THE ADDITION OF PYROLYSIS OIL PATHWAYS TO GHGENIUS

Prepared For:

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EXECUTIVE SUMMARY

The GHGenius model has been developed for Natural Resources Canada over the past eleven years. It is based on the 1998 version of Dr. Mark Delucchi's Lifecycle Emissions Model (LEM). GHGenius is capable of analyzing the energy balance and 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 contaminants 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 or fuel cells for light duty vehicles, for class 3-7 medium-duty trucks, 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 200 vehicle and fuel combinations possible with the model.

There is increased interest in the production and use of pyrolysis oils (or bio-oil) as a means of converting solid biomass into liquid fuels. While pyrolysis oil is not suitable for direct use as a transportation fuel, it can be used in external combustion devices such as boilers, heaters, and turbines. There are also activities underway to refine pyrolysis oil to gasoline and diesel fuel components.

The scope of this work included;

1. Pyrolysis oil production from wood or agricultural cellulosic feedstocks. Both of these feedstock families were already included in GHGenius. There are three wood options, wood waste, short rotation forestry, and harvested wood from natural forests. There are four agricultural cellulosic feedstocks in the model, wheat straw, corn stover, switchgrass, and hay. The model has been expanded so that pyrolysis oil could be made from any of these feedstocks. The emissions from the production of these bio-oils have been added to the Upstream Results sheet.
2. The produced pyrolysis oil could be used in external combustion devices such as heaters and boilers (sheet AD and sheet N). Sheet J has also been expanded so that the emissions from the production of electricity in a turbine system can be modelled.
3. A pathway that refines the pyrolysis oils to blending stock for gasoline and diesel fuel has also been added to the model. Some information on the process is available in

the public domain as a result of work at the National Renewable Energy Laboratory (NREL), the Pacific Northwest National Laboratory (PNNL) and publicly funded work undertaken by UOP in the United States.

All of the existing functionality, e.g. sensitivity solver, Monte Carlo tool, etc, in GHGenius has been maintained. The version of GHGenius that accompanies this report is GHGenius version 3.20. A large number of upgrades are included in this version of the model but the other upgrades are described in separate reports.

Two feedstock families have been included for this work, wood and agricultural lignocellulosic material. In each case, there are feedstocks that are waste products and feedstocks that are purpose grown in the family. Following normal LCA practice, waste feedstocks are deemed to be environmental burden free at the point of generation. This system boundary is discussed below for each of the feedstocks.

There are separate pathways added to the model, one for pyrolysis oils produced from wood and one for pyrolysis oils made from the agriculture feedstocks. This is a slightly different treatment than the cellulosic ethanol, which uses a switch (cell B48) to choose which of the feedstock to use for the single presentation of the results.

Pyrolysis is thermal decomposition occurring in the absence of oxygen. It is also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the primary products.

In general, pyrolysis of organic substances produces gas and liquid products and leaves a solid residue richer in carbon content.

The process is used heavily in the chemical industry, for example, to produce charcoal, activated carbon, and other chemicals from wood, to convert ethylene dichloride into vinyl chloride to make PVC, to produce coke from coal, to convert biomass into syngas, to turn waste into safely disposable substances, and for transforming medium-weight hydrocarbons from oil into lighter ones like gasoline. These specialized uses of pyrolysis may be called various names, such as dry distillation, destructive distillation, or cracking.

Pyrolysis differs from other high-temperature processes like combustion and hydrolysis in that it does not involve reactions with oxygen, water, or any other reagents. In practice it is not possible to achieve a completely oxygen-free atmosphere. Because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs.

If biomass is heated to high temperatures in the total absence of oxygen, it pyrolyzes to a liquid that is oxygenated, but otherwise has some similar characteristics to petroleum. This pyrolysis- or “bio-oil” can be burned to generate heat or electricity, or it can be used to provide base chemicals for biobased products.

The liquid contains varying quantities of water, which forms a stable single phase mixture, ranging from about 15 wt% to an upper limit of about 40 wt% water, depending on how it was produced and subsequently collected. It is immiscible with petroleum-derived fuels.

