Development of Tallow-based Biodiesel Pathway in GREET^{TM}

Jeongwoo Han, Amgad Elgowainy, and Michael Wang

Systems Assessment Group, Energy Systems Division, Argonne National Laboratory

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Introduction

Interest in biofuels has increased recently due to growing environmental concerns (e.g., global warming) and energy security. Many biofuels, however, face sustainability challenges, mainly due to high feedstock cost and the competition of some biofeedstocks against food supply. In this respect, waste-based biofuel feedstocks, including animal fats, yellow grease, manure, wastewater treatment sludge, municipal solid waste, crop residue and forest residue, can play an important role in expanding the biofuel feedstocks so that the biofuel industry can grow sustainably. Among them, lipid-based feedstocks (such as animal fats and yellow grease) can be utilized for biodiesel (BD), and hydroprocessed renewable diesel and jet production.

A major issue with the utilization of waste-based feedstock for biofuel production is the quantity available since it is limited by the consumption of other products or food. According to a U.S. Census Bureau survey (U.S. Census Bureau, 2013), animal fat and grease production (e.g., tallow, grease, lard and poultry fat) accounted for 33% of total oil and edible and inedible fat production in 2009 and 2010 (see Table 1). It should be noted that vegetable oil, accounting for 63% of total oil and edible and inedible fat production, is mainly used for salad and cooking oil, so it is not considered a viable biofuel feedstock. Among animal fat and grease, tallow is the major resource. Assuming a 1:1 conversion ratio from lipid to BD by mass, total tallow and waste-lipid can produce 5.1 and 11 billion pounds (or 0.7 and 1.5 billion gallons) of BD, respectively, which account for 9% and 19% of total U.S. diesel consumption in 2010, respectively (U.S. EIA, 2013).

Currently, tallow is used mainly as livestock feed, and also for the production of soap, lubricants, paint and varnish in a limited quantity. If the majority of tallow is diverted from the current application to fuel production, it may cause indirect effects such as the use of other crops and materials to replace the diverted tallow. In this study, the indirect effects are not considered. Table 2 shows the fatty acid profile of tallow as compared to vegetable oils. With the higher shares of C16:0 and C18:1, tallow is fairly similar to palm oil and is well saturated. Moreover, the fatty acid profiles of edible and inedible tallows are not significantly different. Thus, this study will not distinguish the two types of tallows. Table 3 compares the density and heating values of tallow with soybean, palm and rapeseed oils. Except for the fact that the reported heating values of tallow are slightly higher than other oils, the characteristics of tallow and oils are reasonably consistent.

Table 1 Production of oil and edible and inedible fats (million pounds; U.S. Census Bureau, 2013)

	2009	2010
Oil	**18,742.7**	**18,509.6**
Coconut oil	618.2	843.6
Corn oil	1,539.0	1,456.4
Cottonseed oil	557.0	501.7
Palm oil	319.1	430.1
Rapeseed oil	953.6	1,023.2
Soybean oil	14,755.8	14,254.6
Edible tallow	**1,837.3**	**1,859.3**
Inedible tallow and grease	**6,220.3**	**6,021.9**
Inedible tallow	3,375.6	3,299.0
Grease	2,844.7	2,722.9
Yellow grease	1,632.1	1,403.6
Other grease	1,212.6	1,319.4
Lard	**346.1**	**312.1**
Poultry fat	**1,378.8**	**1,417.6**
Tall oil, crude	**1,217.2**	**1,344.0**
Total	**29,742**	**29,465**

Table 2 Fatty acid profile of tallow compared with vegetable oil

	C8:0	C9:0	C10:0	C12:0	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3	C20:0	C20:1	C22:1	Other
Tallow															
(López et al., 2010)					3.1	25.2	3.7	18.5	44.5	3	0.7				1.3
(Nebel and Mittelbach, 2006)			0.12	2.32		27.9	2.6	20.3	38.6	2.2		0.9	1.2		
(Alcantara et al., 2000)					5.4	32.8	4.3	4.1	35.1	15.7	1.6	0.5			
(Ali et al., 1995): Edible					4.89	28.4	4.63	14.9	44.6	2.6					
(Ali et al., 1995): Inedible	0.02	0.1	0.1	0.05	1.85	23.9	3.3	13.8	47.4	9.5					
Soybean oil (Han et al., 2013)						11.0		4.0	22.0	53.0	8.0				
Palm oil (Han et al., 2013)	0.3		0.6	4.3	1.3	40.8		3.7	37.2	10.1	0.0		0.0	0.0	
Rapeseed oil (Han et al., 2013)						3.0		1.0	17.0	14.0	9.0		11.0	45.0	
Jatropha oil (Han et al., 2013)						13.0	8.0	45.0	34.0						
Camelina oil (Han et al., 2013)						7.8	3.0	16.8	23.0	31.2		12.0		2.8	

