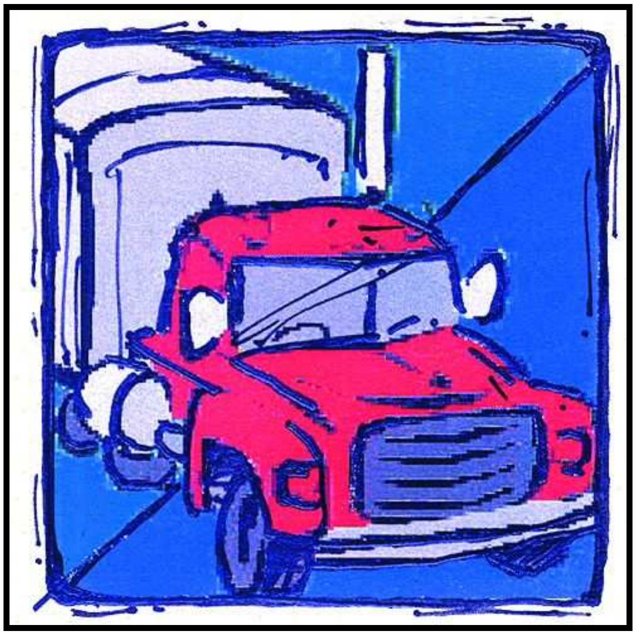
California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Renewable Diesel Produced in California from Tallow (U. S. Sourced)



Stationary Source Division

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The ARB acknowledges contributions from Life Cycle Associates (under contract with the California Energy Commission) during the development of this document

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These comments will be compiled, reviewed, and posted to the LCFS website in a timely manner.

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SUMMARY

CA-GREET Model Pathway for Renewable Diesel from Tallow

Well-To-Tank (WTT) Life Cycle Analysis of a Renewable Diesel (RD) fuel pathway (from tallow) includes steps starting from tallow being transported to a refinery and transformation to final finished fuel. Tank-To-Wheel (TTW) analysis includes actual combustion of this fuel in a heavy-duty vehicle for motive power. WTT and TTW analysis are combined to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the **Gr**eenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory was modified with assistance from Life Cycle Associates to create a modified GREET model called the CA-GREET model. The methodology inherent in the CA-GREET model was utilized to develop a WTW analysis of the conversion of tallow into Renewable Diesel (RD). The pathway documented here includes tallow transport, RD production and transport and use of 100% in a heavy-duty vehicle.

Tallow is animal fat derived from waste at a meat processing plant. Rendering produces two types: edible and inedible tallow. Edible tallow is used by the food industry and most of the inedible tallow is currently used as a supplement in animal feed. Figure 1 provides a step-wise description of the various steps in the RD from tallow pathway. For this document, only transformation of inedible tallow is considered. Any edible tallow that is generated from the rendering process is not considered as feedstock for RD production in the analysis presented in this document. The transformation of tallow to RD includes transport of tallow produced in the Mid-Western United States to a California refinery. The tallow is then co-processed with traditional crude in a refinery to produce Renewable Diesel. Though refinery output of tallow derived RD is co-mingled with Ultra Low Sulfur Diesel (ULSD), for this document, RD is considered to be uniquely produced and used as 100% RD in a heavy-duty vehicle. Combustion of RD in a heavy-duty vehicle is assumed to generate the same CH_4 and N_2O emissions as ULSD.

This document has been developed for a specific case of inedible tallow sourced from rendering operations in the Mid-Western United States transported to California via rail and co-processed in a refinery to Renewable Diesel. All inputs and assumptions used for this analysis are presented in this document. For other feedstock or processing techniques, appropriate modifications to this pathway will be required.

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[1] GREET Model: Argonne National Laboratory: http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