The density of the liquid is very high at around 1.2 kg/litre compared to light fuel oil at around 0.85 kg/ litre. This means that the liquid has about 42% of the energy content of fuel oil on a weight basis, but 61% on a volumetric basis. For this work it has been assumed that the bio-oil could be used in thermal applications as a replacement for heating oil, in a turbine for the production of electric power, or it could be refined to blending components for transportation fuels.

The energy balance results and the lifecycle GHG emissions for the various scenarios modelled are presented in this section along with values for some fossil energy equivalents for comparison. The GHGenius model is set to 2011 and for the average of Canada.

GHGenius can calculate the total energy balance for a pathway or the fossil energy balance. These balances include all of the energy used to make the various secondary energy sources used in a process. In the following table the total energy balance for wood residues and short rotation forestry are compared to the energy balance for heating oil.

Table ES- 1 Total Energy Balance – Wood Feedstocks

Fuel	Heating oil	Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	Joules Consumed/Joule Delivered			
Fuel dispensing	0.0024	0.0063	0.0063	0.0063
Fuel distribution, storage	0.0069	0.0040	0.0040	0.0040
Fuel production	0.1170	0.5747	0.5977	0.5904
Feedstock transmission	0.0117	0.0000	0.0202	0.0202
Feedstock recovery	0.1237	0.0000	0.0357	0.0359
Feedstock Upgrading				
Ag. chemical manufacture	0.0000	0.0000	0.0241	0.0000
Co-product credits	-0.0011	0.0000	0.0000	0.0000
Total	**0.2606**	**0.5850**	**0.6881**	**0.6569**
Net Energy Ratio (J delivered/J consumed)	**3.8373**	**1.7093**	**1.4533**	**1.5224**

The bio-oil systems do require more total energy to produce a unit of energy than producing heating oil does. This situation changes when the fossil energy requirements are considered as shown in the following table. The energy balance for the bio-oil produced from wood residues is quite significant.

Table ES- 2 Fossil Energy Balance– Wood Feedstocks

Fuel	Heating oil	Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	Joules Consumed/Joule Delivered			
Fuel dispensing	0.0005	0.0014	0.0014	0.0014
Fuel distribution, storage	0.0056	0.0031	0.0031	0.0031
Fuel production	0.1099	0.0122	0.0122	0.0122
Feedstock transmission	0.0088	0.0000	0.0200	0.0200
Feedstock recovery	0.1111	0.0000	0.0336	0.0354
Feedstock Upgrading				
Ag. chemical manufacture	0.0000	0.0000	0.0227	0.0000
Co-product credits	-0.0010	0.0000	0.0000	0.0000
Total	**0.2350**	**0.0168**	**0.0931**	**0.0722**
Net Energy Ratio (J delivered/J consumed)	**4.2556**	**59.5705**	**10.7406**	**13.8574**

Similar energy balances have been developed for agriculture feedstocks for the production of pyrolysis oils.

The GHG emissions for the three wood feedstocks is presented in the following table and compared to those of diesel fuel. Since the primary source of the GHG emissions is the electric power that is required for the system the emissions will vary by province depending on the carbon intensity of the electric power in each region.

Table ES- 3 GHG Emissions – Wood Feedstock

Fuel	Heating oil	Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	g CO_2eq/GJ (HHV)			
Fuel dispensing	114	299	301	300
Fuel distribution and storage	478	219	219	219
Fuel production	8,444	2,826	2,844	2,835
Feedstock transmission	902	0	1,567	1,567
Feedstock recovery	8,913	0	2,943	3,116
Feedstock Upgrading				
Land-use changes, cultivation	222	0	3,350	10
Fertilizer manufacture	0	0	1,477	0
Gas leaks and flares	1,773	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-240	0	0	0
Sub-Total Fuel production	20,607	3,344	12,702	8,047
Fuel Combustion	68,717	97	97	97
Grand Total	**89,324**	**3,441**	**12,799**	**8,144**
% Change				

The bio-oil produced can be combusted in a turbine generator set to produce electric power and the emissions intensity of this pathway is compared to other thermal generation options in this section.

The wood to bio-oil to electric power pathway GHG emissions are summarized in the following table. The wood scenarios have an emission intensity 83 to 95% less than a coal fired power plant depending on the source of the wood feedstock.