Table 3 Density and heating values of tallow compared with soybean, palm and rapeseed oil

	Density (g/gal)	LHV (Btu/gal)	HHV (Btu/gal)	LHV (Btu/lb)	HHV (Btu/lb)
Tallow					
(Alcantara et al., 2000)	3,337				
(Ali et al., 1995)	3,482	123,621	132,183	16,105	17,220
Soybean oil (Demirbas, 2008)	3,460	121,193	129,336	15,889	16,956
Palm oil (Demirbas, 2008)	3,494	123,041	131,603	15,974	17,085
Rapeseed oil (Demirbas, 2008)	3,452	120,866	129,315	15,880	16,991

Life-cycle analysis data for GREET development

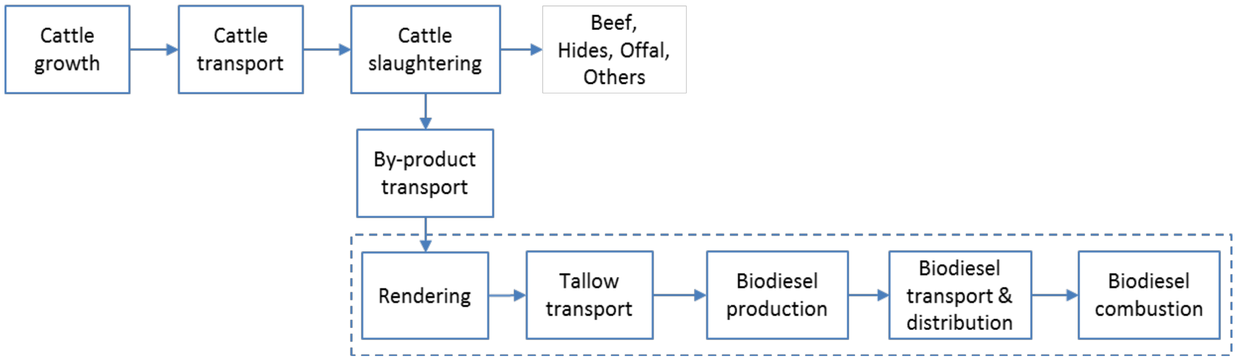


Figure 1 Complete life-cycle of tallow-derived biodiesel

Figure 1 shows the complete life-cycle of tallow-derived BD, starting with cattle growth, transport and slaughtering, succeeded by beef fat transport and rendering, and tallow transport, followed by BD production, transport and distribution, and ending with BD combustion. Considering fats as co-product, a system boundary can be defined to include all of the processes in the life-cycle. In such cases, the energy use and emissions associated with cattle growth, transport and slaughtering need to be allocated among beef, hides, offal, by-products and non-marketable others. Since these are not energy products, either mass- or market value-based allocations will be applicable.

Because the main purpose of the animal growth, transport and slaughtering is to get meat, a different system boundary can be defined starting with the by-product transport, i.e., excluding the animal growth, transport and slaughtering stages. In such case, the feedstock for the rendering plant is considered as a waste, i.e., with no upstream burden. This system boundary would be appropriate if the value of by-products is much lower than the others', which can be estimated from the mass shares and unit prices of each product. Typical mass shares of beef, hides, offal, by-products and non-marketable others are 36%, 8%, 3%, 23% and 30%, respectively. The by-products include fat, residual muscle tissues and others. The market value of beef has increased from $3.77/lb in 2007 to $4.69/lb in 2012 (USDA, 2013a). On the other hand, the market value of hides, offal and by-products are uncertain. USDA weekly reports currently show $0.58/lb for hides and offal. The price of by-products is not readily available, but can be estimated from the shares and unit prices of products from rendering the by-products. Rendering slaughterhouse by-products consist of 28% tallow, 23% meat and bone meal (MBM) and 49% waste. Tallow and MBM are typically traded at $0.35/lb and $0.23/lb (USDA, 2013b). Since the waste is not valuable, and additional energy is required to produce tallow and MBM and to treat waste, the price of slaughterhouse by-products is expected to be lower than the aggregated price of tallow and MBM from the by-products, which is $0.15/lb of by-products. With the estimated price, the market value share of slaughterhouse by-products would be only 2%. Thus, with the market-value share, it would be appropriate to consider the slaughterhouse by-products, or the feedstocks for the rendering plant, as a waste.

