Key Assumptions for the GHGenius Model Runs of Three HECO Specific Model Runs.

1. DIESEL FUEL PRODUCTION

Diesel fuel for the comparison scenario is produced in a petroleum refinery in Hawaii and is based on publicly available information. This refinery sources its crude oil from Southeast Asia, mostly from Vietnam, Thailand, China and Indonesia. The proportion of each country is shown in the following table (US EIA, 2007).

Table 1-1 Refinery Crude Oil Sources

Country	% of Total	Comments
Vietnam	55.2%	All offshore oil production
Thailand	26.9%	85% offshore.
China	9.2%	85% onshore.
Indonesia	6.9%	

The oil from all of these sources is a light sweet crude oil. The average API gravity was 37.3 and the average sulfur was reported to be 0.1% (US EIA, 2007). Not all of the countries are included in GHGenius, so for modeling purposes the Thailand and Indonesian oil is aggregated and the Vietnam and China oil is combined.

Shipping distances are calculated based on Jakarta and Shanghai as the shipping ports and Honolulu as the receiving port.

It is assumed that the diesel fuel is shipped 30 km by truck between the refinery and the power plant. It is assumed that the diesel fuel is ultra low sulfur diesel.

GHGenius has been set up to reflect this crude oil input data. No other changes to the diesel fuel pathway have been made to the model. The refinery that is modeled is the average refinery in the western United States.

The GHG emissions for the production and use of this fuel in a large diesel fired stationary engine are shown in the following table. The emissions are shown on a higher heating value basis.

Table 1-2 Life cycle Emissions Diesel Fuel

Fuel	Diesel	
Feedstock	Crude oil	
	g CO_2 eq/GJ Fuel	Comments
Fuel dispensing	0	
Fuel distribution and storage	296	Emissions related to transportation from refinery to power plant
Fuel production	9,122	Refining emissions
Feedstock transmission	2,230	Crude oil transport emissions
Feedstock recovery	5,886	Energy related emissions from crude oil production
Land-use changes, cultivation	0	
Fertilizer manufacture	0	
Gas leaks and flares	1,238	Leaks and flares associated with crude oil production
CO_2, H_2S removed from NG	0	
Emissions displaced	0	
Sub-Total	18,772	Emissions for fuel production
Combustion	76,462	
Life cycle emissions	95,234	Life cycle emissions

The energy balance calculated by the model for this fuel production pathway is shown in the following table. For every unit of energy delivered to the power plant 0.234 units of energy are consumed producing, refining and transporting the fuel. The energy expended includes the energy used to produce the energy that is used in the process. The Net Energy ratio is the inverse of the energy consumed per unit delivered. In addition to the total energy balance the fossil energy balance is also shown. In this case, any renewable energy used in the production system is not included in the calculation. For the petroleum diesel fuel the differences are relatively small.

Table 1-3 Energy Balance Petroleum Diesel Fuel

Fuel	Diesel Fuel	Diesel Fuel
Feedstock	Crude oil	Crude oil
	Total Energy	Fossil Energy
	Joules consumed/Joule delivered	
Fuel dispensing	0.0000	0.0000
Fuel distribution, storage	0.0039	0.0036
Fuel production	0.1241	0.1188
Feedstock transmission	0.0252	0.0250
Feedstock recovery	0.0831	0.0747
Ag. chemical manufacture	0.0000	0.0000
Co-product credits	0.0000	0.0000
Total	**0.2363**	**0.2221**
Net Energy Ratio (J delivered/J consumed)	**4.2319**	**4.5025**

2. PALM OIL BIODIESEL

The average production rate of the FFB is approximately 19 tonnes/ha on average, the oil extraction rate varies from 19 to 21% producing CPO yields of 3.5 to 3.9 tonnes per hectare. The production rates are dependent on the varieties of oil palm grown and the management methods. Some large scale commercial plantations with advanced breeding programs have been able to achieve yields of greater than 11 tonnes of oil/hectare and well managed plantations with conventional varieties of oil palm have achieved oil yields of 6.0 to 6.4 tonnes/hectare (Hardter). For GHGenius it will be assumed that the yield of FFB is 19 tonnes/ha.