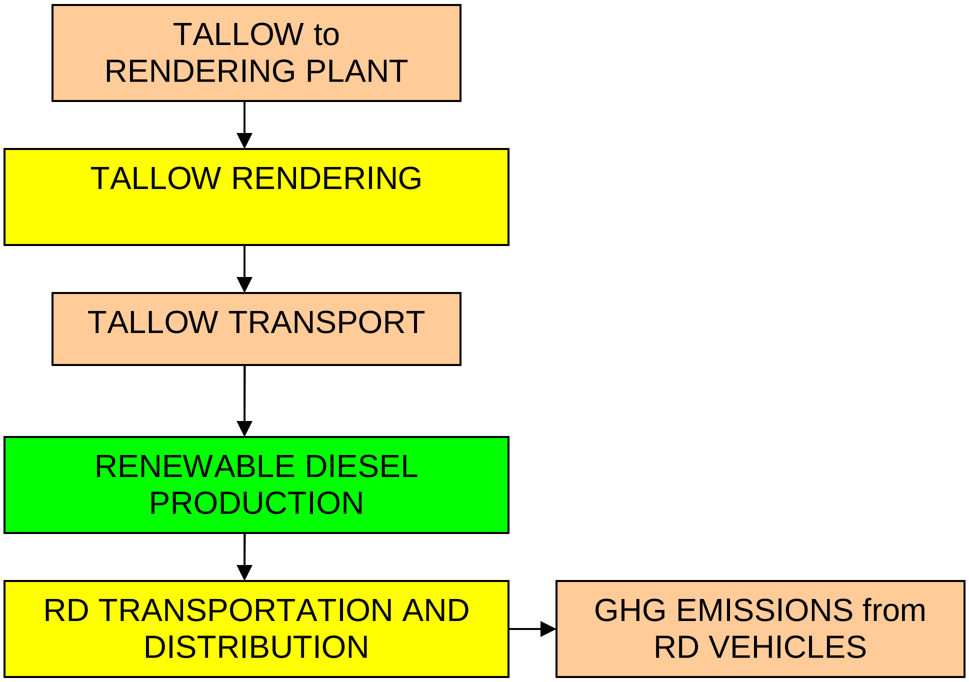


Figure 1. Discrete Components of RD from Tallow Pathway

Currently, use of inedible tallow is mostly as a supplement in animal feed. New regulations under development by the Food and Drug Administration are likely to ban the use of tallow and other animal based waste products (due to bovine spongiform encephalopathy and other similar diseases) and it is likely that use of inedible tallow as feed supplements will diminish in the future. Another factor that is contributing to the diminished use of processed animal waste as feed supplement is the greater availability of Distiller's Dried Grains with Solubles (DDGS, a by-product of ethanol production from corn), a direct result of increased production of ethanol in the United States. DDGS contains 13 to 14% corn oil (fat source) and has been priced competitively in the market relative to animal fat. Nutritionists and animal feeders are using as much DDGS as is practical in feed formulations to reduce feed costs. The increasing use of DDGS in animal feed is directly related to economics of feed and not as a consequence of animal waste being unavailable due to diversion to produce fuel. Given the two situations detailed above, it is unlikely that diversion of tallow to produce a fuel will have any indirect effects. Staff will continue to evaluate this feedstock and make adjustments as warranted.

This document provides detailed calculations, assumptions, input values, and other information required to calculate the energy use and GHG emissions for the tallow to RD pathway. The original Argonne GREET model does not include this fuel pathway. The modified CA-GREET model includes this fuel pathway. A detailed list of all input values used is provided in Appendix B.

Several general descriptions and clarification of terminology used throughout this document are:

- CA-GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, the values being calculated are often utilized in the calculation. For example, crude oil is used as a process fuel to recover crude oil. The total crude oil recovery energy consumption includes the direct crude oil consumption AND the energy associated with crude recovery (which is the value being calculated).

- Btu/mmBtu is the energy input necessary in Btu to produce one million Btu of a finished (or intermediate) product. This description is used consistently in CA-GREET for all energy calculations.

- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC Global Warming Potential (GWP) values and included in the total.

- CA-GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights. This method is also used by the IPCC.

- Process Efficiency for any step in CA-GREET is defined as:

  Efficiency = energy output / (energy output + energy consumed)

- Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the GREET model to compare actual output values from the CA-modified model with values in this document.

Table A provides a summary of the Well-To-Tank (WTT) and Tank-To-Wheel (TTW) energy use and GHG emissions for this pathway. Energy use is presented as Btu/mmBtu and GHG emissions are reported as g CO_2e/MJ, where non-CO_2 gasses (i.e., CH_4 and N_2O) are converted into CO_2 equivalents. Details of converting non-CO_2 gasses to CO_2 equivalents are detailed in Appendix A in this document.

Note: The energy inputs are presented in mmBtu because the calculations in the CA-GREET model use mmBtu.

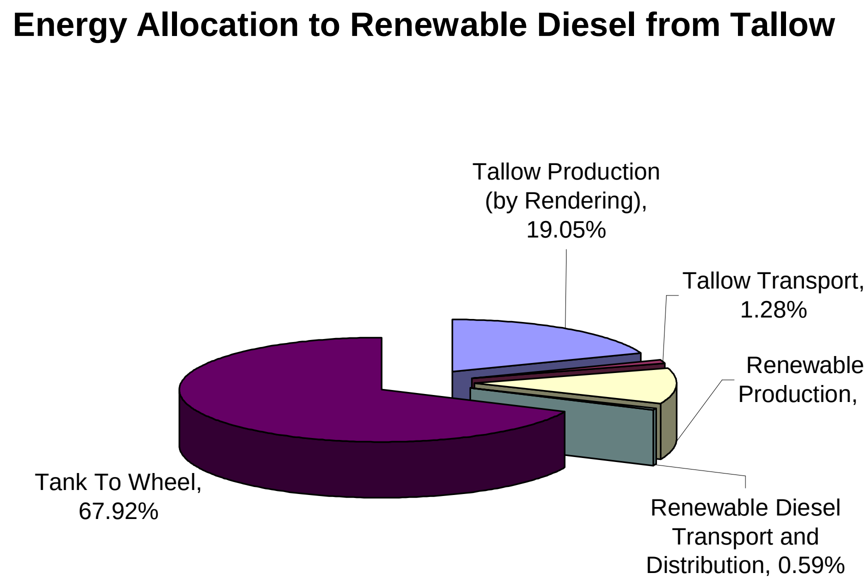
Table A. Summary of Energy Use and GHG Emissions Values for the Renewable Diesel to Tallow Pathway

	Energy Required (Btu/mmBtu)	% Energy Contribution	Emissions (gCO_2e/MJ)	% Emissions Contribution
Tallow Production (by Rendering)	280,436	19.05%	17.19	57.88%
Tallow Transport	18,826	1.28%	1.46	4.92%
Renewable Diesel Production	164,339	11.16%	9.61	32.36%
Renewable Diesel Transport and Distribution	8,662	0.59%	0.66	2.22%
Total (Well To Tank)	**472,263**	**32.08%**	**28.92**	**97.37%**
Total (Tank To Wheel)	**1,000,000**	**67.92%**	**0.78**	**2.63%**
Total (Well To Wheel)	**1,472,263**	**100%**	**29.70**	**100%**

Note: percentages may not add to 100 due to rounding

From Table A, a WTW analysis of RD from Tallow indicates that **1,472,263** Btu of energy is required to produce 1 (one) MMBtu of available fuel energy delivered to the vehicle. From a GHG perspective, **29.70** gCO_2e GHG emissions are generated during the production of 1 (one) MJ of RD.

