AN EVALUATION OF MARINE BASED BIODIESEL USING GHGENIUS

Prepared For:

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Date: November 25, 2004

EXECUTIVE SUMMARY

The GHGenius model has been developed for Natural Resources Canada over the past five years. It is based on the 1998 version of Dr. Mark Delucchi's Lifecycle Emissions Model (LEM). GHGenius is capable of analyzing the emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels.

GHGenius is capable of estimating life cycle emissions of the primary greenhouse gases and the criteria pollutants from combustion sources. The model is capable of analyzing the emissions from conventional and alternative fuelled internal combustion engines for light duty vehicles, for class 8 heavy-duty trucks, for urban buses and for a combination of buses and trucks, and for light duty battery powered electric vehicles. There are over 100 vehicle and fuel combinations possible with the model.

GHGenius has had pathways for the production of biodiesel from canola, soybeans, animal tallow and yellow grease. The goal of this work is to add the generic production of biodiesel from marine oils to GHGenius and to compare those results to a specific Canadian operation, Ocean Nutrition, producing marine oil biodiesel.

Ocean Nutrition produces an ethyl ester from marine oils in Nova Scotia. The process is commercially unique from several perspectives including, the use of ethanol rather than the more common methanol as the alcohol, the use of marine oils as the feedstock, and the co-processing that is carried out to produce Omega 3 oils for nutritional purposes as well as producing biodiesel.

The goal of this work is to:

- Add the commercial harvesting of fish and its reduction to proteins and oils to GHGenius.
- Add a biodiesel pathway that utilizes marine oils as the feedstock to complement the existing animal fats and vegetable oil pathways.
- Modify and expand GHGenius to allow the use of ethanol rather than methanol in the biodiesel production system. Review the literature to determine how others have addressed this issue since the carbon in the ethanol is renewable whereas in the methanol it is not. It may be that the impact is on the glycerine production and how that is ultimately used.
- Address the allocation issues raised by the co-production of biodiesel and the high value Omega-3 oils produced in the Ocean Nutrition process.

The new pathway has been fully integrated into GHGenius, for each fuel cycle the fuel will be used for heavy duty applications so the results for the new pathways are found on sheets AC, AD, Cost HDV, and Summary HDV. Sheets K and I have also been modified to include the new fuel cycles. All of the existing functionality of the model has been retained.

The new model pathway has been used to analyze a number of cases. These include a generic marine biodiesel case, the Ocean Nutrition case with system boundary conditions that include fish harvesting and reduction and a more narrow interpretation of the Ocean Nutrition situation treating the oil from the Omega 3 production as a by-product.

The high protein fishmeal that is produced as part of the fish reduction process plays an important role in the overall lifecycle emissions. The fishmeal is assumed to displace soybean meal in animal feed rations and is therefore credited with the energy and emissions associated with soybean production and crushing. There is some uncertainty about the magnitude of N_2O emissions from crops that are able to fix their nitrogen requirements from the air. The IPCC recommends treating this nitrogen the same as it does synthetic nitrogen fertilizers and Environment Canada is using this approach in determining Canada's national emission inventory. Agriculture and Agri-Food Canada have some data that suggests that this approach overestimates emissions and they are advocating treating N_2O from nitrogen fixing bacteria differently from other sources of nitrogen. The issue is under review by the IPCC and new guidelines are expected to be released in the future. The following table summarizes the lifecycle emission results using the generally accepted IPCC approach for a generic marine biodiesel process, the Ocean Nutrition process with the wide system boundaries and the Ocean Nutrition process with the narrower system boundary that treats the oil feedstock as a by-product. The GHG reductions for the production and use of marine oil biodiesel are similar those for soy biodiesel using a generic marine based biodiesel pathway with a broad system boundary. The GHG emission benefits from the specific Ocean Nutrition case are about 65% of the benefits of soy biodiesel because of the reduced co-product credit (no glycerine) and the use of ethanol rather than methanol. Taking a narrower view of the system boundary for the Ocean Nutrition process results in GHG emission reductions similar to soy biodiesel.

Table ES- 1 Summary of Results, IPCC Approach

General fuel	Petrol diesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Feedstock	Crude oil	Soy	Fish	Fish	Fish
Fuel spec (feedstock)	0.003% S	SD100	FD100	FD100	FD100
	g/mile	g/mile	g/mile	g/mile	g/mile
Approach			Generic Process	Ocean Nutrition Process	No Upstream
Vehicle operation	1,798.5	1,776.1	1,776.1	1,776.1	1,776.1
C in end-use fuel from CO_2 in air	0.0	-1,731.0	-1,731.0	-1,731.0	-1,731.0
Net Vehicle operation	1,798.5	45.1	45.1	45.1	45.1
Fuel dispensing	4.7	4.0	4.0	5.2	5.2
Fuel storage and distribution	14.0	33.5	32.4	33.0	33.0
Fuel production	179.0	374.5	1,635.5	1,802.0	377.0
Feedstock transport	49.6	61.0	113.3	116.6	0.0
Feedstock and fertilizer production	185.9	816.1	1,390.1	1,429.7	0.0
Land use changes and cultivation	0.0	1,970.8	0.0	0.0	0.0
CH_4 and CO_2 leaks and flares	69.0	0.0	0.0	0.0	0.0
Emissions displaced by co-products	0.0	-2,835.8	-2,708.0	-2,325.5	0.0
Sub total (fuelcycle)	2,300.7	469.3	512.4	1,106.0	460.3
% changes (fuelcycle)	--	-79.5	-77.6	-51.9	-80.0
Vehicle assembly and transport	17.0	17.0	17.0	17.1	17.1
Materials in vehicles	19.2	20.0	20.0	19.2	19.2
Grand total	2,337.0	506.2	549.4	1,142.3	496.6
% changes (grand total)	--	-78.3	-76.4	-51.1	-78.7

The same results are shown in the following table but using the AAFC approach to N_2O emissions. In this case, the GHG emission benefit is greatly reduced or eliminated. This shows that much of the GHG benefit from marine based biodiesel is from the N_2O emissions displaced from not growing soybeans. The possibility exists that the N_2O emission factor from nitrogen fixing crops may be reduced in the future and this would reduce the attractiveness of marine based biodiesel.

Table ES- 2 Summary of Results, AAFC Approach

General fuel	Petrol diesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Feedstock	Crude oil	Soy	Fish	Fish	Fish
Fuel spec	0.003% S	SD100	FD100	FD100	FD100
	g/mile	g/mile	g/mile	g/mile	g/mile
			Generic Process	Ocean Nutrition Process	No Upstream
Vehicle operation	1,798.5	1,776.1	1,776.1	1,776.1	1,776.1
C in end-use fuel from CO_2 in air	0.0	-1,731.0	-1,731.0	-1,731.0	-1,731.0
Net Vehicle operation	1,798.5	45.1	45.1	45.1	45.1
Fuel dispensing	4.7	4.0	4.0	5.2	5.2
Fuel storage and distribution	14.0	33.5	32.4	33.0	33.0
Fuel production	179.0	374.5	1,635.5	1,896.3	377.0
Feedstock transport	49.6	61.0	113.3	116.6	0.0
Feedstock and fertilizer production	185.9	816.1	1,390.1	1,429.7	0.0
Land use changes and cultivation	0.0	802.3	0.0	0.0	0.0
CH_4 and CO_2 leaks and flares	69.0	0.0	0.0	0.0	0.0
Emissions displaced by co-products	0.0	-1,298.5	-1,251.5	-869.3	0.0
Sub total (fuelcycle)	2,300.7	838.0	1,968.9	2,656.6	460.3
% changes (fuelcycle)	--	-63.4	-14.1	15.5	-80.0
Vehicle assembly and transport	17.0	17.0	17.0	17.1	17.1
Materials in vehicles	19.2	20.0	20.0	19.2	19.2
Grand total	2,337.0	874.9	2,005.8	2,692.9	496.6
% changes (grand total)	--	-62.4	-13.9	15.2	-78.7

The lifecycle analysis of marine based biodiesel faces a number of issues that are not present (at least to the same degree) in other fuel cycles. There are very wide variations in the harvesting practices and efficiencies of fisheries in different parts of the world. This variation is combined with very different oil yields from the fish in different regions and even from year to year in the same region. The result is that it is difficult to arrive at a reasonable case that models the global fishery. It is necessary therefore to look at the issue on a regional basis where there is a narrower range for the inputs and outputs for the process.

The energy consumed by the production of marine based biodiesel is slightly greater than that produced for the specific situation analyzed. The type of energy used as inputs is mostly diesel fuel with some electricity and the energy produced is biodiesel, which substitutes for diesel fuel. There is little net gain in the availability of diesel fuel as a result of the production and use of marine based biodiesel. There are other fuel cycles that consume almost as much energy as is produced but these cycles convert the energy from a solid or a gaseous form to a more useful liquid form. That is not the case with marine based biodiesel.

The lifecycle GHG emissions for marine based biodiesel are strongly influenced by the credits that are assigned to the fishmeal that is co-produced by the pathway. In GHGenius, a system expansion has been undertaken between soybean production and crushing and canola production and crushing to determine the allocation of energy consumption and emissions associated with soymeal production. The credits that are awarded to other protein sources in the model are based on the displacement of soybean meal in animal rations by the other protein source.

The specific marine based biodiesel pathway analyzed here produces significant GHG reductions when the IPCC guidelines are used. This benefit can be reduced or eliminated if a less efficient fishery is analyzed or if the N_2O emission factor for soybean production is reduced.

In addition to the energy and GHG emission analysis, it is worthwhile considering the production potential of fish oil. The fishmeal production data shown in the report shows no growth in the market over the past five years. A longer term look at the global fish catch shows that the capture sector has shown little growth over the past fifteen years and that all of the growth has been in the aquaculture sector.

In addition to the lack of growth in the capture segment of the world fishery, much of the fish oil is currently consumed in the aquaculture sector as part of the fish feed. The continued rapid growth in this sector will make less fish oil available to use in other applications such as biodiesel.