2.1 Fertilizer Use

The fertilizer requirements for oil palm are shown in the following table (Hai). Nitrogen fertilizer is also supplied to the fields through the planting of legume cover crops that can fix up to 250 kg nitrogen per hectare of plantation and the recycling of the fronds and empty fruit bunches from the oil mills. All of this natural fertilizer must be accounted for in the model since it will lead to nitrogen emissions. The nitrogen fixed by the legumes is equivalent to 13.15 kg/tonne of fresh fruit bunches (FFB) but it may only be useful for the first five years of the plantation before the palm tree canopy reduces the sunlight needed for the legumes. It has been assumed that 3.5 kg of nitrogen is fixed per tonne of FFB produced.

Table 2-1 Oil Palm Synthetic Fertilizer Requirements

	Kg/tonne Fresh Fruit Bunches
Nitrogen	10.35
Phosphorus	1.76
Pesticides	0.44

A high level of recycling is practiced in the plantations with an estimated 80 to 95% of the pruned fronds and trunks being recycled at replanting. In addition about 65% of the empty fruit bunches recovered from oil mills are returned as organic fertilizer and mulch to the fields. One tonne of oil palm's pruned fronds returns an equivalent of 9.81 kg of potassium, 7.5 kg of nitrogen, 2.79 kg magnesium and 1.06 kg of phosphate to the soil. About 10 tonnes of pruned fronds are produced per hectare per year. In Malaysia, about 35 million tonnes of fronds are returned to the soil each year. This translates into a massive reduction in chemical fertilizer usage and prevention of environmental damage. Empty fruit bunches (EFB), which are rich in organics and potash, are also recycled back to the soil as mulch. Very little of the nutrients absorbed by the plant during growth leave the site due to the recycling of organic matter and as a result the net nutrient requirements of the palm are low.

2.2 Land Use Issues

The total biomass production from palm trees is between 40 and 45 tonnes of dry matter per hectare per year. In addition to the 19 tonnes of FFB produced each year, there are about 10 to 15 tonnes of fronds produced per hectare and the standing biomass addition ranges from 4 to 5 tonnes/ha/year. Roots account for the remainder. The ratio of total biomass to FFB has been modeled at 2.3 to 1.0.

One study has shown that an oil palm plantation assimilates 44.0 tonnes of dry matter per hectare per year compared to 25.7 tonnes of dry matter per hectare per year a rainforest assimilates. In view of this, the approach taken for modeling has been not to include any change in above or below ground biomass for oil palm cultivation. This may be a conservative approach.

Palm oil production can be expected to increase over time as older plantations with less productive varieties are replaced with new higher yielding oil palm varieties. As noted earlier, new well managed plantations can produce almost twice the oil of the industry average. For this increased production there may be an increase in above ground biomass compared to the old plantations.

In the case of soil carbon, some researchers (Mattsson) have reported that there is some loss of soil carbon in the early stages of plantation establishment but that later the decomposition of the roots increases the soil carbon. As in the case of above ground biomass no changes in soil organic carbon will be included in the base case of the model to be conservative.

2.3 Palm Oil Extraction
The palm produces three main economic products i.e., palm oil, palm kernel oil and palm kernel cake. Palm oil is extracted from the fruit mesocarp. It is mainly used for food with some industrial applications. The crude palm oil may also be refined and upgraded for some applications. The palm kernel oil and the palm kernel meal are extracted from the palm kernels. The meal is used mostly for animal feed and it has a protein content of about 17% (Sundu), the palm kernel oil is used mostly for industrial applications.

There may be multiple locations for each of these processing steps as there are more CPO mills (352) than there are kernel crushing plants (38) and oil refineries (47) (WWF, 2002). The crude palm oil mills are located close to the palm plantations as the FFB do not travel well and they must be processed within hours of harvesting to minimize any degradation of the CPO. The transportation from the plantation to the mill is assumed to be 20 km by truck.

Table 2-2 Oil Extraction Balance

	Input	Output
Fresh Fruit Bunches	100 kg	
Crude palm oil		20 kg
Palm Kernel oil		2.5 kg
Total oil		22.5 kg
Empty Fruit bunches		22 kg
Residue and nut shells		17 kg
Palm Kernel Meal		2.5 kg
Moisture		34 kg
Total	100 kg	100 kg

For the modeling it has been assumed that 4.0 kg of palm FFB are required to produce 1 liter of oil. From this quantity of FFB, 0.100 kg of palm kernel meal is produced. Both the quantity and protein level of the co-product from palm oil production are much lower than for canola and soy and thus the co-product credits for the meal can be expected to be much lower as well.