The values in Table A are illustrated in Figure 2, showing energy use and GHG contributions of each of the discrete components of the entire fuel pathway. The charts are shown separately for energy use and GHG emissions. From an energy perspective, most of the energy is in the fuel (67.92%). From a GHG perspective, rendering of tallow generates the largest (57.88%) GHG emissions for this pathway.



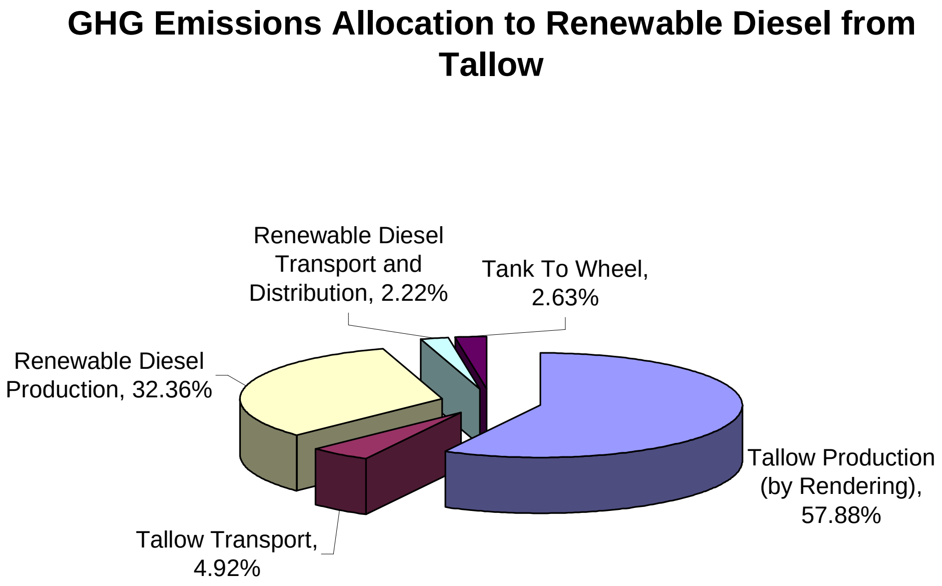


Figure 2. Percent Energy Use and GHG Emissions Contributions for the Various Components of the Renewable Diesel from Tallow Pathway

The section below provides an expanded summary of the energy use and GHG emissions for the various components of this pathway. Complete details are provided in Appendix A.

WTT Details - Rendering of Tallow

Tables B and C provide the energy use and GHG emissions from rendering of tallow respectively. Complete details are provided in Appendix A.

Table B. Total Energy Use for Tallow Rendering

Energy Result	Energy
Upstream Energy (of the fuels used in the process) (Btu/lb Tallow)	919
Direct Energy (Btu/lb Tallow)	3,881
Total Energy (Btu/lb Tallow)	**4,800**
Total Energy (Btu/mmBtu)	**280,436**

Table C. Total GHG Emissions from Rendering of Tallow

GHG Species	GHG Emissions
VOC (g /lb Tallow)	0.035
CO (g/lb Tallow)	0.19
CH_4 (g/lb Tallow)	0.532
N_2O (g/lb Tallow)	0.002
CO_2 (g/lb Tallow)	296
Total GHG Emissions (gCO_2e/mmBtu)	**19,187**
Total Adjusted GHG Emissions (gCO_2e/MJ)	**17.19**

WTT Details - Tallow Transport to RD Plant

Table D provides a breakdown of energy use for tallow transport by heavy-duty diesel truck to a rail transport facility which is then shipped via rail to California. Detailed calculations are provided in Appendix A.

Table D. Total Energy Use for Tallow Transport

Energy Result	Energy
Direct Energy for Tallow Transport (Btu/ton Tallow)	552,253
Upstream Energy from Transportation Fuel Used (Btu/ton Tallow)	90,028
Total Energy (Btu/ton Tallow)	**642,281**
Total Energy (Btu/mmBtu)	**18,826**

In a similar manner, GHG emissions associated with tallow transportation to RD production plant in CA are shown in Table E below. Additional details are provided in Appendix A.

Table E. Total GHG Emissions from Tallow Transport

GHG Species	GHG Emissions
CO_2 (Btu/ton Tallow)	1,461
CH_4 (Btu/ton Tallow)	1.639
N_2O (Btu/ton Tallow)	0.034
CO (Btu/ton Tallow)	3.74
VOC (Btu/ton Tallow)	1.09
Total GHG Emissions (gCO_2e/mmBtu)	**1,521**
Total GHG Emissions (gCO_2e/MJ)	**1.46**

WTT Details - Renewable Diesel Production

Table F shows the energy necessary for producing one million Btu of RD from tallow using the co-processing method. Additional details are provided in Appendix A.

Table F. Energy Consumed for Production of Renewable Diesel

Energy Result	Energy
Natural Gas (Btu/lb RD**)**	89
Electricity (Btu/lb RD)	264
Hydrogen (Btu/lb RD)	2,939
Total Production Energy (Btu/lb RD)	**3,291**
Total Production Energy (Btu/mmBtu)	**164,339**

Table G provides details of GHG emissions resulting from RD production. The fuel consumption and other specifics necessary for this calculation are detailed in the Appendix A.