In many cases, slaughterhouses and rendering plants are integrated (called as integrated rendering plants). Even with independent rendering plants (collecting fats and greases from various offsite sources), transport distances are reasonably short. Thus, this study defines a system boundary starting with the rendering process by considering the slaughterhouse by-products as waste and neglecting the impact of by-products transport.

Rendering

Two types of rendering processes exist: edible and inedible rendering. Edible rendering process operates at lower temperatures, and produces edible fats and proteins for use in food products, pet foods, soap, and others. Edible rendering process consist of fat trimming, grinding, melting, disinfecting, 1^{st} centrifugal separation, heating, and 2^{nd} centrifugal separation. Melting and heating temperatures are typically 110° and 200°F, respectively. The 1^{st} centrifuge separates protein solids from melted fat and water, and the 2^{nd} centrifuge separates edible fat from water. Due to these low temperatures, minimal or no vapors are emitted.

On the other hand, inedible rendering process operates at higher temperatures, producing inedible tallow and grease for use in animal feed, soap, fatty acids and fuel production. There are two inedible tallow rendering processes: wet and dry processes. The wet process boils raw material in water to separate fats while the dry process dehydrates raw material by cooking it directly. Due to the high cost of energy and the low fat quality, the wet rendering process is no longer used in the U.S. The dry rendering process can be done in a batch or a continuous process. The two processes are very similar except for the fact that a single continuous cooker is used in the continuous process (see Figure 2) while several batch cookers are used in the batch process. According to Garcia et al. (2006) and Meeker (2006), the continuous process dominates the rendering process in the U.S. In the continuous process, the raw material is crushed to 1 to 2 inches in size for more efficient cooking. Cooking temperature and time depend on the type of raw materials. Typical cooking time and temperature are 1.5 to 2.5 hours and 250 to 275°F, respectively. From the cooked material, fats are separated by drainer and screw press. The remainder, processed meal cake with high protein contents and 10 % of the fat, could be used as animal feed. The fat could be further processed by a centrifuge to remove residual solids and an evaporator to remove water.

As mentioned above, the rendering process takes a large amount of heat (to cook the raw materials) as well as electricity. The heat is generated by the combustion of NG, fuel oil, diesel or even produced fat and grease (López et al., 2010). Table 4 summarizes the rendering process parameters collected in open literature (including NG, fuel oil, diesel, fat, electricity use, fat feed and meat bone meal yield). CARB (2009) and $(S\&T)^2$ Consultants Inc. (2011) provided data from three and two rendering plants, which are listed separately in Table 4. The table only includes rendering plants in U.S., thus excludes a couple of additional data points available for UK and Canada cases (Ramirez et al., 2012; Rollefson and Fu, 2004). Only four studies reported the specific types of energy consumed at the rendering plant, while the other studies only provided total thermal energy use. Thus, we used the specific energy uses to estimate total thermal energy use assuming a boiler efficiency (LHV) of 85%, and then compared the estimated total thermal energy use with the other reported values, which showed reasonable agreement.

It should be noted that the data by López et al. (2010) is based on a survey of 25 rendering plants, which account for 10% of the total tallow production. They plotted the fuel and electricity consumptions against the rendered products as shown in Figure 3. Due to the size and quality of data, this study selected input values for GREET simulations similar to those in (López et al. 2010).