The thermal energy and electric power requirements are usually supplied by the combustion of biomass produced from the process or the gas from the anaerobic digesters. Very little detailed information on the energy requirements has been identified in the search for operating data. It would appear that the steam requirements are about 230 kg/tonne of FFB (Thailand Department of Public Works). Assuming that the combustion systems are relatively low efficiency and that electric power is produced by a steam turbine it has been assumed that 1 GJ of biomass is burned per tonne of FFB processed (0.225 kg/liter of oil produced).

Almost all oil is extracted by physical pressing and not through the solvent extraction process used for canola and soybean systems. There are therefore no hexane losses for the system.

2.4 Biodiesel Production
The conversion of palm oil to biodiesel uses the vegetable oil esterification step in the model. The values that will be used for the modeling are shown in the following table.

Table 2-3 Esterification Input for Modeling

	Power	Fuel	Methanol	Sodium Hydroxide
GHGenius	20 kWh/tonne	1500 MJ/tonne	100 kg/tonne	10 kg/tonne
	0.02 kWh/liter	35.16 L natural gas/liter	0.108 liter/liter	0.009 kg/liter

The conversion process is highly efficient and yields of biodiesel per gallon of feedstock can reach 99.5%. The input value in GHGenius has been set to provide a 98% yield.

3. RESULTS

Scenario 1: The palm oil would be grown in Malaysia, transported to Grays Harbor, Washington, converted to biodiesel and then the biodiesel would be transported to Honolulu.

The results of the analysis of the first palm oil biodiesel scenario based on the inputs described above are shown in the following table.

Table 3-1 Life cycle Emissions Palm Biodiesel Fuel

Fuel	Biodiesel	
Feedstock	Palm oil	
	g CO_2 eq/GJ Fuel	Comments
Fuel dispensing	0	
Fuel distribution and storage	1,234	Emissions related to transportation from biodiesel plant to power plant
Fuel production	5,815	Palm oil and biodiesel production emissions
Feedstock transmission	3,200	Emissions related to FFB collection and palm oil to biodiesel plant and ship
Feedstock recovery	1,864	Energy related emissions from palm oil production
Land-use changes, cultivation	13,954	Emissions related to fertilizer use
Fertilizer manufacture	4,856	Emissions related to fertilizer manufacture
Gas leaks and flares	0	Leaks and flares associated with crude oil production
CO_2, H_2S removed from NG	0	
Emissions displaced	-16,253	Co-product credit for palm protein and crude glycerin
Sub-Total	14,670	Emissions for fuel production
Combustion	8,627	Stationary diesel engines have relatively high N_2O emissions. No carbon related emissions from biofuels.
Life cycle emissions	23,297	Life cycle emissions

The energy balance information for this scenario is shown in the following table. Both the total energy balance and the fossil energy balance are presented. There is a larger difference between the two approaches with the biodiesel than the petroleum diesel because of the use of biomass to supply the energy at the palm oil extraction facility.

Table 3-2 Energy Balance Palm Biodiesel Fuel –Scenario 1

Fuel	Palm Biodiesel	Palm Biodiesel
Feedstock	Palm oil	Palm oil
	Total Energy	Fossil Energy
	Joules consumed/Joule delivered	
Fuel dispensing	0.0000	0.0000
Fuel distribution, storage	0.0147	0.0143
Fuel production	0.2115	0.0754
Feedstock transmission	0.0408	0.0406
Feedstock recovery	0.0164	0.0163
Ag. chemical manufacture	0.0793	0.0768
Co-product credits	-0.1652	-0.1285
Total	**0.1975**	**0.0949**
Net Energy Ratio (J delivered/J consumed)	**5.0633**	**10.5374**

Scenario 2: The palm oil would be grown in Malaysia, transported to Honolulu, converted to biodiesel and used in Honolulu.

Scenario 3: The palm oil would be grown in Malaysia, converted to biodiesel in Malaysia. The biodiesel would then be transported to Hawaii and used in Honolulu.

The palm oil could be shipped directly to Hawaii and converted into biodiesel there or it could be converted to biodiesel in Malaysia and shipped to Hawaii. This would reduce some of the shipping requirements (~6,720 km) and reduce the related GHG emissions. The Hawaii plant would not have natural gas so diesel fuel has been used to supply the biodiesel requirements instead. The life cycle emissions for this scenario are shown in the following table. There is very little difference in the emissions for these two scenarios.

