodiesel conversion technology may significantly impact the result of the NER. Therefore, NER values for these two cases were calculated: A, self-integration of rendered lipids as boiler fuel in rendering and conversion to

Table 10. Energy Ratios for the Cases Considered in the Sensitivity Analysis

case	scenario	tallow biodiesel	poultry fat biodiesel	SBO grease biodiesel
A	I	5.00	5.12	4.39
	II	3.41	3.34	3.27
B	I	4.09	4.55	4.27

biodiesel; and B, synthesis of biodiesel using solid catalyst and supercritical conditions.

Case A. Rendered Lipids as Fuel for Generation of Thermal Energy. In our baseline process, we have assumed that fossil natural gas is the only fuel employed in the generation of thermal energy in rendering and in the conversion to biodiesel. However, self-integration of straight rendered lipids as on-site boiler fuel is also possible despite having a relatively high viscosity.[62,82] As a first approximation, we assumed that the free fatty acids and glycerides have the same gross calorific value (tallow[62] = 40 054 kJ/kg, poultry fat (from survey data) = 39 540 kJ/kg, SBO[62] = 39 280 kJ/kg) and that the boiler thermal efficiency would be 1. As shown in Table 10, under these conditions all fossil energy ratios increase significantly, suggesting that the utilization of rendered fats may be beneficial from an energy standpoint.

Case B. Novel Biodiesel Synthesis Methods. The energy required for the conversion of lipids to biodiesel has a significant impact on the assessment of the energy life cycle (biodiesel mass allocation is 88.5%). We assumed that the conversion process would involve refining, esterification, and transesterification. This baseline combination of processes resulted in a thermal energy requirement of 4.2 MJ/kg biodiesel, which is similar to the energy requirements reported for the integrated acid−alkali homogeneous catalyzed process (3.7 MJ/kg biodiesel[83]). Other methodologies that have been proposed may employ enzymes, solid catalysts, or supercritical alcohols. Low temperature biological conversion routes are typically less energy intensive and have been shown to require less steam than the inorganic NaOH catalyzed method.[84] However, such milder methods would require much longer residence times and have the disadvantage of enzyme susceptibility to denaturing and higher cost. Thus, this alternative was not considered. Catalyst-free methodologies, such as supercritical alcohol processing, have also been found suitable for converting FFA-containing feedstocks.[85] Nevertheless, the higher energy required to operate under supercritical conditions has limited commercial applications of this technology (8364 kJ/kg biodiesel[83]). Similarly, solid acid catalyzed processes normally require higher reaction temperatures to compensate for lower intrinsic reaction rates.[58,86−88] Interestingly, the combination of these two latter methodologies has been reported to result in ultrafast biodiesel formation, which may compensate for the higher energy requirement.[89]

Using the Aspen Plus 2006 process simulator, the energy balance for the combination of supercritical methanol and heterogeneous acid catalyzed methodologies was determined. The simulation details are provided in the Supporting Information. The hypothetical thermal energy balances were all below 1.9 MJ/kg biodiesel. Using a thermal efficiency of 86%, this value would be equivalent to that of the homogeneous catalyzed process (2.2 MJ/kg biodiesel[16]), in agreement with previous suggestions by McNeff and co-workers.[89] Nevertheless, the electricity requirement for this hypothetical process was found to be about 10 times higher than that of the homogeneous catalyzed process (109.6 kJ/kg biodiesel[16]). For these calculations, the same mass allocation percentages were employed (Table 8) and no energy burden was ascribed to the production of the dimethyl ether byproduct. The net fossil energy ratios for case B were all found to be >4 (Table 10). These results suggest that elimination of physical refining and esterification processes together with some degree of heat integration may prove favorable to the life cycle energy balance.

7. Conclusions

In this study, we evaluated the energy life cycle balances for biodiesel synthesized from lipids rendered in the United States. The results of scenarios I and II suggest that producing biodiesel from rendered lipids may be beneficial from an energy perspective. For animal fats, though, if the farming stage is considered in the life cycle energy balance, the net energy ratio is estimated to be much lower than 1. The energy balance may be improved by reintegrating part of the rendered lipids as fuel for process boilers and by utilizing more efficient biodiesel conversion methodologies. However, decisions regarding the utilization of rendered lipids as biodiesel feedstock should be evaluated jointly with other environmental impact assessments and economic sustainability studies.[90] Also, the currently debated indirect land use should be addressed as animal production would not only require land change for pasture but most importantly for the production of animal feed. Unless Americans experience a dramatic change in their animal protein consumption habits, it would appear that it is energetically favorable to render animal byproducts for the production of lipids to synthesize biodiesel.

Acknowledgment

This study was financed by the Animal Co-Products Research and Education Center (ACREC) at Clemson University with funding from the Fats and Protein Research Foundation. The authors are grateful to Dr. David Meeker for his invaluable assistance in conducting the renderer's survey. The authors also thank Christy Braswell and Eugene Jordan for their assistance with sampling yellow grease. We acknowledge BASF (Iselin, NJ) for the donation of the sodium methoxide catalyst.

Supporting Information Available: Included are A, renderer's survey structure; B, fatty acid composition of poultry fat and yellow grease; and C, simulation of biodiesel production using Aspen Plus 2006. This information is available free of charge via the Internet at http://pubs.acs.org.

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Received for review May 29, 2009
Revised manuscript received November 24, 2009
Accepted December 17, 2009

IE900884X