Given the feedstock availability issues, the wide variation in fishery practices and to a degree the uncertainty about the N_2O emissions displaced by fishmeal, governments should be careful about encouraging the development of marine based biodiesel. Specific special cases of marine based biodiesel probably do offer significant GHG emissions reductions. These special cases would usually involve fish oil that is either a co-product or clearly a waste product in the local market.

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1. INTRODUCTION

The GHGenius model has been developed for Natural Resources Canada over the past five years. It is based on the 1998 version of Dr. Mark Delucchi's Lifecycle Emissions Model (LEM). GHGenius is capable of analyzing the emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels.

GHGenius is capable of estimating life cycle emissions of the primary greenhouse gases and the criteria pollutants from combustion sources. The specific gases that are included in the model include:

- Carbon dioxide (CO_2),
- Methane (CH_4),
- Nitrous oxide (N_2O),
- Chlorofluorocarbons (CFC-12),
- Hydro fluorocarbons (HFC-134a),
- The CO_2-equivalent of all of the pollutants above.
- Carbon monoxide (CO),
- Nitrogen oxides (NOx),
- Non-methane organic compounds (NMOCs), weighted by their ozone forming potential,
- Sulphur dioxide (SO_2),
- Total particulate matter.

The model is capable of analyzing the emissions from conventional and alternative fuelled internal combustion engines for light duty vehicles, for class 8 heavy-duty trucks, for urban buses and for a combination of buses and trucks, and for light duty battery powered electric vehicles. There are over 100 vehicle and fuel combinations possible with the model.

GHGenius can predict emissions for past, present and future years through to 2050 using historical data or correlations for changes in energy and process parameters with time that are stored in the model. The fuel cycle segments considered in the model are as follows:

- Vehicle Operation
  Emissions associated with the use of the fuel in the vehicle. Includes all greenhouse gases.
- Fuel Dispensing at the Retail Level
  Emissions associated with the transfer of the fuel at a service station from storage into the vehicles. Includes electricity for pumping, fugitive emissions and spills.
- Fuel Storage and Distribution at all Stages
  Emissions associated with storage and handling of fuel products at terminals, bulk plants and service stations. Includes storage emissions, electricity for pumping, space heating and lighting.
- Fuel Production (as in production from raw materials)
  Direct and indirect emissions associated with conversion of the feedstock into a saleable fuel product. Includes process emissions, combustion emissions for process heat/steam, electricity generation, fugitive emissions and emissions from the life cycle of chemicals used for fuel production cycles.
- Feedstock Transport
  Direct and indirect emissions from transport of feedstock, including pumping, compression, leaks, fugitive emissions, and transportation from point of origin

to the fuel refining plant. Import/export, transport distances and the modes of transport are considered.

- Feedstock Production and Recovery
  Direct and indirect emissions from recovery and processing of the raw feedstock, including fugitive emissions from storage, handling, upstream processing prior to transmission, and mining.
- Fertilizer Manufacture
  Direct and indirect life cycle emissions from fertilizers, and pesticides used for feedstock production, including raw material recovery, transport and manufacturing of chemicals. This is not included if there is no fertilizer associated with the fuel pathway.
- Land use changes and cultivation associated with biomass derived fuels
  Emissions associated with the change in the land use in cultivation of crops, including N_2O from application of fertilizer, changes in soil carbon and biomass, methane emissions from soil and energy used for land cultivation.
- Carbon in Fuel from Air
  Carbon dioxide emissions credit arising from use of a renewable carbon source that obtains carbon from the air.
- Leaks and flaring of greenhouse gases associated with production of oil and gas
  Fugitive hydrocarbon emissions and flaring emissions associated with oil and gas production.
- Emissions displaced by co-products of alternative fuels
  Emissions displaced by co-products of various pathways. System expansion is used to determine displacement ratios for co-products from biomass pathways.
- Vehicle assembly and transport
  Emissions associated with the manufacture and transport of the vehicle to the point of sale, amortized over the life of the vehicle.
- Materials used in the vehicles
  Emissions from the manufacture of the materials used to manufacture the vehicle, amortized over the life of the vehicle. Includes lube oil production and losses from air conditioning systems.

GHGenius uses mostly US units of measurements. The results in this report are presented in the units that are produced by the model. The model inputs specified in the report are given in the units that the model requires. Where appropriate some input data are also presented in metric units.

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addressed this issue since the carbon in the ethanol is renewable whereas in the methanol it is not. It may be that the impact is on the glycerine production and how that is ultimately used.

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2. MARINE OIL PRODUCTION

The global annual catch of fish and shellfish is about 90 million tonnes. Of this total, 27 million tonnes is caught to produce fishmeal and fish oil as opposed to human food (Fishmeal Information Network). With about 6 million tonnes of trimmings from food fish processing this produces a total of 33 million tonnes of fresh raw fish used to produce fishmeal and fish oil. Raw fish has a very high moisture content so the products of the fish reduction industry are currently approximately 6.2 million tonnes of fishmeal and 1.2 million tonnes of oil each year. There are some 400 dedicated factories around the world. The main producing and exporting countries are Peru, Chile, Iceland, Denmark and Norway.

2.1 SYSTEM DESCRIPTION

The overall process to produce marine based biodiesel has been modelled in a two-step process. In the first step, the fish are harvested and reduced to fishmeal and fish oil. In the second step, the fish oil is converted to biodiesel. This approach is taken for two reasons, first there has been some experimentation with the use of fish oil (and vegetable oils) in engines without the esterification step (Steigers) and having the intermediate results would enable this fuel use to be added to GHGenius in the future quite easily. Secondly, more flexibility can be built into the model with a two-step process. The existing one step biodiesel pathways will be converted to this approach in the near future.

The fish oil production system includes the catching of the fish and the reduction of the fish into fishmeal and fish oil. The focus of this discussion is on the South American fishery, as that is the source of most of the fish oil imported to Canada. The GHGenius model is flexible so that if data for other fisheries are available they too can be modelled.

In the first step, the feedstock for marine oil is raw fish and the feedstock recovery and feedstock transmission stages are combined and reported as feedstock recovery in the model. The fuel production stage for fish oil is the reduction of the fish to fishmeal and fish oil. In the second step of the process the “fuel produced” in the first step becomes the feedstock for the second step of esterification to biodiesel. As noted above the fish oil could also be used directly as a fuel. Only the esterification pathway is examined in this report.

Information on the world production of fishmeal is summarized in the following table (USDA). It can be seen that Peru and Chile are the world’s largest fishmeal producers with about 40% of the world’s production.

Table 2-1 World Fishmeal Production

	1999/2000 1,000 tonnes	2000/2001 1,000 tonnes	2001/2002 1,000 tonnes	2002/2003 1,000 tonnes	2003/2004 1,000 tonnes (p)[1]	2004/2005 1,000 tonnes (f)[2]
Peru	2,380	1,873	1,768	1,179	1,360	1,365
Chile	832	790	800	750	775	760
EU-25	521	527	503	514	503	500
Others	483	449	429	390	401	394
China	500	500	500	400	400	380
Thailand	360	380	380	370	360	370
Japan	330	338	346	346	305	305
Iceland	272	284	325	265	300	300
United States	210	250	250	250	250	255
Norway	280	280	252	250	248	250
South Africa	84	84	84	84	84	84
Ecuador	79	90	65	75	75	75
World Total	6,331	5,845	5,702	4,873	5,061	5,038

Unlike fishmeal, the yield of fish oil per tonne of raw fish processed can vary widely. Depending on the species being processed, the time of year, the general condition of the fish and the efficiency of the recovery process, oil yield rates can vary from lows of just 2% to highs of 16%. Globally, average yield rates typically range between 3 and 5%. Of the 1.0 to 1.25 million tonnes of fish oil produced each year, 55 to 70% of it is currently used in the production of aquaculture feeds (Barlow). Only 10% of the fish oil is used for industrial applications. The remainder is used for edible and pharmaceutical applications. Fishmeal and fish oil production have been mostly static for the past decade and the industry believes it has reached a plateau. The availability of fish oil for biodiesel production may therefore be limited.

2.2 PRODUCTION INPUTS

The production inputs are discussed below for each of the two stages of marine oil production.

2.2.1 Feedstock Recovery

Between 75 and 90% of total energy inputs to commercial fisheries take the form of direct fuel inputs for vessel propulsion, gear deployment and in some cases limited on-board processing (Tyedmers). For simplicity, only direct fuel inputs associated with the fish harvesting stage are modelled and these are assumed to be exclusively diesel fuel. Fuel consumption per mass of fish caught varies considerably with the location, species being caught, technology employed on the vessel, vessel size and other factors. The fuel

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[1] Preliminary
[2] Forecast

consumption can range from a low of 20 litres/tonne of raw fish to a high of 3,400 litres/tonne of fish (Tyedmers).

Reduction fisheries, such as those of South America, are more energy efficient than fisheries that focus on fish for human consumption. In the Atlantic, the energy consumption ranges from 20 to 110 litres/tonne for species such as herring and menhaden (Tyedmers).

There is little public information on the fuel consumption of the Peruvian and Chilean reduction fishery fleets. One recent report (Bloomberg) claimed that the average fuel consumption for the 900 vessels involved in the Peruvian industry was about 50 gallons of diesel per tonne of fishmeal produced. This is equivalent to 43 litres (11.4 USG/tonne) of diesel per tonne of fish caught. This is a reasonable value compared to the range reported above for the Atlantic fishery and is used for the modelling done here.

The fish are processed in reduction plants in Peru and Chile to produce fishmeal and fish oil. The environmental impact of reduction facilities in Peru was reported by Bimbo as part of a cooperative effort of several Peruvian agencies and the US EPA. The mass balance for the process is shown in the following table.