Table 3-3 Life cycle Emissions Palm Biodiesel Fuel – Scenario 2 and 3

Fuel	Biodiesel	Biodiesel	
Feedstock	Palm oil	Palm oil	
Manufacturing	Malaysia	Hawaii	
	g CO_2 eq/GJ Fuel		Comments
Fuel dispensing	0	0	
Fuel distribution and storage	2,766	219	Emissions related to transportation from biodiesel plant to power plant
Fuel production	5,815	8,363	Palm oil and biodiesel production emissions
Feedstock transmission	482	2,757	Emissions related to FFB collection and palm oil to biodiesel plant and ship
Feedstock recovery	1,864	1,864	Energy related emissions from palm oil production
Land-use changes, cultivation	13,954	13,954	Emissions related to fertilizer use
Fertilizer manufacture	4,856	4,856	Emissions related to fertilizer manufacture
Gas leaks and flares	0	0	Leaks and flares associated with crude oil production
CO_2, H_2S removed from NG	0	0	
Emissions displaced	-16,253	-16,253	Co-product credit for palm protein and crude glycerin
Sub-Total	13,484	15,760	Emissions for fuel production
Combustion	8,627	8,627	Stationary diesel engines have relatively high N_2O emissions. No carbon related emissions from biofuels.
Life cycle emissions	22,111	24,387	Life cycle emissions

The energy balance information for the case where the biodiesel is manufactured in Malaysia is shown in the following table. The results are better than the Washington state case due to the reduced transportation distances involved.

Table 3-4 Energy Balance Palm Biodiesel Fuel –Scenario 3 Malaysia Plant

Fuel	Palm Biodiesel	Palm Biodiesel
Feedstock	Palm oil	Palm oil
	Total Energy	Fossil Energy
	Joules consumed/Joule delivered	
Fuel dispensing	0.0000	0.0000
Fuel distribution, storage	0.0322	0.0317
Fuel production	0.2115	0.0754
Feedstock transmission	0.0062	0.0061
Feedstock recovery	0.0164	0.0163
Ag. chemical manufacture	0.0793	0.0768
Co-product credits	-0.1652	-0.1285
Total	**0.1804**	**0.0778**
Net Energy Ratio (J delivered/J consumed)	**5.5432**	**12.8535**

The energy balance results for the Hawaii plant are shown in the following table.

Table 3-5 Energy Balance Palm Biodiesel Fuel –Scenario 2 Hawaii Plant

Fuel	Palm Biodiesel	Palm Biodiesel
Feedstock	Palm oil	Palm oil
	Total Energy	Fossil Energy
	Joules consumed/Joule delivered	
Fuel dispensing	0.0000	0.0000
Fuel distribution, storage	0.0031	0.0028
Fuel production	0.2166	0.0806
Feedstock transmission	0.0352	0.0350
Feedstock recovery	0.0164	0.0163
Ag. chemical manufacture	0.0793	0.0768
Co-product credits	-0.1652	-0.1285
Total	**0.1854**	**0.0830**
Net Energy Ratio (J delivered/J consumed)	**5.3937**	**12.0482**

4. DISCUSSION

There is a significant difference in the life cycle GHG emissions between petroleum derived diesel fuel and palm oil biodiesel. Most of the difference is caused by the renewable nature of the palm oil derived biodiesel.

4.1 FINDINGS

In the following table the GHG emissions for the three biodiesel scenarios is presented and compared to the petroleum diesel case. The differences in transportation emissions can be seen in the three biodiesel scenarios where the feedstock transmission and the fuel distribution emissions are lower when the biodiesel plant is built in Hawaii or Malaysia.

Table 4-1 Comparison of the Life cycle GHG Emissions of Petroleum Diesel and Palm Oil Biodiesel

Fuel	Petroleum Diesel	Biodiesel	Biodiesel	Biodiesel
Feedstock	Crude Oil	Palm oil	Palm oil	Palm oil
Manufacturing Location	Hawaii	Washington	Malaysia	Hawaii
	g CO_2 eq/GJ Fuel			
Fuel dispensing	0	0	0	0
Fuel distribution and storage	296	1,234	2,766	219
Fuel production	9,122	5,815	5,815	8,363
Feedstock transmission	2,230	3,200	482	2,757
Feedstock recovery	5,886	1,864	1,864	1,864
Land-use changes, cultivation	0	13,954	13,954	13,954
Fertilizer manufacture	0	4,856	4,856	4,856
Gas leaks and flares	1,238	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	0	-16,253	-16,253	-16,253
Sub-Total	18,772	14,670	13,484	15,760
Combustion	76,462	8,627	8,627	8,627
Life cycle emissions	95,234	23,297	22,111	24,387
% Reductions		-75.5	-76.8	-74.4
Reductions per liter of biodiesel used, kg CO_2 eq		2.7	2.7	2.6

The GHG emissions for the three biodiesel scenarios are 74.4, to 76.7% less than the petroleum pathway emissions. The use of biodiesel saves 2.6 to 2.7 kg of CO_2 eq GHG emissions for every liter of biodiesel produced and consumed.