Table G. Total GHG Emissions for Renewable Diesel Production

GHG Species	GHG Emissions
CO_2 (g/lb RD)	194
CH_4 (g/lb RD)	0.396
N_2O (g/lb RD)	0.001
CO (g/lb RD)	0.069
VOC (g/lb RD)	0.024
Total GHG Emissions (gCO_2e/MMBtu)	**10,728**
Total GHG Emissions (gCO_2e/MJ)	**9.61**

<u>WTT Details - Renewable Diesel Transport and Distribution</u>

Tables H and I provide the energy use and GHG emissions from transporting and distributing RD respectively. Details of all the calculations are presented in Appendix A.

Table H. Energy Use for RD Transportation and Distribution

Transport mode	Energy
RD transportation by truck to bulk terminal (Btu/mmBtu)	2,665
RD distribution by HDD truck (Btu/mmBtu)	5,997
Total Energy (Btu/mmBtu)	**8,662**

Table I. GHG Emissions from Transporting and Distributing RD

GHG Species	**GHG Emissions**
CO_2 (g/mmBtu)	663
CH_4 (g/mmBtu)	0.816
N_2O (g/mmBtu)	0.016
CO (g/mmBtu)	1.273
VOC (g/mmBtu)	0.281
Total GHG Emissions (gCO_2e/mmBtu)	**691.2**
Total GHG Emissions (gCO_2e/MJ)	**0.66**

TTW Details - Combusting RD in a Heavy-Duty Vehicle

Table J below provides a summary of the Tank-To-Wheel emissions from combusting 100% RD in a heavy-duty vehicle in CA. Complete details are provided in Appendix A.

Table J. TTW Emissions from Combusting RD in a Heavy-Duty Vehicle

CO_2 from fuel = **0.78** g CO_2e/MJ

APPENDIX A

Section 1. Energy Consumption and GHG Emissions Tallow Transport

1.1 Energy Use for Rendering of Tallow

Tallow is typically rendered from by-products of beef (commercial tallow could come from various sources such as cattle, sheep, pigs, etc.). Rendering plants process animal byproducts into tallow, grease, and high protein meat and bone meal. For the pathway modeled here, raising livestock for tallow is not included since tallow is a by-product of the primary reason for raising livestock. The continuous, dry rendering process consists of several steps, as shown in Figure 3. The raw materials are first conveyed to a crusher where it is reduced in size to one to two inches. It is then fed through a steam-jacketed, cylindrical vessel (the cooker) to liquefy the fat. After leaving the cooker, the fat (tallow) is drained from the protein solids. The protein solids are introduced into a screw press to remove additional fat, which is added to that already drained. The fat is then filtered or centrifuged before storage.

The rendering process for animal by-products consists of both mechanical and thermal processes. The raw material is crushed, and the finished product pressed and centrifuged or filtered, processes which require energy (electricity). The separation of the fat from the raw material is achieved by heating. Raw material is assumed to have 50% moisture.

Tallow rendering process assumptions:

- Petroleum: U.S average
- Electricity: U.S average mix
- Fuels use: 82.5% Natural Gas (for boiler), 10.9% electricity (for crusher, centrifugal, etc.), and 6.6% tallow as fuel.

Tallow properties assumptions:

- LHV: 16,075 Btu/lb
- Density: 7.5 lbs/gal

Survey data collected from 7 meat rendering plants (2 of them located in California) was provided to staff by Fred Wellons[2]. This was compared to data from published literature of the National Renderers Association, Natural Resources Canada, and Fat Proteins Research Foundation. Based on the plant data available and comparison with published literature data, the average thermal and electrical energy use of the 7 plants was used as average direct energy use for the rendering process modeled here. The energies correspond to **28,813 Btu/gal** and **0.93 KWh/gal** of thermal and electrical energy, respectively, and the calculations are shown in Table 1.01.

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[2] Wellons, Fred, Tellurian Biodiesel, Personal Communication, June 2, 2009.

Table 1.01 Rendering Energy for Production of Tallow

Rendering Energy Data Source	Thermal Energy	Electrical Energy	Notes
	Btu/gal	kWh/gal	
Survey of U.S. Rendering Plants2[3]			
Plant 1	22,921	0.819	
Plant 2	24,640	0.335	
Plant 3	22,148	0.927	
Plant 4	27,776	0.852	
Plant 5	22,943	0.886	
Plant 6	40,807	1.435	
Plant 7	40,454	1.253	
Average Plants 1-7	**28,813**	**0.930**	
Nelson and Schrock, 2006[4]	14,420	NR	Thermal energy includes energy used to generate electricity
Nelson and Schrock, undated[5]	42,857	0.900	Appears to allocate all rendering energy to fat and none to meat and bone meal
National Renderers Association, 2009[6]	16,170	NR	Assuming 50% moisture in raw material, 126,900 Btu/gallon for fat consumed
Natural Resources Canada, 2005[7]	18,836	0.736	For typical Canadian renderers; energy allocated based on mass of products
Fats Proteins Research Foundation, 2005[8]	15,247	0.278	Electricity based on soybean processing; thermal energy based on evaporation of 50% moisture in raw material

Note: NR = not reported

The direct energy and upstream energy consumption of the rendering process is calculated as shown in table 1.02. The total energy required for rendering is allocated between the rewewable diesel and co-product propane produced

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[3] Wellons, Fred, Tellurian Biodiesel, Personal Communication, June 2, 2009.