Table ES- 4 GHG Emissions from Power Generation - Wood

	Coal	Fuel oil	NG/boiler	NG turbine	Bio-oil	
					Wood Residues	Wood SRF
	g-CO_2-eq/GJ					
g-CO_2-eq/GJ-generated	295,699	275,224	153,528	125,074	12,361	43,978
Distribution efficiency	0.92	0.92	0.92	0.92	0.92	0.92
g-N_2O/kWh-delivered	0	0	0	0	0	0
g-CO_2-eq of SF6/GJ-generated	561	561	561	561	561	561
g-CO_2-eq/GJ-delivered	322,535	300,304	168,169	137,274	14,892	49,222
g-CO_2-eq/kWh-delivered	1161.1	1081.1	605.4	494.2	53.6	177.2
% change vs. coal plant	n.a.	-6.9%	-47.9%	-57.4%	-95.4%	-84.7%

A demonstration project to refine pyrolysis oils to transportation fuels is underway in Hawaii (US DOE, 2010). This project will process one ton per day of biomass into transportation fuels. The primary technology participants are UOP and Ensyn. The Ensyn RTP™ technology will be used for the production of pyrolysis oils and the upgrading technology is being supplier by UOP.

The bio-oil refining is a two step process, the oil must first be stabilized by hydrotreating the oil to lower the acidity and then the stabilized oil is hydrocracked to produce products in the gasoline boiling range and the diesel fuel boiling range. The hydrogen required for both stages could be supplied by natural gas reforming or from increased utilization of biomass.

In the following table the total energy balance for wood residues and short rotation forestry are compared to the energy balance for diesel. The total energy balance is not as good as diesel fuel produced from crude oil, as one might expect given the amount of cracking of the molecules.

Table ES- 5 Total Energy Balance – Refined Bio Oil - Wood Feedstocks

Fuel	Diesel Fuel	Refined Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	Joules Consumed/Joule Delivered			
Fuel dispensing	0.0024	0.0024	0.0024	0.0024
Fuel distribution, storage	0.0069	0.0120	0.0120	0.0120
Fuel production	0.1170	0.4363	0.4363	0.4363
Feedstock transmission	0.0117	0.0087	0.0266	0.0266
Feedstock recovery	0.1237	0.0000	0.0316	0.0318
Feedstock Upgrading				
Ag. chemical manufacture	0.0000	0.0000	0.0213	0.0000
Co-product credits	-0.0011	0.0000	0.0000	0.0000
Total	**0.2606**	**0.4594**	**0.5303**	**0.5092**
Net Energy Ratio (J delivered/J consumed)	**3.8373**	**2.1768**	**1.8858**	**1.9641**

This situation changes when the fossil energy requirements are considered as shown in the following table. The change is not as significant as it was for the production of pyrolysis oils as a significant quantity of natural gas is used to produce the hydrogen that is consumed in the process.

Table ES- 6 Fossil Energy Balance – Refined Bio Oil -– Wood Feedstocks

Fuel	Diesel Fuel	Refined Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	Joules Consumed/Joule Delivered			
Fuel dispensing	0.0005	0.0005	0.0005	0.0005
Fuel distribution, storage	0.0056	0.0114	0.0114	0.0114
Fuel production	0.1099	0.3729	0.3729	0.3729
Feedstock transmission	0.0088	0.0086	0.0263	0.0263
Feedstock recovery	0.1111	0.0000	0.0298	0.0314
Feedstock Upgrading				
Ag. chemical manufacture	0.0000	0.0000	0.0201	0.0000
Co-product credits	-0.0010	0.0000	0.0000	0.0000
Total	**0.2350**	**0.3933**	**0.4609**	**0.4424**
Net Energy Ratio (J delivered/J consumed)	**4.2556**	**2.5423**	**2.1696**	**2.2605**

The GHG emissions for the three wood feedstocks is presented in the following table and compared to those of diesel fuel. Since the primary source of the GHG emissions is the electric power that is required for the system the emissions will vary by province depending on the carbon intensity of the electric power in each region.