Table 2-2 Mass Balance Fish Reduction

	Solids	Fats	Moisture	Total
Raw Fish	200 kg	90 kg	710 kg	1,000 kg
Fishmeal	200 kg	14 kg	17 kg	231 kg
Fish Oil	0 kg	76 kg	0 kg	76 kg
Condensate			487 kg	488 kg
Dryer Exhaust			200 kg	200 kg
Total Output	200 kg	90 kg	704 kg	994 kg

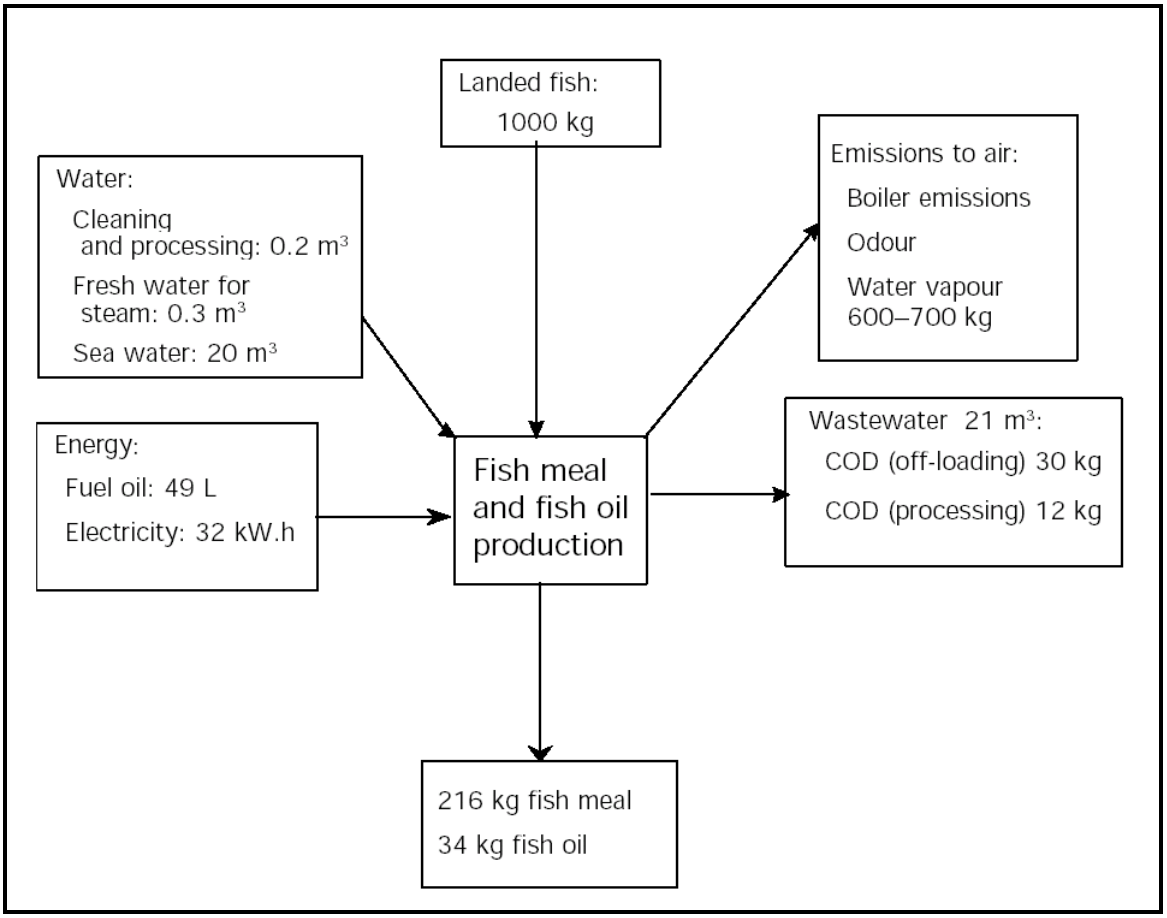
The harvesting energy of 43 litres per tonne of fish is thus equivalent to 0.566 litres/kg of fish oil or 0.497 litres of diesel fuel per litre of fish oil. This is a very high energy consumption rate but considerable fish protein is co-produced as well as the fish oil. This is not a global average energy consumption figure but one that is specific to the South America industry.

There are a number of factors that could influence the results if other fisheries were being considered. Note that the fish oil yield of the Peruvian industry (7.6%) is about double the global average (3.6%). There are also fisheries that use more diesel fuel than is being modelled here. Some fisheries that focus on human consumption might discard a portion of their catch because of lack of markets for all species. These factors could all influence the results and if other fisheries were modelled, the results could be considerably different.

2.2.2 Fish Oil Production

The energy requirements for the reduction facility were not provided in the Bimbo report. Two additional sources of information were found for fish reduction facilities. COWI provided mass and energy balances for fish reduction facilities in Europe. That information is shown in the following figure. Note that the different fishery has a different meal and oil yield compared to the South American fishery.

Figure 2-1 Mass and Energy Balance Fish Reduction



The FAO (1986) reported on energy consumption for various sizes and designs of fish processing plants. The fuel oil and electric power consumptions are summarized in the following tables.

Table 2-3 Fuel Oil Consumption Fish Reduction

Size of plant: raw material (tonne/24 h)	Fuel oil consumption (kg) per tonne of raw material		
	Presscake meal	Whole meal	
	Without evaporation plant	With evaporation plant	With additional waste recovery heat
10-60	35	55	-
100-200	34	50	44
250-500	33	48	41
More than 500	30	45	38

Table 2-4 Electric Power Consumption

Size of plant: raw material (tonne/24 h)	kWh consumption per tonne of raw material	
	Without evaporation plant	With evaporation plant
10- 60	30	35
100- 200	28	33
250- 500	26	31
More than 500	25	30

The Peruvian industry appears to utilize evaporators according the information in the Bimbo report but did not utilize advanced heat recovery. The typical plant size reported was 600 t per day. The expected energy consumption based on the FAO report would be 45 kg (53 litres) of fuel oil per tonne of fish (0.613 USG/USG fish oil) and 30 kWh/tonne of fish (1.31 kWh/USG fish oil). These values are very close to those reported by COWI and will be used in the modelling.

Again note that when the energy consumption is expressed on the basis of energy per unit of fish oil the oil yield becomes an important part of the equation. Fisheries other than the South American region will use more energy per unit of fish oil produced due to the lower oil yields in the reduction process.

2.3 ALLOCATION PROCESS

The primary product produced by the reduction plants is fishmeal both in volume and in revenue, however for transportation fuel applications the product that is of interest is the fish oil. Fishmeal is a high protein meal that is used primarily in animal feed. The composition of fishmeal will vary with species but the typical composition of the product is shown and compared to soybean meal in the following table (FAO).

Table 2-5 Fishmeal Composition

	Soya 45% protein	White Fishmeals	Herring type Fishmeals	S. American type Fishmeals
Proximate Analysis (%)				
Moisture	10.5	10.0	8.0	10.0
Crude protein	45.9	65.0	72.0	65.0
Crude fat	1.4	5.0	9.0	9.0
Crude ash	5.9	20.0	10.0	16.0
Crude fibre	5.7	0	0	0
Energy Content				
Poultry M.E. MJ/kg	9.0	12.1	14.0	13.2
Pigs M.E. MJ/kg	15.6	15.6	18.5	16.8
Ruminants M.E. MJ/kg	11.7	13.6	16.4	13.1

Fishmeal has a higher protein content than soybean meal and has a higher level of ruminant by-pass protein as well. Fishmeal protein has been shown in feed trials to perform similarly to soymeal protein (Broderick). The meal is used in aquaculture feeds as well as in feed for poultry, swine and ruminants. The disposition of the meal use is shown in the following table (Barlow). While vegetable protein meals are not generally used in aquaculture feeds, they are widely used in poultry and swine feeds with soybean meal being the dominant protein meal used.

Table 2-6 Fishmeal Disposition

	Percent
Aquaculture	34
Poultry	27
Swine	29
Ruminants	1
Other	9

GHGenius includes the production of soybeans and crushing of the beans to produce oil and meal. The allocation of energy and emissions for soybeans is undertaken through a systems expansion process with canola production and crushing. This system expansion allows the energy associated with the cultivation and crushing of soybeans and canola to be calculated without any assumptions or arbitrary allocations. The allocation process is described in the GHGenius User Manual ((S&T)^2)but the primary equation that results from the process is:

Energy Credit SBM=1.61*Energy required for SB milling- 0.73*Energy for Canola Milling

A similar equation can be developed for Canola meal based on the displacement factor between canola meal and soybean meal:

Energy Credit Canola Meal=1.21*Energy required for SB milling- 0.55*Energy for Canola Milling

Note that the system expansion process ties together the soybean and canola systems so that changes in one of the pathways influences the energy credits (and thus the emissions) of the other system. This is one of the iterative calculation processes within GHGenius and it makes the model dynamic, where changes in one pathway will influence the results of another pathway.

Soybean meal is the dominant feedstock in the world protein meal trade contributing about 70% of the 210 million tonne market (Agriculture and Agri-Food Canada). For the fishmeal, it will be assumed that the material displaces soybean meal on a protein equivalent basis. Therefore, one kilogram of fishmeal will displace 1.4 kg of soybean meal. The high by-pass protein of fishmeal and its high lysine value make it a more attractive feed component than soybean meal so this displacement ratio should be conservative. The credit for fishmeal can therefore be represented as:

Energy Credit Fishmeal=2.25*Energy required for SB milling- 1.02*Energy for Canola Milling

The energy required for the cultivation and crushing of both soybeans and canola influence the energy and emissions credit that is applied to fishmeal.

To produce one kilogram of fish oil requires 13.16 kilograms of fish and co-produces 3.04 kilograms of fishmeal. For one kilogram of fish oil, the energy consumed and emissions resulting from the production of 4.26 kg of soybean meal (1 USG fish oil equals 22.3 lbs. fish meal) are credited against the energy and emissions from the harvesting and production of fishmeal and the net result is the energy and emissions for fish oil.