[4] Nelson, R.G. and M.D. Schrock, Energetic and Economic Feasibility Associated with the Production, Processing, and Conversion of Beef Tallow to a Substitute Diesel Fuel. Paper Accepted for Publication in *Biomass & Bioenergy 2006.*

[5] Nelson, R.G. and M.D. Schrock, Energetic and Economic Feasibility Associated with the Production, Processing, and Conversion of Beef Tallow to Diesel Fuel. Kansas State University, undated.

[6] National Renderers Association website: http://nationalrenderers.org/environmental/footprint accessed June 5, 2009.

[7] Natural Resources Canada, 2005.

[8] Fats Proteins Research Foundation, Biodiesel Advisory Board, Life-Cycle Analysis Calculation For Biodiesel Produced from Animal Fats and Recycled Cooking Oils, November 2005.

downstream of rendering. An energy allocation factor is used (94.5%), which represents the energy content of the renewable diesel yield divided by the total energy contained in the renewable diesel and propane. See Section 2 for a discussion and derivation of the energy allocation factor.

Table 1.02 Direct and Upstream Energy in Tallow Rendering Process

Inputs	Direct Energy	Upstream Energy	Total Energy
NG (heat) (Btu/lb)	((28,813 Btu/gal) / (7.5 lbs/gal))* 92.54% * 0.9 = **3,200**	223	3,422
Tallow (heat) (Btu/lb)	((28,813 Btu/gal) / (7.5 lbs/gal))* 7.46% * 0.9 =**258**	0	258
Electricity (U.S. Average) (Btu/lb)	(0.93 kWh/gal) *(3,412 Btu/kWh) /(7.5 gal/lb) = **423**	697	1,120
Total Energy (Btu/lb)	**3,881**	**919**	**4,800**
Total Energy (Btu/mmBtu)	**(3,881Btu/lb)/(16,075 Btu/lb) * 10^6 = 239,917**	**56,841**	**296,758**
Total Allocated Energy* (Btu/mmBtu)			**280,436**

Note: LHV/HLV = 0.9. Upstream energy is WTT energy of NG and electricity. Please refer to CNG from NG document and electricity document on the LCFS website for details (www.arb.ca.gov/fuels/lcfs/lcfs.htm). For the heat energy, 92.54% is from NG and 7.46% from tallow based on data provided by Fred Wellons. Total adjusted energy includes allocation (94.5%) and downstream loss factor (1.000) To convert Btu/lb RD to Btu/mmBtu RD:
[(4,800 Btu/lb RD)/(18,925 Btu/lb)*10^6 = 296,758 Btu/mmBtu RD (where 18,925 Btu/lb is RD LHV)
Adjusted Energy: 296,758*94.5% = 280,436 Btu/mmBtu

1.2 GHG Emissions from Tallow Rendering

The GHG emissions resulting from the tallow rendering process is shown in Table 1.03. The total greenhouse gas emissions are allocated to renewable diesel fuel production using the 94.5% energy allocation factor (see Section 2).

Table 1.03 GHG Emissions from Direct and Upstream Energy Used in Rendering of Tallow

Emission Species	**Direct Emissions (g/lb Tallow)**	**Upstream Emissions (g/lb Tallow)**	**Total Emissions (g/lb Tallow)**	**Total Emissions (g/mmBtu)**
VOC	0.006	0.029	0.035	2.157
CO	0.072	0.12	0.19	11.83
CH_4	0.004	0.528	0.532	32.888
N_2O	0.001	0.001	0.002	0.13
CO_2	186	109.84	296	18,301
Total Emissions	187	124	310	19,187
Total Emissions (gCO_2e/MJ)				**18.19**
Total Adjusted Emissions (gCO_2e/MJ)				**17.19**

Note:
Adjusted to Global Warming Potential: CH_4: 25, N_2O: 298, CO_2: 1
To convert from g/tallow to g/MMBtu RD:
(310 g/lb tallow)*(1.17 lbs tallow/lb RD)/(18925 Btu/lb)*10^6 = 19,187 g/MMBtu RD (where 18,925 Btu/lb is LHV of RD.

1.3 Energy Use for Transporting Tallow

Tallow is produced at a rendering plant in the Midwest and transported by heavy-duty truck to a rail station and is then transported by rail to a refinery in California. The U.S. average regional parameters are used in CA-GREET for tallow transport. The key transport energy and distance parameters are shown in Table 1.04. Using these parameters, the direct, upstream and total energy use for transport of tallow is calculated and is shown in Table 1.05.

Table 1.04 Tallow Transport Parameters

Parameters	**Heavy Duty Truck**	**Rail**
Mode Share	100%	100%
Fuel	Diesel	Diesel
Fuel Economy	5	-
Distance (mi)	10	1,400
LHV (Btu/lb)	18,925	18,925
Density (g/gal)	2,948	2,948
Energy Intensity (Btu/ton-mi)	1,713	370
Upstream Diesel Energy Factor (Btu/Btu)	0.216	0.216

Table 1.05 Direct, Upstream and Total Energy of Tallow Transport

Energy Result	Heavy Duty Truck	Rail
Direct Energy for Tallow Transport (Btu/ton tallow)	34,253	518,000
Upstream Energy from Transportation Fuel Used (Btu/ton tallow)	5,584	84,444
Total Energy (Btu/ton Tallow)	39,837	602,444
Total Energy (Btu/mmBtu RD)	**1,236**	**18,686**
Total Energy (Btu/mmBtu RD)		**19,922**
Total Adjusted Energy* (Btu/mmBtu RD)		**18,826**

Note:
Total adjusted energy includes allocation (94.5%) and downstream loss factor (1.000)
To convert Btu/ton tallow to Btu/MMBtu RD:
[(39,837 Btu/ton tallow)/(2,000 lbs/ton)*(1.17 lb tallow/lb RD)/(18,925 Btu/lb)*10^6 = 1,236 Btu/MMBtu RD
Adjusted Energy: (19,922 Btu/MMBtu RD)*94.5% = 18,826 Btu/MMBtu RD

1.4 GHG Emissions from Transport of Tallow

The analysis assumes 10 miles heavy-duty truck transport and 1,400 miles rail transport to the fuel production facility in CA. Table 1.06 provides details of direct emissions, upstream emissions, and total emissions related to transport of tallow to a refinery in California.