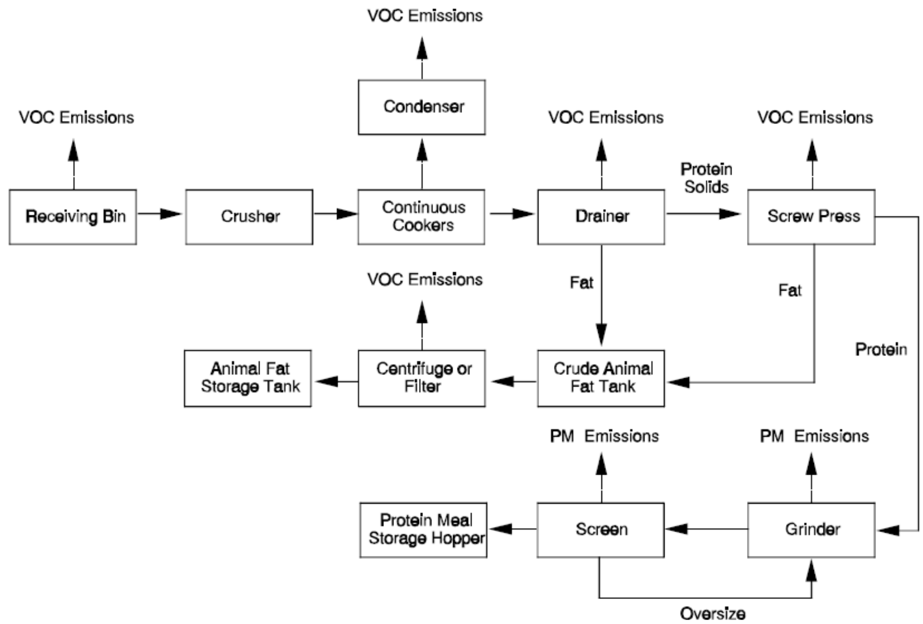


Figure 2 Schematics of typical continuous rendering process (EPA, 1995)

Table 4 Rendering energy use, fat feed and meat bone meal yields

	NG use	Fuel oil use	Diesel use	Fat use	Total thermal use	Electricity use	Fat feed	meat bone meal yield
	Btu/lb fat	Btu/lb fat	Btu/lb fat	Btu/lb fat	Btu/lb fat	Btu/lb fat	lb/lb fat	lb MBM/lb fat
(Dufour and Iribarren, 2012)	3,231				2,747	450	3.55	0.81
(Gooding, 2012)	2,405	1,421			3,252	518	4.93	1.08
(López et al., 2010)	2,913	1,862	14	1,531	5,372	874	3.55	0.81
(Nelson and Schrock, 1993)	5,732				4,872	418		
((S&T)2 Consultants Inc., 2011)					12,974	1,900		
((S&T)2 Consultants Inc., 2011)					2,016	593		
(CARB, 2009)					5,950	671		
(CARB, 2009)					5,816	698		
(CARB, 2009)					6,084	643		
(FPRF, 2005)					3,452	379	2	1
Selected values for GREET	**2,900**	**1,900**	**0**	**1,500**	**5,355**	**800**	**3.5**	**0.8**

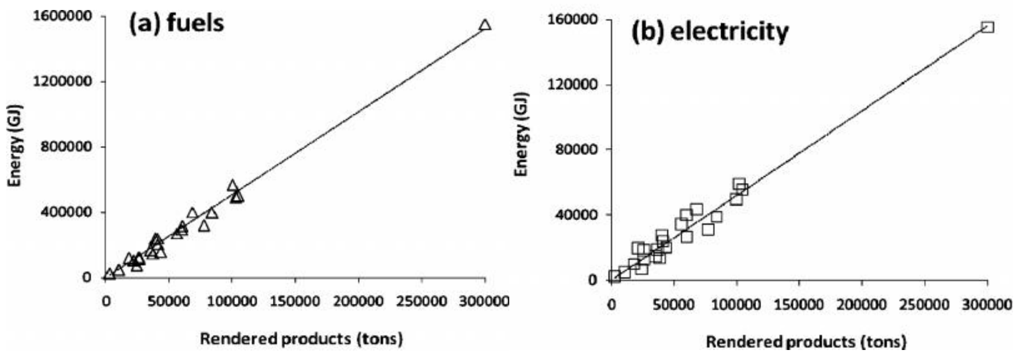
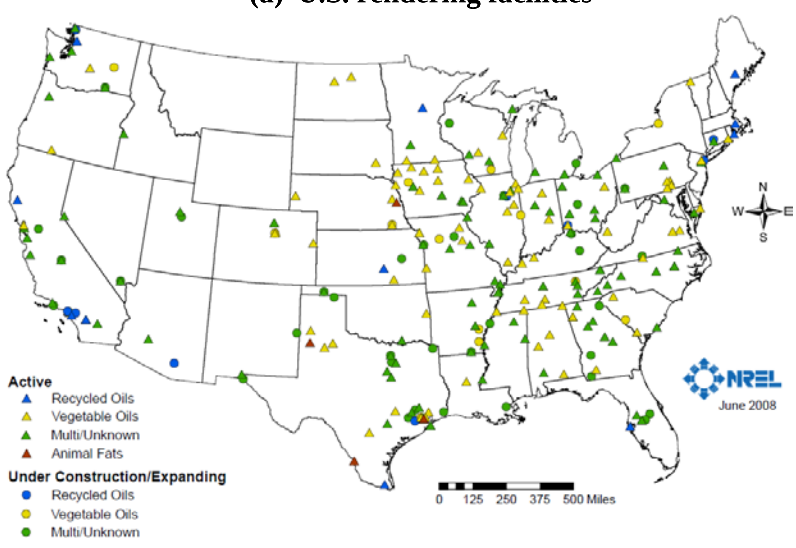