One of the areas of greatest uncertainty in lifecycle analysis is the GHG emissions from agricultural soils. The mechanisms involved are complex and difficult to measure. GHGenius follows the revised IPPC guidelines for estimating the emissions associated with fertilizer application and soil use. Some of the emission factors used by the IPCC are based on limited data and many of the emission mechanisms would appear to vary with factors such as soil type, drainage, rainfall and other environmental factors. There are many, including Agriculture and Agri-Food Canada, who think that the IPCC emission factors overestimate N_2O emissions from agricultural soils. If that is the case then in GHGenius all protein sources will be impacted because they are all credited with the emissions avoided by displacing soybean meal. The IPCC is currently evaluating the issue and more guidance may become available in the future. The current IPCC approach is the most widely accepted and should be used until more definitive information is available.

The different approaches create a significant difference in emissions for soybeans, and since other protein meals are credited with the emissions displaced by soymeal production they are impacted as well. Fishmeal produced in South America is likely to displace soybean meal produced in the US or South America rather than any Canadian soybean meal production. GHGenius is capable of modelling both approaches and the results will be shown later for both approaches.

2.4 MODEL INPUTS

The inputs for the model are done on a per gallon of fish oil produced basis to be consistent with the other biodiesel production pathways. The input data described above is summarized in the following table on this basis.

Table 2-7 Model Inputs

Stage	Input per USG Fish Oil	Input per USG Fish Oil
Fish Harvesting		
Diesel Fuel	1.88 litres	0.497 USG
Fish Reduction		
Diesel Fuel	2.32 litres	0.613 USG
Electricity	1.31 kWh	1.31 kWh
Co-products		
Fish Meal	10.11 kg	22.3 lbs.

The energy requirements for harvesting and processing of raw fish are quite high which is not unexpected considering the large amount of water that must be transported and evapourated in the reduction process. The quality of data on the energy consumed in the reduction process is thought to be reasonable since it is based on multiple well researched sources. The data quality for the harvesting portion of the lifecycle is lower since it is based on a single reference in the popular press rather than scientific publications.

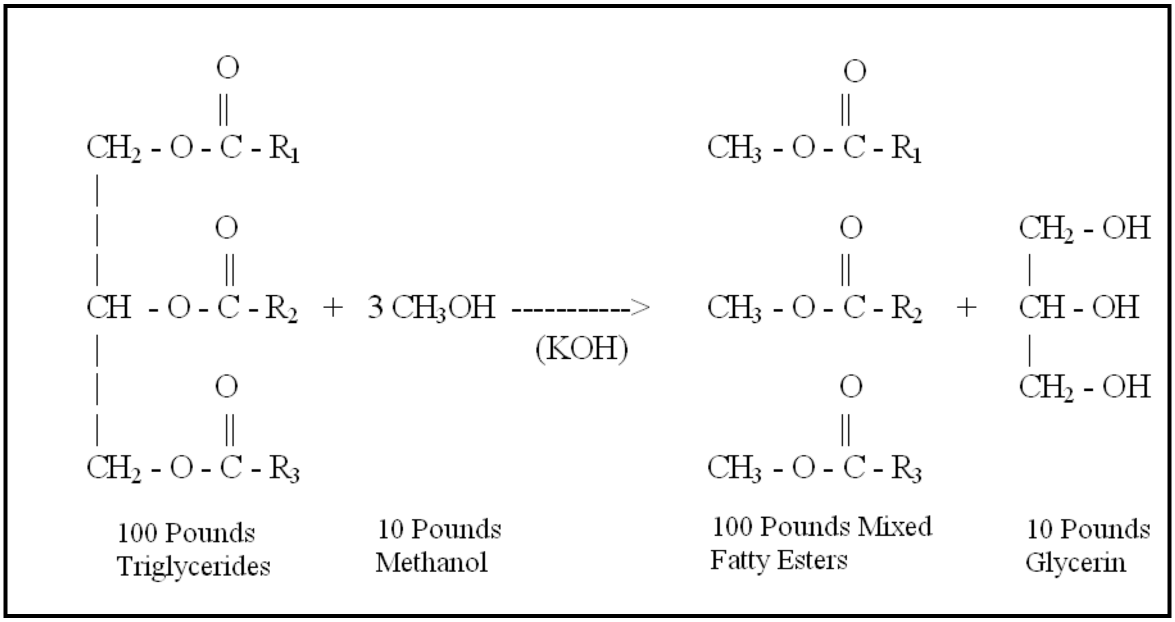
The energy requirements for the reduction of fish will be a function primarily of the moisture content of the fish but when they are expressed on the basis of fish oil produced then the oil yield becomes an important parameter. The South American reduction fishery has oil yields double the global average and thus the results from this fishery are not necessarily applicable to other regions.

3. MARINE OIL BIODIESEL PRODUCTION

Marine oils are used to produce biodiesel by Ocean Nutrition and some marine oil has been processed by Pacific Biodiesel in Hawaii on an experimental basis (Steigers). The basic conversion process for marine oils is the same as for other biodiesel feedstocks.

The production of biodiesel, or methyl esters, is a well-known process. The basic chemical reaction is depicted below. One hundred pounds of a fat or oil is reacted with 10 pounds of methanol in the presence of a catalyst to produce 10 pounds of glycerine and 100 pounds of methyl esters or biodiesel. The methanol is charged in excess to assist in quick conversion and recovered for reuse. The catalyst is usually sodium or potassium hydroxide, which has already been mixed with the methanol. R_1, R_2, and R_3 indicate the fatty acid chains associated with an individual fat.

Figure 3-1 Basic Biodiesel Production Steps

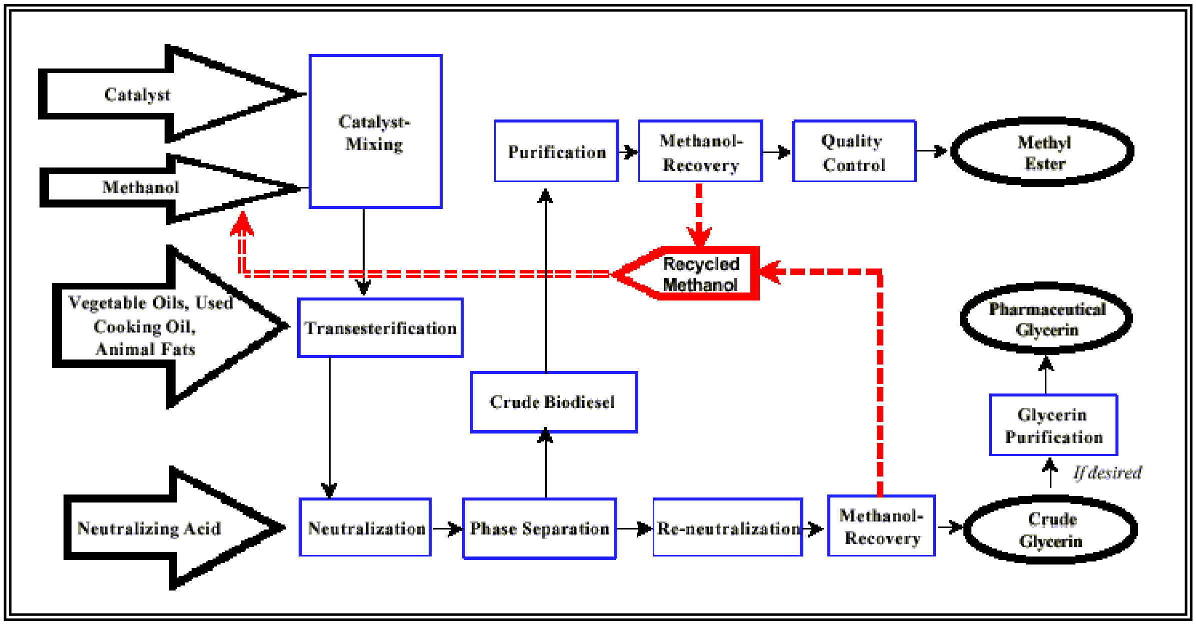


As can be seen, the mass balance is such that 100 pounds of oil or fat produces 100 pounds of methyl ester. The density of the methyl ester is 0.888 kg/litre. Thus, 100 pounds of oil produces 51 litres (13.5 US gallons) of methyl ester or 7.38 pounds of oil are required per gallon of methyl ester produced.

3.1 PRODUCTION SYSTEM

The general biodiesel production process, as described by the National Biodiesel Board (2002) shown in the following figure, consists of the following steps:

Figure 3-2 Biodiesel Production Process



Mixing of methanol and catalyst. The catalyst is typically sodium hydroxide (caustic soda). Dry caustic is dissolved in methanol by simple mixing. Care must be exercised to ensure the dry caustic (typically pellets or flakes) does not take on too much water in storage. This could cause the formation of large clumps, which are hard to dissolve. Water also has an adverse impact on downstream processing.

Reaction. The methanol/catalyst mix is then charged into a reactor, either continuously or batch, and the oil is added. The reaction mix is kept at approximately 65 °C for between 1 and 8 hours under vigorous agitation. Excess methanol is normally utilized to ensure total conversion of the fat/oil to esters. The catalyst will first react with any free fatty acids in the oil to form soap. There must be enough additional catalyst to catalyze the reaction, as well as to react with the free fatty acids. If the free fatty acid level is too high (above 0.5% to 1%), or if any water is present, the soap formed will begin to form emulsions with the methanol and oil, preventing the reaction from occurring. In some cases, the emulsion can be so strong it becomes unbreakable and forms a cottage cheese looking product. In this case, the product must be physically removed from the system and most likely scrapped. For these reasons, the incoming oil is treated to remove fatty acids and all feed streams are kept free of water.

Methanol removal. In some systems, the excess methanol is removed at this stage via a simple flash process or distillation. In other systems, the methanol is removed after the glycerine and esters have been separated. In either case, the methanol is recovered and reused using conventional equipment. Care must be taken to ensure no water accumulates in the recovered methanol stream.

Separation. Once the reaction is complete and the methanol has been removed, two major products exist: glycerine and methyl esters. Due to the density difference between glycerine (1.0 kg/l) and methyl esters (0.88 kg/l) the two are allowed to gravity separate and glycerine is simply drawn off the bottom. In some cases, a centrifuge is used to separate the two. Any rag layer is either recycled or sent to sewage treatment.