Table 1.06 Direct, Upstream and Total Greenhouse Gas Emissions from Tallow Transport

	Tallow Plant to Rail Station	**Transport to Refinery in CA**
Mode	Heavy Duty Truck	Rail
Mode Share	100%	100%
Distance, miles	10	1,400
Fuel	Diesel	Diesel
Energy Intensity, Btu/ton-mile	1,713	370
Direct Emissions, (g/ton tallow)		
VOC	1.029	30.925
CO	5.243	111.370
CH_4	0.052	2.041
N_2O	0.072	1.036
CO_2	2,667	40,230
Upstream Emissions, (g/ton tallow)		
VOC	0.282	4.272
CO	0.603	9.118
CH_4	3.360	50.810
N_2O	0.005	0.076
CO_2	454	6,867
Total Emissions, (g/mmBtu)		
VOC	0.041	1.092
CO	0.181	3.737
CH_4	0.106	1.639
N_2O	0.002	0.034
CO_2	97	1,461
GHG (gCO_2e/MMBtu)	101	1,521
GHG (gCO_2e/MJ)	**0.10**	**1.44**
Total GHG Emissions (gCO_2e/mmBtu)		**1.54**
Total Adjusted GHG Emissions (gCO_2e/MJ))		**1.46**

Note: To convert from g/lb tallow to g/MMBtu:
(g/ton tallow)/(2,000 lbs/ton)*(1.17 lb tallow/lb diesel)/18,925 Btu/lb RD)*10^6 = g/MMBtu RD
(where 1.17 lb tallow/lb is RD yield and 18,925 Btu/gal is assumed LHV of RD)

Section 2. Renewable Diesel Production

2.1 Energy for Renewable Diesel Production

Renewable diesel can be produced using many different methods and process configurations within a refinery. In this analysis, tallow-based renewable diesel is produced via a “coproduction process” with crude oil. Figure 3 shows the co-production configuration for RD in a refinery. The dashed box in the figure indicates the processes included in the life cycle analysis of co-produced Renewable Diesel; crude, crude processing and petroleum products are excluded from the analysis. Energy use and GHG emissions related only to RD production are considered in this section.

The co-processing method analyzed in this pathway report is not represented in the original Argonne GREET model, as GREET models only renewable diesel I (Super Cetane) and renewable diesel II (UOP standalone process). Hence, appropriate adjustments were made to include this pathway in the CA-GREET model. Figure 3 shows the steps involved in the co-processing of tallow with crude in a refinery. Assuming the feedstock is free of impurities, the tallow is first heated to reaction temperature. The heated feedstock is then comingled with the distilled crude oil stream and processed in a hydrotreater.

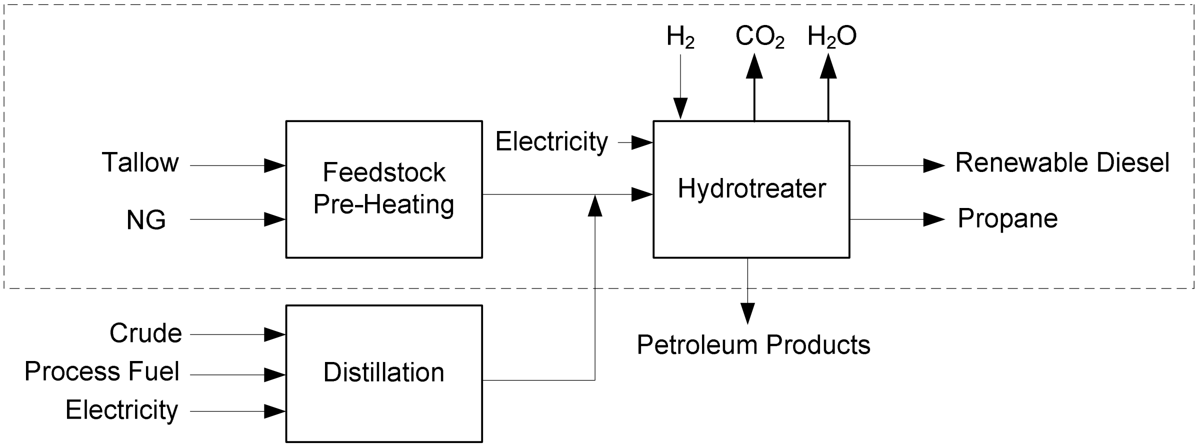

Figure 3. Co-Processing Configuration for Tallow Conversion to Renewable Diesel.