Figure 3 Energy consumed by the surveyed rendering facilities in 2007 (López et al., 2010)

(a) U.S. rendering facilities



(b) U.S. biodiesel production facilities

Figure 4 Locations of a) U.S. rendering facilities (Garcia et al. 2006) and b) biodiesel production facilities (U.S. Department of Energy, 2008)

Transportation of tallow

Figure 4 shows the locations of U.S. rendering and BD production facilities. The 28% of the more than 250 rendering facilities are located in the states of Texas, Nebraska, California, and Illinois (Garcia et al. 2006). On the other hand, only 4 BD production facilities that receive only animal fats are available in the U.S. (3 in Texas and 1 in Illinois). However, if the facilities with multiple sources are included, the BD production facilities cover ~80% of the rendering facilities within 100 miles radius, and most of the remaining facilities are located within 400 miles from the BD production facilities. Thus, assuming truck and rail are suitable and economical modes for local and long-distance transportation, respectively, this study assumes that 80% of tallow is transported by truck for 100 miles, and the rest is transported by rail for 400 miles.

Biodiesel Production

Table 5 summarizes the energy, chemical and fat uses and glycerin yield in BD production. Compared to BD production from soybean oil in GREET, animal fat conversion to BD takes much larger thermal and electrical energy. The reason for the larger energy consumption is unknown. The data from the open literature are reasonably consistent except for Nelson and Schrock (1993). Since that data is possibly outdated, this study recommends values close to the average of the values from the first three studies reported in Table 5.

Table 5 BD production energy, chemical and fat uses, and glycerin yield

	Thermal use	NG use	Electricity use	Methanol use	NaOH use	$NaOCH_3$ use	HCl use	Fat use	Glycerin output
	Btu/lb	Btu/lb	Btu/lb	Btu/lb	lb/lb	lb/lb	lb/lb	lb/lb	lb/lb
(Dufour and Iribarren, 2012)	821	N/A	92	979	0.004	0.01	0.01	1.02	0.12
(López et al., 2010)	801	106	335	864	0.004	0.01	0.01	1.01	0.10
(Nelson and Schrock, 2006)	1,013	N/A	47	928	0.001	N/A	N/A	0.99	0.10
(Nelson and Schrock, 1993)	3,826	N/A	59	874	0.010	N/A	N/A	0.99	N/A
GREET[1]		373	55	785	0.001	0.02	0.04	1.04	0.21
Selected Values for GREET		**1,100**	**160**	**920**	**0.003**	**0.01**	**0.01**	**1.01**	**0.11**

[1] GREET default value is about BD production from soybean oil (Omni Tech International, 2010).

Conclusions and Discussion

This study defines the system boundary of a tallow-based BD pathway, which consists of rendering, tallow transport and BD production. For each process, key parametric assumptions are compiled from various data sources in the open literature, and recommended values are selected for GREET simulations. A couple of outstanding issues, however, have yet to be investigated;

these are the life-cycle system boundary, and the indirect impacts of diverting tallow to fuel production and the associated displacement ratios.

As discussed in Section 2, the system boundary of tallow-based BD pathway can be defined in various ways depending on the value associated with the byproducts from the slaughtering plant. If animal growth, transport and slaughtering are included, these processes need to be carefully investigated. For example, animal feeds vary by the type of animal consuming the feed. Also, energy use and emissions associated with manure treatment should be included and allocated among all products. To handle the co-products from slaughtering plants, mass- or market value-based allocations are applicable since the co-products are not energy products and slaughterhouse by-products are not the main-product.

Currently, tallow is used as animal feed, soap, fatty acids and fuel production. If a large amount of tallow is diverted from the current use to fuel production, it may cause indirect effects, such as increase in the consumption of other crops and materials, which may warrant further investigation.

During rendering, meat and bone meal (MBM) is co-produced. This study assumes MBM performs as effectively to promote animal growth as soybean meal (SBM), thus displacing 1.2 lb of soybean per 1 lb of MBM. Because of growing concerns about bovine spongiform encephalopathy, however, most countries restrict MBM's feed use. In the U.S., MBM with ruminant tissue is used in feed for monogastric animals (e.g., poultry, swine, cat, dog and fishes) (Garcia et al. 2006). Thus, different displacement ratios would represent the practice better.

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