Glycerine neutralization. The resulting glycerine contains unused catalyst and soaps, which are neutralized with an acid (usually hydrochloric or phosphoric) to form salts and sent to storage as crude glycerine. In some cases (for example, if potassium hydroxide is used as the catalyst rather than sodium hydroxide and phosphoric acid is used as the quench acid), the salt is recovered for fertilizer. In most cases, however, a caustic soda catalyst and hydrochloric acid are used, creating sodium chloride, which is simply left in the glycerine. The glycerine is typically 80-88% pure and ready to be sold as crude glycerine.

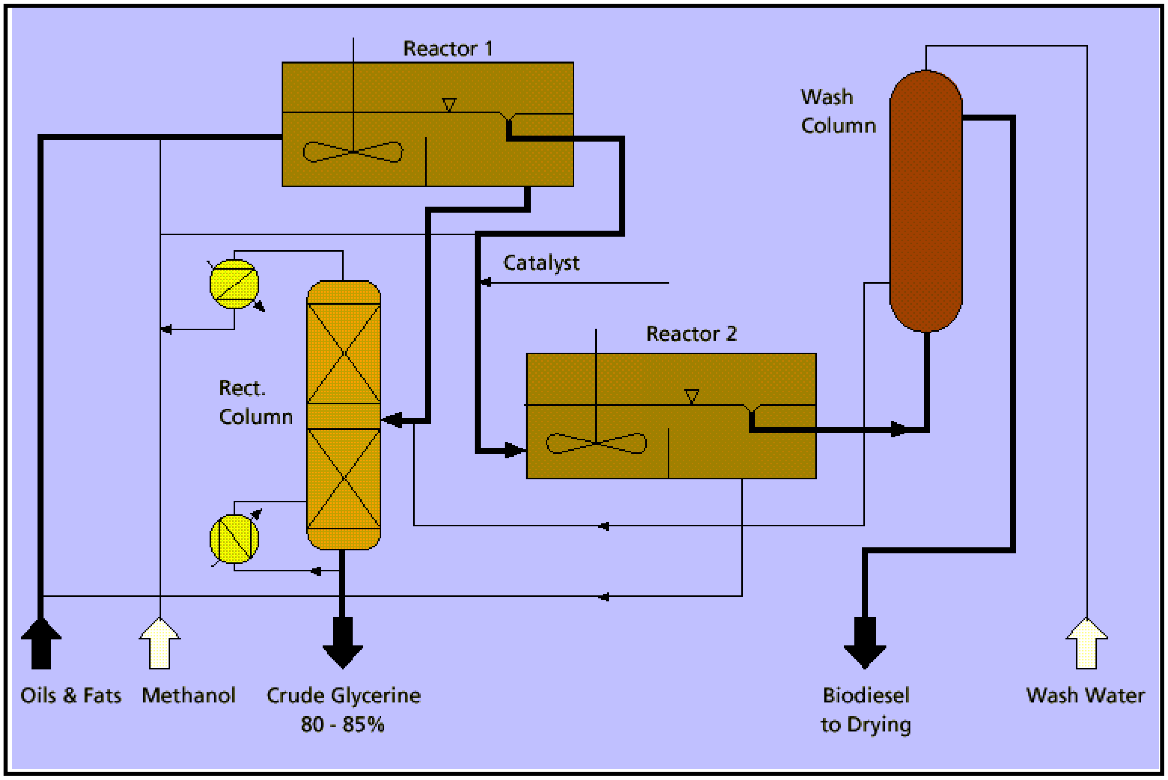
Methyl Ester Wash. Once separated from the glycerine, the methyl esters are washed gently with warm water to remove residual catalyst or soaps, dried, and sent to storage. Some processes can eliminate this washing step through the use of clean feedstock. It is typically 98% ester and ready to be sold as fuel. In some cases, the esters are distilled under vacuum to achieve even higher purity. The washing step can be greatly affected by the free fatty acid level of the feed, since all the free fatty acids form soaps in the reaction. If the soap content in the washing step is too high, a water wash will entrain the esters and yields will be diminished, sometimes severely.

3.2 PRODUCTION INPUTS

There are a number of process developers that offer biodiesel production plants. There are some small differences in the processes used and in the energy consumed.

Lurgi, a German company, is one leading developer of process technology. They offer a variety of process technologies for processing fatty acids including biodiesel production. Lurgi offer biodiesel plants in sizes from 100 to 1,000 tpd and have built a number of plants in Germany. The typical Lurgi process flow is shown in the following figure (Lurgi, Fatty Acid Technology).

Figure 3-3 Lurgi Transesterification Process



In the Lurgi process, neutralized oils and methanol are reacted in a two-stage mixer/settler arrangement in the presence of catalysts. The glycerine produced in the reaction is dissolved in the surplus methanol and can be recovered in a rectification column. Most of the glycerine and methanol are removed from the methyl ester in a counter current scrubber.

For the situation where the plant is producing crude glycerine and is processing oils with very low free fatty acid content then the process energy and chemical requirements for the production of one tonne of biodiesel are as shown in the following table (Lurgi, Biodiesel). Higher amounts of energy and materials will be required if pre-processing is necessary to reduce the free fatty acid content or to produce pharmaceutical quality glycerin.

Table 3-1 Lurgi Process Energy Requirements

Input	Requirement/tonne Biodiesel
Feedstock	1,000 kg dried, degummed, oil
Steam Requirement	415 kg
Electricity	12 kWh
Methanol	96 kg
Catalyst	5 kg
Hydrochloric acid (37%)	10 kg
Caustic soda (50%)	1.5 kg
Nitrogen	1 NM^3
Process water	20 kg

This data is also used in the model for the production of biodiesel from soy oil and Canola oil since neither of these raw materials need pretreatment.

The free fatty acid level of fish oil will depend on how it is produced and processed. It can vary from less than 1 % to up to 3%. It will be assumed that the low FFA level allows the esterification process to be similar to the vegetable oil process and the vegetable oil inputs will be used for modelling in GHGenius. On a per gallon of biodiesel produced basis the inputs are shown in the following table.

Table 3-2 Marine Oil Biodiesel System

	Requirements per gal of Biodiesel
Marine oil, lb	7.3
Natural gas, SCF	3.8
Electricity, kWh	0.04
Methanol, USG	0.108
Catalyst, lb.	0.037
Hydrochloric acid (37%), lb.	0.074
Caustic soda (50%), lb.	0.011
Nitrogen, lb.	0.206
Process water, l	0.067

The process will produce glycerine as a co-product. The amount produced is 0.74 lb. per gallon of biodiesel.

3.3 FEEDSTOCK AND DISTRIBUTION

The marine oils are produced in South America and are transported by ship to either eastern or Western Canada. The transportation distance is assumed to be 5000 miles.

The biodiesel that is produced will have to be transported to a location where it is blended with petroleum diesel and then dispensed to customers. The default values that are included in GHGenius are summarized in the following table.

Table 3-3 Finished Product Distribution

Mode	Fraction Shipped	Distance
By Rail	0.35	400
Domestic water	0.00	600
International water	0.00	0
Pipeline, tram, conveyor	0.00	500
Truck	1.00	140

3.4 CO-PRODUCT ALLOCATION PROCESS

Synthetic glycerine is produced from petrochemical building blocks via several processing steps designed to achieve the desired concentration and high product quality. One process involves chlorination and the hydrolysis of propylene.

Glycerine, whether recovered from triglycerides or synthesized, is principally used as a highly refined and purified product, with a very high concentration of glycerol. Glycerol, the main component of glycerine, has the chemical formula $C_3H_5(OH)_3$. It is a trihydric alcohol, possessing two primary and one secondary hydroxyl groups, which are its potential reaction sites and the basis for glycerine's versatility as a chemical raw material. The physical properties and characteristics of glycerin are as significant as its chemical properties for many applications. These qualities enable glycerine to be used as a humectant, plasticizer, emollient, thickener, solvent, dispersing medium, lubricant, sweetener, bodying agent, antifreeze and processing aid.

In GHGenius, the allocation of energy and emissions credits for glycerine is based on Delucchi (2003). The model calculates the replacement credit for glycerine assuming that the glycerine produced replaces synthetic glycerine. The production of one pound of synthetic glycerine requires 0.62 pounds (0.281 kg) of propylene, 2.00 pounds (0.907 kg) of chlorine, 0.45 pounds (0.204 kg) of sodium chloride, and 0.45 pounds (0.204 kg) of sodium hydroxide. The energy contents of these raw materials are 8,577, 5,319, 592, and 11,275 BTUs per pound (or 5.539, 3.435, 0.382, and 7.281 kWh per kg), respectively. Based on these figures, the energy required to produce a pound of glycerine is 21,296 BTUs (or 13.75 kWh per kg), ignoring the small amount of energy used in the final synthesis of the glycerin (the reaction is exothermic, requiring no heat or pressure, and only a small amount of electricity is used to stir the reactors), and any potential recovery of the (very inexpensive) reactants. Approximately one tenth of a pound of glycerine is produced for every pound of biodiesel or one gallon of biodiesel will produce 0.74 pounds of glycerin and thus replace 15,710 BTUs of energy. It should be noted that Delucchi has used 17,010 BTUs in his documentation and model although the calculation would suggest a lower value.

In Bioenergy for Europe: Which Ones Fit Best? (Reinhardt) the authors have proposed the same approach of substituting synthetic glycerine for the co-product of biodiesel production. The actual value used is not given in the report but a review of the spreadsheet used for calculation shows a total of 44,465 BTU/lb. of glycerine was used as a credit for coal, oil and natural gas.

We will use the value of 15,710 BTUs per gallon of biodiesel produced since we assume that Delucchi's data came from North American production and the value is more conservative than the value from Europe. On a per million BTU of biodiesel produced basis, the energy credit for glycerine production is 118,547 BTU.

4. OCEAN NUTRITION BIODIESEL

Ocean Nutrition Canada is a wholly owned subsidiary of Clearwater Fine Foods – one of North America's largest seafood harvesters, processors and exporters. Ocean Nutrition is in the business of discovering, manufacturing and marketing marine based ingredients, which improve human health. One of the products that they manufacture and market are Omega 3 fatty acids. These are extracted and concentrated from marine oils. These Omega 3 products are available in three forms, ethyl esters, triglycerides, or free fatty acid forms.