Process inputs include natural gas, electricity, and hydrogen. The process inputs are presented in Table 2.01. Natural gas assumed share is 3.8%, electricity is 6.1% (assumed from RD II pathway from GREET), and the balance is attributed to H_2. H_2 is modeled as produced at the refinery via reforming of natural gas derived from North American natural gas. California marginal electricity mix is used for the production process detailed in this section. For complete details on NG, H_2 and electricity pathways, please refer to the respective pathway documents available from the LCFS website at www.arb.ca.gov/fuels/lcfs/lcfs.htm). The hydrogen input is usually considered as the weight percent of the feedstock. Typical hydrogen requirements range 1.5 – 3.8 wt%. The analysis presented here assumes 3.8 wt% (1,960 Btu/lb feedstock) hydrogen consumption for RD production via co-processing. The direct energy consumption is 2,175 Btu/lb of RD.

Table 2.01 Direct Energy Consumption for RD Production

Process Fuel Type	**Fuel Shares**	**Calculation**	**Direct Energy Consumption**
Natural Gas	3.8%	3.8% * 2,175 (Btu/lb of RD)	83
Electricity	6.1%	6.1% * 2,175 (Btu/lb of RD)	132
Hydrogen	90.1%	90.1% * 2,175 (Btu/lb of RD)	1,960
Direct Energy Consumption for RD Production (Btu/lb)			**2,175**

The values provided in Table 2.01 are for direct energy consumption per lb of RD produced. The total energy includes the direct and upstream energy components, and the total energy requirement is then adjusted between RD and co-product based on energy content (see allocation factor calculation below)[9].

$$\text{RD Allocation Factor} = \frac{18{,}925 \text{ Btu/lb RD}}{(18{,}925 \text{ Btu/lb RD} + (18{,}568 \text{ Btu/lb propane})*(0.059 \text{ lb propane/lb RD})} = 94.5\%$$

Table 2.02 details the energy contributions from the direct and upstream energy for each fuel used in the production process and provides a total for the energy use in the production of RD in a refinery.

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[9] The allocation factor is based on propane and RD produced and energy used in the process.

Table 2.02 Direct and Upstream Energy Consumption for RD Production

Process Fuel Type	**Direct Energy (Btu/lb)**	**Upstream Energy (Btu/lb)**	**Total Energy Consumption, Btu/lb**
Natural Gas	83	$83*(1+68,861/10^6)$	89
Electricity	132	$132*(111,568+1,884,989)/10^6$	264
Hydrogen	1,960	$1,960/10^6*(10^6+71,556+427,847)$	2,939
Total Energy Consumption for RD Production (Btu/lb)			3,291
Total Energy Consumption (Btu/mmBtu RD)			173,903
Total Adjusted Energy* Consumption for RD Production (Btu/mmBtu RD)			**164,339**

Note: For values used in the Table above, please refer to the NA NG to CNG, H_2 and electricity pathway documents published in February 2009 on the Low Carbon Fuel Standard ARB website (www.arb.ca.gov/fuels/lcfs/lcfs.htm). *Adjusted energy is calculated as 173,903*94.5% = 164,339.

2.2 Greenhouse Gas Emissions from Renewable Diesel Production

Greenhouse gas emissions for RD production include direct and upstream emissions for natural gas, electricity production (only upstream for this component) and hydrogen production. California marginal electricity mix is used to calculate emissions from electricity generation. Hydrogen is modeled as being produced from the reforming of natural gas. Table 2.03 provides details of the direct and upstream emissions and also provides the total GHG emissions for the production of RD in a refinery.

Table 2.03 Direct, Upstream and Total Greenhouse Gas Emissions for RD Production

Species	**Direct Emissions (g/lb RD)**	**Upstream Emissions (g/lb RD)**	**Total Emissions (g/lb RD)**	**Total Emissions (g/MMBtu RD)**
VOC	0.000	0.024	0.024	0.077
CO	0.002	0.067	0.069	0.108
CH_4	0.000	0.396	0.396	20.87
N_2O	0.000	0.001	0.001	0.037
CO_2	5	190	194	10,194
GHG Emissions ($gCO_2e/mmBtu$)				**10,728**
Total GHG Emissions (gCO_2e/MJ)				**10.17**
Total Adjusted GHG Emissions (gCO_2e/MJ)				**9.61**

Section 3. Renewable Diesel Transport and Distribution

3.1 Energy Calculations for Renewable Diesel Transport to Retail Stations

The next step in the RD pathway is transport from the production plant in California to a retail station. Table 3.01 provides the transport assumptions and calculations for this final step.

80% of the renewable diesel is transported by heavy-duty truck 50 miles from the plant to bulk terminal; the remaining 20% is distributed directly from the plant. RD is then transported 90 miles by heavy-duty truck from the bulk terminal to refueling stations. The energy for each mode is multiplied by the mode share shown in Table 3.01 to yield the total energy. No allocation factor adjustment is made for RD transport. The calculations for transport energy and emissions are similar to that for the soyoil derived biodiesel pathway published on the Low Carbon Fuel Standard website (www.arb.ca.gov\fuels\lcfs\lcfs.htm).

Table 3.01 Parameters Used and Energy Use Results for the Transport and Distribution of RD

Parameter	Units	Plant to Bulk Terminal	Distribution	Total
Mode	-	Heavy Duty Truck	Heavy Duty Truck	
Mode Share	%	80%	100%	
Distance	Miles	50	90	
Payload	Tons	25	25	
Fuel Economy	mi/gal	5	5	
Fuel	-	Diesel	Diesel	
Fuel LHV	Btu/gal	128,450	128,450	
Energy Intensity	Btu/ton-mile	1,028	1,028	
Direct Energy (Btu/mmBtu)[1]		2,741	4,934	
Upstream Energy (Btu/mmBtu)[1]		591	1,063	
Total Energy (Btu/mmBtu)[1]		3,332	5,997	
Total Energy (Btu/mmBtu)		**2,665**	**5,997**	**8,662**

[1] Excludes mode share, which is accounted for in the total energy
Note: Energy Intensity = LHV / fuel economy / payload = 1,028 Btu/mile-ton
Direct truck energy doubles the miles to take into account round trip energy.