The total energy balances for the four cases considered are shown in the following table. The biodiesel pathways are slightly more energy efficient than the petroleum diesel route.

Table 4-2 Total Energy Balance Comparison

Fuel	Diesel Fuel	Palm Biodiesel	Palm Biodiesel	Palm Biodiesel
Feedstock	Crude oil	Palm Oil	Palm Oil	Palm Oil
Manufacturing Location	Hawaii	Washington	Malaysia	Hawaii
	Joules consumed/Joule delivered			
Fuel dispensing	0.0000	0.0000	0.0000	0.0000
Fuel distribution, storage	0.0039	0.0147	0.0322	0.0031
Fuel production	0.1241	0.2115	0.2115	0.2166
Feedstock transmission	0.0252	0.0408	0.0062	0.0352
Feedstock recovery	0.0831	0.0164	0.0164	0.0164
Ag. chemical manufacture	0.0000	0.0793	0.0793	0.0793
Co-product credits	0.0000	-0.1652	-0.1652	-0.1652
Total	**0.2363**	**0.1975**	**0.1804**	**0.1854**
Net Energy Ratio (J delivered/J consumed)	**4.2319**	**5.0633**	**5.5432**	**5.3937**

The fossil energy balance for the four cases is shown in the following table. The biodiesel pathways are considerably better than the petroleum diesel case.

Table 4-3 Fossil Energy Balance Comparison

Fuel	Diesel Fuel	Palm Biodiesel	Palm Biodiesel	Palm Biodiesel
Feedstock	Crude oil	Palm Oil	Palm Oil	Palm Oil
Manufacturing Location	Hawaii	Washington	Malaysia	Hawaii
	Joules consumed/Joule delivered			
Fuel dispensing	0.0000	0.0000	0.0000	0.0000
Fuel distribution, storage	0.0036	0.0143	0.0317	0.0028
Fuel production	0.1188	0.0754	0.0754	0.0806
Feedstock transmission	0.0250	0.0406	0.0061	0.0350
Feedstock recovery	0.0747	0.0163	0.0163	0.0163
Ag. chemical manufacture	0.0000	0.0768	0.0768	0.0768
Co-product credits	0.0000	-0.1285	-0.1285	-0.1285
Total	**0.2221**	**0.0949**	**0.0778**	**0.0830**
Net Energy Ratio (J delivered/J consumed)	**4.5025**	**10.5374**	**12.8535**	**12.0482**

References

Energy Information Administration. 2007. http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/company_level_imports/historical/2007/data/impa07d.xls

Hai, Teoh Cheng. Selling the Green Palm Oil Advantage. Oil Palm Industry Economic Journal. Volume 4, Number 1. 2004. http://palmoilis.mpob.gov.my/publications/opiejv4n1-teoh.pdf

Hardter, R., Fairhurst, T. Introduction. http://www.ppippic.org/ppiweb/filelib.nsf/0/77993A376614AA4D48256D7900335327/$file/01%20HF%20Intro.pdf

Mattsson, B., Cederberg, C., Blix, L. 2000. Agricultural Land use in Life Cycle Assessment (LCA): Case Studies of Three Vegetable Oil Crops. Journal of Cleaner Production, 8 (2000) 283-292. http://doi.eng.cmu.ac.th/Thailca/pdf/Agricultural_land_use_in_LCA.pdf

Sundu, B., Dingle, J. Use of Enzymes to Improve the Nutritional Value of Palm Kernel Meal and Copra Meal. Proceedings of Queensland Poultry Science Symposium Australia, Vol 11 (14) 1-15. http://www.idp.com/adsjakarta/returnedstudents/BSundu01.pdf

Thailand Department of Public Works. Environmental Management Guideline for the Palm Oil Industry. http://www.elaw.org/assets/pdf/th.palm.oil.industry.guidelines.pdf

World Wildlife Federation. 2002. The Palm Oil Industry in Malaysia, From Seed to Frying Pan. http://www.sustainable-palmoil.org/PDF/Resources/OP_Chain_Part%20A_new.pdf