The ethyl esters result from breaking apart the original triglyceride molecules through the esterfication process, which Ocean Nutrition calls ethylation. This is done to increase or concentrate the level of Omega-3, while removing less-desired fatty acids. The triglyceride form consists of either unconcentrated fish oil, or concentrated fish oil that has been reconverted (re-esterified) back to the triglycerides form. The free fatty acid form results from saponification and neutralization of the triglycerides, whereby the glycerol backbone is severed, leaving only the free fatty acid.

4.1 PRODUCTION SYSTEM

Ocean Nutrition uses a unique multi-step process for producing concentrated Omega-3 fish oils and the co-product biodiesel.

- **Raw Material Acquisition.** The fish oils are sourced from South America.
- **Deodorization.** Removes heavy metals, PCBs and other unwanted elements for cleaner, scent-free oil with no aftertaste. Also removes free fatty acids from the feedstock.
- **Esterification.** Undertakes an esterification process with ethanol to produce the ethyl esters.
- **Molecular distillation.** Completely refines the oil and ensures removal of man-made pollutants such as PCBs in both standard and concentrated oils. As in any distillation process, it is based on molecular weight fractionation. This step separates and concentrates the Omega 3 product for food and nutrition supplements from the biodiesel portion.
- **Winterization.** Removes saturated fats present in the raw oil, leaving a clear-coloured oil with more long-chain fatty acids and no saturated fat.

There are several unique aspects to the Ocean Nutrition system that differentiate the process from other biodiesel producers.

- Ethanol is used as the alcohol rather than the more common methanol.
- The biodiesel is a co-product of the nutritional supplements.
- The process thermal energy is supplied by burning a portion of the biodiesel produced rather than a fossil fuel.
- The glycerine produced is not extracted for sale but is currently disposed of in the facility's waste water treatment facility.

To accommodate these unique aspects several enhancements have been made to GHGenius. These include:

- The addition of ethanol as an ingredient for the production of alternative fuels on Sheet X.
- The separation of the portion of biodiesel co-products that adds to new production into different factors for glycerine and protein meals on Sheet Y. This will allow the elimination of glycerine as a co-product.

GHGenius can handle the use of the produced biodiesel as the fuel on Sheet X so no fundamental changes were required to deal with this aspect.

4.2 PRODUCTION INPUTS

The production inputs for the Ocean Nutrition process are shown in the following table.

Table 4-1 Process Inputs

Input	Per Litre Biodiesel	Per USG Biodiesel
Fish oil	2 kg	2.27 USG
Ethanol	0.56 kg	0.71 USG
Catalyst	0.018 kg	0.15 lbs.
Citric acid	0.04 kg	0.33 lbs.
Electricity	0.50 kWh	1.89 kWh
Biodiesel	0.057 kg	6.4 %
Clay	0.026 kg	0.22 lbs.

The process produces about 55% Omega 3's and 45% biodiesel. The glycerine produced by the process is not collected.

4.3 ALLOCATION

There are several allocation processes that could be chosen for the Ocean Nutrition case. The Omega 3 could be treated as a co-product and credited with the energy and emissions avoided by the displacement other of sources of Omega 3 with this source of Omega 3. While this approach is actually preferred in LCA work, it is dependent on data on alternative Omega 3 production processes that is not readily available and the investigation of these alternative pathways is beyond the scope of this work. Other methods of allocation used in LCA work include the mass method, the volume allocation and using the financial value of the products to allocate energy and emissions. The financial value is usually regarded as the least attractive allocation process. Because of the high value of the Omega 3, that allocation process would see more of the upstream energy and emissions allocated to Omega 3 than to biodiesel. The approach used here will be the mass allocation method.

There is little difference chemically between the biodiesel production and the Omega 3 production other than the molecular weights of the ethyl ester chains. The inputs can therefore be allocated based on the weight of the two products being produced. The allocated inputs for 100% biodiesel production are therefore as shown in the following table.

Table 4-2 Allocated Process Inputs

Input	Per Litre Biodiesel	Per USG Biodiesel
Fish oil	0.88 kg	1 USG
Ethanol	0.25 kg	0.32 USG
Catalyst	0.008 kg	0.07 lbs.
Citric acid	0.018 kg	0.15 lbs.
Electricity	0.22 kWh	0.85 kWh
Biodiesel	0.025 kg	6.4 %
Clay	0.011 kg	0.22 lbs.

Almost all biodiesel LCA performed have assumed that the biodiesel is 100% produced from biomass in spite of the use of methanol as a process input. It is rationalized that the fossil carbon in the methanol is part of the glycerine co-product and since the glycerine displaces synthetic glycerine, there would be no change in the emissions from the ultimate end disposal of the glycerine. In the case of the use of ethanol produced from biomass as the input, this would not be the case and if the glycerine were being collected, there would be an additional credit for the production of the glycerine. In the Ocean Nutrition situation, the glycerine is not collected but rather oxidized in the wastewater treatment plant so there is no glycerine credit and no changes need to be made to the model. The biodiesel is clearly made from 100% biomass.

5. RESULTS

The results for marine oil biodiesel are presented in several parts, the first describes the use of marine oils in a conventional biodiesel plant using methanol and producing glycerine as a co-product. The second considers the unique aspects of the Ocean Nutrition facility and the third considers the impact of alternative system boundaries.

GHGenius has been set using 2004 as the year and the default values for most of the settings. The crude oil is the crude oil consumed in Canada and the sulphur content of the diesel fuel is set to 300 ppm. For the base case Canada is modelled by setting the Country Weight factors for Canada East to 0.2, Canada Central to 0.5 and Canada West to 0.3.

5.1 GENERIC MARINE BIODIESEL

The generic marine oil biodiesel facility uses the assumptions presented in the previous sections. Marine oils are produced by the South America reduction fishery and are shipped to Canada for processing into biodiesel and glycerine in a Lurgi type process.

Marine oils have more long chain triglycerides than animal fats and vegetable oils and this may impact the final fuel properties. A small amount (<5,000 USG) of biodiesel has been produced from Alaska fish oil and analyzed (Steigers). The characteristics of that material are compared to other biodiesel (NREL, 2003) in the following table. The T90 is higher than other biodiesel and potentially problematic from a standards compliance perspective. The other characteristics are similar to vegetable oil biodiesel.

Table 5-1 Marine Biodiesel Characteristics

Parameter	ASTM Standard	Marine Biodiesel	Soy Biodiesel	Tallow Biodiesel
Viscosity	1.9-6.5 cSt.	4.4	4.55	4.93
Copper Strip Corrosion	3	1B	1A	1A
Cetane	47 min	49.4	47.2	61.7
T90	360 °C	379°C	364°C	359°C
Cloud Point	Report	-1°C	2°C	23°C

5.1.1 Energy Balance

The energy balance for the generic marine biodiesel facility is shown in the following table. The results are compared to petroleum diesel and soyoil biodiesel. In the marine based biodiesel case the fish harvesting is shown as feedstock recovery and the fish reduction and fish oil esterification is combined in the fuel production stage. This is consistent with the treatment of soybean crushing and esterification. The same treatment is used in the energy balance results tables, the upstream GHG emission result tables and the full cycle emission results tables.

The biodiesel from fish oil has a negative energy balance primarily due to the high-energy consumption in both the fish harvesting and fish oil production stages. The high moisture content of the fish has a significant impact on both of these stages. The co-product credits for the fishmeal are similar to those for the soybean crushing. The higher per pound credit for the high protein fishmeal is offset by the lower protein to oil ratio of the fish compared to soybeans resulting in a very similar result.

Table 5-2 Energy Balance

Fuel	Hwy diesel	Biodiesel	Biodiesel
Feedstock	Crude oil	Soybeans	Fish Oil
	BTU consumed/BTU Produced	BTU consumed/BTU Produced	BTU consumed/BTU Produced
Fuel dispensing	0.0018	0.0020	0.0020
Fuel distribution, storage	0.0045	0.0107	0.0107
Fuel production	0.0785	0.1576	0.6931
Feedstock transmission	0.0089	0.0191	0.0419
Feedstock recovery	0.1002	0.2071	0.5138
Ag. chemical manufacture	n.a.	0.0834	0.0000
Co-product credits	0.0000	-0.2248	-0.2192
Total	**0.19**	**0.26**	**1.04**

The energy balance would still be very poor, but not negative, even if less diesel fuel were used in the fish harvesting stage of the lifecycle. On the other hand, lower oil yields would reduce the amount of oil produced for the same inputs and the energy balance would become much more negative. The quality of the data for the feedstock recovery stage can effect the energy balance conclusion significantly so care must be taken in interpreting these results.

5.1.2 Greenhouse Gas Emissions

The upstream (well to tank) greenhouse gas emission results for marine oil biodiesel are presented in the following table. Comparisons are provided to soy biodiesel and petroleum diesel fuel. For the two biodiesel fuels, the results are presented for both the generally accepted IPCC assumptions regarding N_2O and for Agriculture and Agri-Food Canada's approach. The difference between the two approaches is larger for marine oils than it is for soy biodiesel since in the soy case, the land use emissions change as well as the co-product emissions, and thus they partially offset each other. For the marine oils, there are no offsetting emissions and the emissions are strongly impacted by the different approaches. The diesel fuel from crude oil will have emissions of approximately 72,000 grams/million BTU that will have to be accounted for in the combustion process whereas the biodiesel fuels have close to zero emissions that have to be accounted for resulting from combustion.