3.2 GHG Calculations for Renewable Diesel Transport to Retail Stations

Renewable Diesel is assumed to be transported as follows in CA-GREET:

- 80% transported 50 miles by heavy-duty diesel truck (HDD) from plants in CA to bulk terminal
- 100% distributed 90 miles by heavy-duty truck

Table 3.02 provides the direct emissions, upstream emissions (without accounting for mode share), and total emissions, accounting for mode share.

Table 3.02 GHG Emissions from Transport and Distribution of RD

	Plant to Bulk Terminal	**Fuel Distribution**	**Total Transport**
Mode	**HDD Truck**	**HDD Truck**	
Mode Share	80%	100%	
Distance, miles	50	90	
Fuel	Diesel	Diesel	
Energy Intensity, Btu/ton-mile	1,028	1,028	
GHG Species	**Emissions**	**Emissions**	
Direct Emissions[1] (g/mmBtu)			
VOC	0.082	0.148	
CO	0.420	0.755	
CH_4	0.004	0.008	
N_2O	0.006	0.010	
CO_2	213	384	
Upstream Emissions[1] (g/mmBtu)			
VOC	0.0296	0.047	
CO	0.07	0.126	
CH_4	0.310	0.557	
N_2O	0.001	0.001	
CO_2	42	75	
Total Emissions[2], (g/mmBtu)			
VOC	0.086	0.047	0.281
CO	0.392	0.126	1.273
CH_4	0.251	0.557	0.816
N_2O	0.005	0.001	0.016
CO_2	204	462	663
GHG Emissions (gCO_2e/mmBtu)	212.7	478.5	691.2
GHG Emissions (gCO_2e/MJ)	**0.20**	**0.46**	**0.66**

[1] Direct and upstream emissions exclude mode share; total emissions accounts for mode share

[2] Total Emissions accounts for mode share

Energy Intensity = LHV / fuel economy / payload

Direct truck energy doubles the miles to take into account round trip energy.

Section 4. GHG Emissions from a Renewable Diesel-Fueled Vehicle

4.1 Tailpipe Emissions from RD Combustion

When a fuel is combusted during an energy transformation process, the CA-GREET model accounts only for CO_2 emissions derived from fossil carbon in fuel. Any biologically (renewable) derived component of fuel carbon is considered to be carbon neutral. Since all of the carbon in RD is derived from a biological source (tallow), there are no attributable fossil CO_2 emissions from the RD vehicle. The only GHG emissions are from the combustion process where CH_4 and N_2O emissions are produced. For this document, combustion of 100% RD in a heavy-duty vehicle is considered to generate the same emissions as ULSD. Vehicle tailpipe emissions from the combustion process are shown in Table 4.01 (see published ULSD pathway document for complete details on tailpipe emissions from combustion)[10].

Table 4.01 Tailpipe Emissions from Combustion of RD

Details	Emissions
Tailpipe Emissions	0.78
Total GHG Emissions (gCO_2e/MJ)	**0.78**

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[10] http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

APPENDIX B

Input Values for Renewable Diesel from Tallow Pathway

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	CA-GREET Default
CH_4		25	CA-GREET Default
N_2O		298	CA-GREET Default
VOC		3.1	CA-GREET Default
CO		1.6	CA-GREET Default
Tallow or RD Transportation			
Transportation to Oil Companies			
Heavy Duty Diesel Truck		100%	CA-GREET Default
Travel Distance	miles	10	One way
Truck Energy Intensity	Btu/mile-ton	1,028	CA-GREET Calculation
Rail Transport to CA		100%	CA-GREET Default
Travel Distance	Miles	1400	CA-GREET Default
Rail Energy Intensity	Btu/mile-ton	370	CA-GREET Calculation
Transportation to Terminal			
Heavy Duty Diesel Truck		100%	One way
Travel Distance	miles	50	CA-GREET Default
Truck Energy Intensity	Btu/mile-ton	1,028	One way
Distribution to Pumps			
Heavy Duty Diesel Truck		100%	CA-GREET Default
Travel Distance	miles	90	One way
Truck Energy Intensity	Btu/mile-ton	1,028	One way
Renewable Diesel Production			
RD Allocation Factor		94.5%	CA-GREET Calculation
RD Yield	lb tallow/lb RD	1.17	CA-GREET Default
Process Shares			
Natural Gas		3.8%	CA-GREET Default
Electricity		6.1%	CA-GREET Default
Hydrogen		90.1%	CA-GREET Default
Equipment shares			
Large Industrial Boiler - Natural Gas		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/MMBtu	58,198	CA-GREET Default
Small Industrial Boiler – Natural Gas		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/MMBtu	58,176	CA-GREET Default
Gas Fuel Properties	**LHV (Btu/ft^3)**	**Density (Bt/ft^3)**	
Natural Gas	930	20.4	CA-GREET Default
Liquid Fuel Properties	**LHV (Btu/gal)**	**Density (g/gal)**	
Renewable Diesel	18,925	2,948	CA-GREET Default
Transportation Mode			
Heavy Diesel Duty Truck	tons	25	Tallow (assumed)
	tons	25	Renewable Diesel (CA-GREET Default)