Table 5-3 Upstream GHG Emissions Marine Biodiesel

Fuel	Hwy diesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Feedstock	Crude oil	Soy Bean	Soy Bean	Fish Oil	Fish Oil
		IPCC N_2O	AAFC N_2O	IPCC N_2O	AAFC N_2O
	g/million BTU	g/million BTU	g/million BTU	g/million BTU	g/million BTU
Fuel dispensing	150	164	164	164	164
Fuel distribution & storage	512	1,378	1,378	1,331	1,331
Fuel production	7,059	15,389	15,389	67,203	67,203
Feedstock transmission	1,006	2,507	2,507	4,657	4,657
Feedstock recovery	8,896	27,270	27,270	57,119	57,119
Land-use changes, cultivation	0	80,982	32,966	0	0
Fertilizer manufacture	0	6,265	6,265	0	0
Gas leaks and flares	2,680	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0
Emissions displaced	0	-116,522	-53,357	-111,271	-51,425
Total	20,302	17,431	32,582	19,203	79,049

The biodiesel can be used as a fuel as B100 or as a blend with petroleum diesel. In the following table the GHG emissions for B100 are compared on the basis of distance driven. These results are compared to petroleum diesel and for the two approaches to N_2O emissions. The GHG emissions are reduced by 76.4% compared to petroleum diesel fuel in the case using the IPCC emission rates for N_2O but are reduced by only 13.9% for the case using the AAFC approach regarding N_2O emissions from nitrogen fixing crops. For lower level blends of biodiesel and petroleum diesel the GHG emissions are reduced on a proportional basis to the biodiesel portion of the blend.

The difference in results is much larger for the marine oils than it is for the vegetable oil biodiesel and the attractiveness of this feedstock is largely dependent on which approach to N_2O emissions is most appropriate. The IPCC approach is the most widely accepted at this time.

Table 5-4 Full Cycle GHG Emissions Marine Biodiesel

General fuel	Petrol diesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Fuel spec	0.003% S	SD100	SD100	FD100	FD100
Feedstock	Crude oil	Soy	Soy	Fish	Fish
	g/mile	g/mile	g/mile	g/mile	g/mile
Approach		IPCC N_2O	AAFC N_2O	IPCC N_2O	AAFC N_2O
Vehicle operation	1,798.5	1,776.1	1,776.1	1,776.1	1,776.1
C in end-use fuel from CO_2 in air	0.0	-1,731.0	-1,731.0	-1,731.0	-1,731.0
Net Vehicle operation	1,798.5	45.1	45.1	45.1	45.1
Fuel dispensing	3.6	4.0	4.0	4.0	4.0
Fuel storage and distribution	12.4	33.5	33.5	32.4	32.4
Fuel production	171.7	374.5	374.5	1,635.5	1,635.5
Feedstock transport	24.5	61.0	61.0	113.3	113.3
Feedstock and fertilizer production	216.4	816.1	816.1	1,390.1	1,390.1
Land use changes and cultivation	0.0	1,970.8	802.3	0.0	0.0
CH_4 and CO_2 leaks and flares	65.2	0.0	0.0	0.0	0.0
Emissions displaced by co-products	0.0	-2,835.8	-1,298.5	-2,708.0	-1,251.5
Sub total (fuelcycle)	2,292.3	469.3	838.0	512.4	1,968.9
% changes (fuelcycle)	--	-79.5	-63.4	-77.6	-14.1
Vehicle assembly and transport	16.9	17.0	17.0	17.0	17.0
Materials in vehicles	19.9	20.0	20.0	20.0	20.0
Grand total	2,329.2	506.2	874.9	549.4	2,005.8
% changes (grand total)	--	-78.3	-62.4	-76.4	-13.9

5.2 OCEAN NUTRITION BIODIESEL

For the specific case of the Ocean Nutrition biodiesel, the GHGenius model has been set to model fuel production in eastern Canada. The crude oil input has also been set to Canada East. The other aspects of the petroleum cycle have been kept the same as for the generic marine biodiesel process.

The Ocean Nutrition biodiesel process has been modelled with ethanol used rather than methanol, biodiesel as the energy source for production and no glycerine co-product.

5.2.1 Energy Balance

The energy balance is shown in the following table. The results are compared to petroleum diesel and soyoil biodiesel. The soy biodiesel values are the same as shown in the generic case and have not been modelled for an eastern Canada case since soybeans are produced primarily in central Canada.

The biodiesel from fish oil has a negative energy balance primarily due to the high-energy consumption in both the fish harvesting and fish oil production stages. The high moisture content of the fish has a significant impact on both of these stages. The co-product credits for the fishmeal are similar to those for the soybean crushing. The higher per pound credit for the high protein fishmeal is offset by the lower protein to oil ratio of the fish compared to soybeans resulting in a very similar result. There is no energy credit for the glycerine compared to the generic case and thus the overall energy balance is worse. Again, it must be remembered that it is the South American fishery that is being modelled and not the global average fishery. Other fisheries could have different energy balances depending on the oil yield and the energy consumed in harvesting.

Table 5-5 Energy Balance Ocean Nutrition Biodiesel

Fuel	Hwy diesel	Biodiesel	Biodiesel
Feedstock	Crude oil	Soybeans	Fish Oil
	BTU consumed/BTU Produced	BTU consumed/BTU Produced	BTU consumed/BTU Produced
Fuel dispensing	0.0018	0.0020	0.0020
Fuel distribution, storage	0.0049	0.0107	0.0107
Fuel production	0.0735	0.1576	0.7219
Feedstock transmission	0.0179	0.0191	0.0428
Feedstock recovery	0.0727	0.2071	0.5246
Ag. chemical manufacture	n.a.	0.0834	0.0000
Co-product credits	0.0000	-0.2248	-0.1006
Total	**0.17**	**0.26**	**1.20**

5.2.2 Greenhouse Gas Emissions

The upstream (well to tank) greenhouse gas emission results for Ocean Nutrition biodiesel are presented in the following table. Comparisons are again provided to soy biodiesel and petroleum diesel fuel. The soy diesel results are the same as those shown earlier and are for a Canada case rather than an Eastern Canada case. This accounts for some of the differences in emissions in the individual stages. For the two biodiesel fuels, the results are presented for both the generally accepted IPCC assumptions regarding N_2O and for Agriculture and Agri-Food Canada's approach. The difference between the two approaches is again larger for marine oils than it is for soy biodiesel since in the soy case the land use emissions change as well as the co-product emissions and they partially offset each other. For the marine oils there are no offsetting emissions and the emissions are strongly impacted by the different approaches.

Table 5-6 Upstream GHG Emissions Ocean Nutrition Biodiesel

Fuel	Hwy diesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Feedstock	Crude oil	Soy Bean	Soy Bean	Fish Oil	Fish Oil
		IPCC N_2O	AAFC N_2O	IPCC N_2O	AAFC N_2O
	g/million BTU	g/million BTU	g/million BTU	g/million BTU	g/million BTU
Fuel dispensing	195	164	164	214	214
Fuel distribution & storage	575	1,378	1,378	1,355	1,355
Fuel production	7,358	15,389	15,389	74,042	77,918
Feedstock transmission	2,039	2,507	2,507	4,789	4,789
Feedstock recovery	7,644	27,270	27,270	58,747	58,747
Land-use changes, cultivation	0	80,982	32,966	0	0
Fertilizer manufacture	0	6,265	6,265	0	0
Gas leaks and flares	2,836	0	0	0	0
CO_2, H_2S removed from NG	0	0	0	0	0
Emissions displaced	0	-116,522	-53,357	-95,556	-35,718
Total	20,648	17,431	32,582	43,591	107,306

The biodiesel can be used as a fuel as B100 or as a blend with petroleum diesel. In the following table the GHG emissions for B100 are compared on the basis of distance driven. These results are compared to petroleum diesel and for the two approaches to N_2O emissions. The GHG emissions are reduced by 51.1% compared to petroleum diesel fuel in the case using the IPCC emission rates for N_2O but are increased by 15.2% for the case using the AAFC approach regarding N_2O emissions from nitrogen fixing crops.

The emissions for the Ocean Nutrition Process are negatively impacted by the lack of the glycerine co-product and the higher emissions associated with the production of ethanol rather than methanol. The use of biodiesel rather than fuel oil in the production process has little impact because of the high emissions associated with the fish harvesting and reduction stages.

Table 5-7 Full Cycle GHG Emissions Ocean Nutrition Biodiesel

General fuel	Petrol diesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Fuel spec	0.003% S	SD100	SD100	FD100	FD100
Feedstock	Crude oil	Soy	Soy	Fish	Fish
	g/mile	g/mile	g/mile	g/mile	g/mile
Approach		IPCC N_2O	AAFC N_2O	IPCC N_2O	AAFC N_2O
Vehicle operation	1,798.5	1,776.1	1,776.1	1,776.1	1,776.1
C in end-use fuel from CO_2 in air	0.0	-1,731.0	-1,731.0	-1,731.0	-1,731.0
Net Vehicle operation	1,798.5	45.1	45.1	45.1	45.1
Fuel dispensing	4.7	4.0	4.0	5.2	5.2
Fuel storage and distribution	14.0	33.5	33.5	33.0	33.0
Fuel production	179.0	374.5	374.5	1,802.0	1,896.3
Feedstock transport	49.6	61.0	61.0	116.6	116.6
Feedstock and fertilizer production	185.9	816.1	816.1	1,429.7	1,429.7
Land use changes and cultivation	0.0	1,970.8	802.3	0.0	0.0
CH_4 and CO_2 leaks and flares	69.0	0.0	0.0	0.0	0.0
Emissions displaced by co-products	0.0	-2,835.8	-1,298.5	-2,325.5	-869.3
Sub total (fuelcycle)	2,300.7	469.3	838.0	1,106.0	2,656.6
% changes (fuelcycle)	--	-79.5	-63.4	-51.9	15.5
Vehicle assembly and transport	17.0	17.0	17.0	17.1	17.1
Materials in vehicles	19.2	20.0	20.0	19.2	19.2
Grand total	2,337.0	506.2	874.9	1,142.3	2,692.9
% changes (grand total)	--	-78.3	-62.4	-51.1	15.2

5.3 ALTERNATE SYSTEM BOUNDARIES AND ALLOCATION PROCEDURES

There are alternative system boundaries and allocation processes that could be chosen for the Ocean Nutrition case as described earlier. It is always worthwhile to investigate alternative system boundaries and allocation processes as they provide additional information and context for the preferred approach.

A case could be made that the Ocean Nutrition process should have different system boundaries, that the production of Omega 3 would continue even without the production of biodiesel and that the more appropriate system boundary for the biodiesel would begin with the fish oil delivered from the Omega 3 process. This is essentially a derivation of the financial allocation process where all of the upstream energy consumption and emissions are borne by the highest value product. All of the fish harvesting and reduction emissions would be allocated to the Omega 3 production, as would the co-product credits for the fishmeal production. In this case, the N_2O emission issue is non-existent, since there are no soybean emissions displaced.

While this alternative allocation or system boundary is not the preferred means of analyzing any fuel pathway it is considered here in part because of the uncertainty over the fishmeal credit and by evaluating alternative system boundaries it puts the results from the referred procedure into context. The upstream emissions for this cycle are compared with the full cycle emissions shown earlier in the following table.

Table 5-8 Upstream GHG Emissions Ocean Nutrition Narrow System Boundaries

Fuel	Hwy diesel	Biodiesel	Biodiesel	Biodiesel
Feedstock	Crude oil	Fish Oil	Fish Oil	Fish Oil
Approach		IPCC N_2O	AAFC N_2O	No Upstream
Fuel dispensing	195	214	214	214
Fuel distribution & storage	575	1,355	1,355	1,355
Fuel production	7,358	74,042	77,918	15,492
Feedstock transmission	2,039	4,789	4,789	0
Feedstock recovery	7,644	58,747	58,747	1
Land-use changes, cultivation	0	0	0	0
Fertilizer manufacture	0	0	0	0
Gas leaks and flares	2,836	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	0	-95,556	-35,718	0
Total	20,648	43,591	107,306	17,062

For this case, the full lifecycle emissions for B100 are shown in the following table and they are compared to petroleum diesel fuel and the results from the wider system boundary. The results are comparable to those for soy biodiesel with the IPCC emission assumption. Again, this is not the preferred approach to dealing the system boundaries or allocation issues.

Table 5-9 Full Cycle GHG Emissions Ocean Nutrition Narrow System Boundaries

General fuel	Petrol diesel	Diesel Mix	Diesel Mix	Diesel Mix
Fuel spec (feedstock)	0.003% S	FD100	FD100	FD100
Production process energy	Crude oil	Oil, fish	Oil, fish	Oil, fish
	g/mile	g/mile	g/mile	g/mile
Approach		IPCC N_2O	AAFC N_2O	No Upstream
Vehicle operation	1,798.5	1,776.1	1,776.1	1,776.1
C in end-use fuel from CO_2 in air	0.0	-1,731.0	-1,731.0	-1,731.0
Net Vehicle operation	1,798.5	45.1	45.1	45.1
Fuel dispensing	4.7	5.2	5.2	5.2
Fuel storage and distribution	14.0	33.0	33.0	33.0
Fuel production	179.0	1,802.0	1,896.3	377.0
Feedstock transport	49.6	116.6	116.6	0.0
Feedstock and fertilizer production	185.9	1,429.7	1,429.7	0.0
Land use changes and cultivation	0.0	0.0	0.0	0.0
CH_4 and CO_2 leaks and flares	69.0	0.0	0.0	0.0
Emissions displaced by co-products	0.0	-2,325.5	-869.3	0.0
Sub total (fuelcycle)	2,300.7	1,106.0	2,656.6	460.3
% changes (fuelcycle)	--	-51.9	15.5	-80.0
Vehicle assembly and transport	17.0	17.1	17.1	17.1
Materials in vehicles	19.2	19.2	19.2	19.2
Grand total	2,337.0	1,142.3	2,692.9	496.6
% changes (grand total)	--	-51.1	15.2	-78.7

6. DISCUSSION

The lifecycle analysis of marine based biodiesel faces a number of issues that are not present (at least to the same degree) in other fuel cycles. There are very wide variations in the harvesting practices and efficiencies of fisheries in different parts of the world. This variation is combined with very different oil yields from the fish in different regions and even from year to year in the same region. The result is that it is difficult to arrive at a reasonable case that models the global fishery. It is necessary therefore to look at the issue on a regional basis where there is a narrower range for the inputs and outputs for the process.

The addition of the marine based biodiesel to the GHGenius model has been carried out with the flexibility to model any fishery. This report has used the model to analyzed one specific region, the South America fishery. This region would appear to be one of the more energy efficient and produce the highest oil yield. The results reported are therefore better than those that could be expected from other regions.

GHGenius can calculate the energy balance; the criteria air emissions and the GHG emissions for fuel production pathways. Of particular interest for this work are the energy balance and the GHG emissions results.

The energy consumed by the production of marine based biodiesel is slightly greater than that produced for the specific situation analyzed. The type of energy used as inputs is mostly diesel fuel with some electricity and the energy produced is biodiesel, which substitutes for diesel fuel. There is little net gain in the availability of diesel fuel as a result of the production and use of biodiesel. There are other fuel cycles that consume almost as much energy as is produced but these cycles convert the energy from a solid or a gaseous form to a more useful liquid form. That is not the case with marine based biodiesel.

The lifecycle GHG emissions for marine based biodiesel are strongly influenced by the credits that are assigned to the fishmeal that is co-produced by the pathway. In GHGenius, a system expansion has been undertaken between soybean production and crushing and canola production and crushing to determine the allocation of energy consumption and emissions associated with soymeal production. The credits that are awarded to other protein sources in the model are based on the displacement of soybean meal in animal rations by the other protein source.

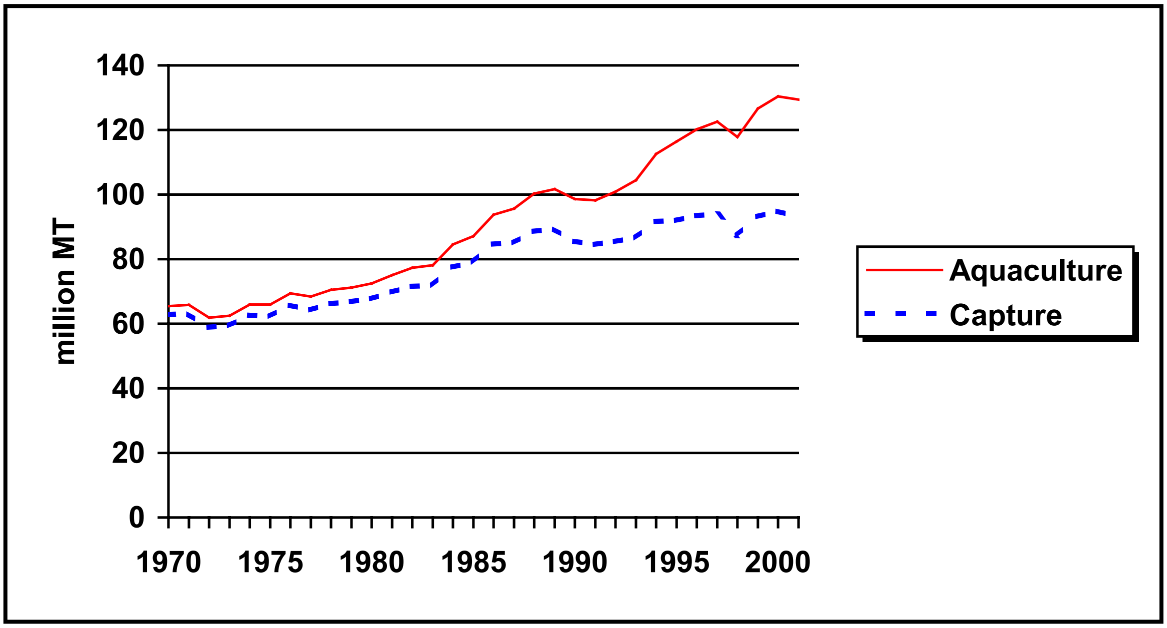
There is some uncertainty regarding the GHG emissions arising from soybean cultivation. The Intergovernmental Panel on Climate Change (IPCC) currently assumes that nitrogen fixing plants, such as soybeans, emit N_2O at the same rate as the application of synthetic nitrogen fertilizers do. The United States, which is the world's largest producer of soybeans, follows this approach in their national GHG emissions inventory. Agriculture and Agri-Food Canada on the other hand, has some data which suggests that this may not be the case in Canada. Environmental conditions are known to influence the N_2O emission rate and it may be that the drier Canadian conditions have impacted the Canadian data.

The specific marine based biodiesel pathway analyzed here produces significant GHG reductions when the IPCC guidelines are used. This benefit can be reduced or eliminated if a less efficient fishery is analyzed or if the N_2O emission factor for soybean production is reduced.

The analysis undertaken has also included a revised system boundary with a narrower focus. This system treats the fish oil as a by-product of another process and attributes the emissions associated with harvesting and reducing the fish to the primary product and not the fish oil. In this case the GHG emission benefits are similar to those produced by soy biodiesel using the IPCC assumptions and slightly better than the broader fish biodiesel system using the IPCC guidelines. With the narrower system boundary, there is no fishmeal co-product so the results are the same using both the IPCC and AAFC emission factors.

In addition to the energy and GHG emission analysis, it is worthwhile considering the production potential of fish oil. The fishmeal production data shown in the report shows no growth in the market over the past five years. A longer term look at the global fish catch (Josupeit) shows that the capture sector has shown little growth over the past fifteen years and that all of the growth has been in the aquaculture sector.

Figure 6-1 Global Fish Production



In addition to the lack of growth in the capture segment of the world fishery, much of the fish oil is currently consumed in the aquaculture sector as part of the fish feed. The continued rapid growth in this sector will make less fish oil available to use in other applications such as biodiesel.

Given the feedstock availability issues, the wide variation in fishery practices and to a degree the uncertainty about the N_2O emissions displaced by fishmeal, governments should be careful about encouraging the development of marine based biodiesel. Specific special cases of marine based biodiesel probably do offer significant GHG emissions reductions. These special cases would usually involve fish oil that is either a co-product or clearly a waste product in the local market.

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