The lifecycle GHG emissions for the gasoline fraction of refined bio oil blended at the 10% level is shown in the following table and compared to gasoline. These are for the default light duty vehicle in GHGenius. The source of the feedstock has some impact on the GHG emissions but the range of reductions is from 5 to 6% for the 10% blend.

Table ES- 7 Lifecycle GHG Emissions Gasoline Fraction Refined Bio Oil

General fuel	Gasoline	Refined Bio-Oil		
Fuel specification	RFG30ppm S	RBO10	RBO10	RBO10
Feedstock	crude oil	Wood Residues	Short Rotation Forestry	Standing Timber
	g CO_2eq/km			
Vehicle operation	211.1	211.1	211.1	211.1
C in end-use fuel from CO_2 in air	0.0	-20.5	-20.5	-20.5
Net Vehicle Operation	211.1	190.6	190.6	190.6
Fuel dispensing	0.4	0.4	0.4	0.4
Fuel storage and distribution	1.5	1.7	1.7	1.7
Fuel production	40.8	45.1	45.2	45.2
Feedstock transport	2.9	2.9	3.8	3.8
Feedstock recovery	28.9	25.9	26.8	26.9
Feedstock Upgrading		0.0	0.0	0.0
Land-use changes, cultivation	0.7	0.7	1.7	0.7
Fertilizer manufacture	0.0	0.0	0.4	0.0
Gas leaks and flares	5.9	5.3	5.3	5.3
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0
Emissions displaced by co-products	-0.8	-0.7	-0.7	-0.7
Sub total (fuel cycle)	291.5	271.8	275.2	273.7
% changes (fuel cycle)	0.0	-6.9	-5.8	-6.3
Vehicle assembly and transport	*2.8*	*2.8*	*2.8*	*2.8*
Materials in vehicles (incl. Storage) and lube oil production/use	*27.6*	*27.6*	*27.6*	*27.6*
Grand total	322.0	302.3	305.7	304.2
% changes to CG (grand total)	-0.2	-6.3	-5.2	-5.7
% changes to RFG (grand total)	0.0	-6.1	-5.1	-5.5

Table ES- 8 GHG Emissions – Wood Feedstock

Fuel	Diesel Fuel	Refined Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	g CO_2eq/GJ (HHV)			
Fuel dispensing	114	114	114	114
Fuel distribution and storage	478	931	931	931
Fuel production	8,444	25,027	25,069	25,048
Feedstock transmission	902	674	3,449	3,449
Feedstock recovery	8,913	0	2,606	2,760
Feedstock Upgrading				
Land-use changes, cultivation	222	0	2,967	9
Fertilizer manufacture	0	0	1,308	0
Gas leaks and flares	1,773	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-240	0	0	0
Sub-Total Fuel production	20,607	26,746	36,446	32,311
Fuel Combustion	70,276	1,738	1,738	1,738
Grand Total	90,883	28,484	38,184	34,049
% Reduction		68.7%	58.0%	62.5%

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1. INTRODUCTION

The GHGenius model has been developed for Natural Resources Canada over the past eleven years. It is based on the 1998 version of Dr. Mark Delucchi's Lifecycle Emissions Model (LEM). GHGenius is capable of analyzing the energy balance and 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:

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- Sulphur dioxide (SO_2),
- Total particulate matter.

The model is capable of analyzing the emissions from conventional and alternative fuelled internal combustion engines or fuel cells for light duty vehicles, for class 3-7 medium-duty trucks, 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 200 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:

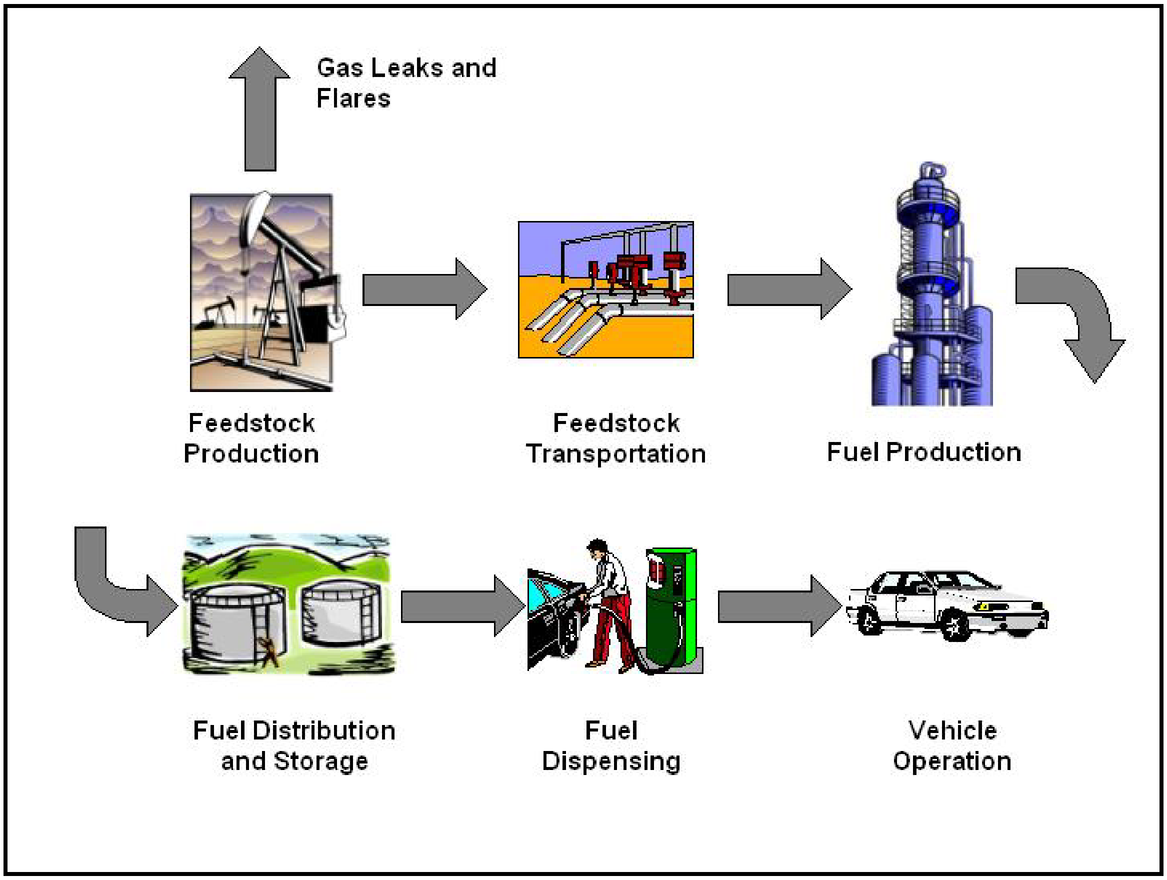
- Vehicle Operation
  Emissions associated with the use of the fuel in the vehicle. Includes all greenhouse gases.
- Fuel Dispensing at the Retail Level
  Emissions associated with the transfer of the fuel at a service station from storage into the vehicles. Includes electricity for pumping, fugitive 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. Includes energy and emissions associated with the transportation infrastructure construction and maintenance (trucks, trains, ships, pipelines, etc.)

- 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.

The main lifecycle stages for crude oil based gasoline or diesel fuel are shown in the following figure.

Figure 1-1 Petroleum Lifecycle Stages



1.1 SCOPE OF WORK

There is increased interest in the production and use of pyrolysis oils (or bio-oil) as a means of converting solid biomass into liquid fuels. While pyrolysis oil is not suitable for direct use as a transportation fuel, it can be used in external combustion devices such as boilers, heaters, and turbines. There are also activities underway to upgrade pyrolysis oil to gasoline and diesel fuel components.

The scope of this work included;

1. Pyrolysis oil production from wood or agricultural cellulosic feedstocks. Both of these feedstock families are already included in GHGenius. There are three wood options, wood waste, short rotation forestry, and harvested wood from natural forests. There are four agricultural cellulosic feedstocks in the model, wheat straw, corn stover, switchgrass, and hay. The model has been expanded so that pyrolysis oil could be made from any of these feedstocks. The emissions from the production of these bio-oils have been added to the Upstream Results sheet.
2. The produced pyrolysis oil could be used in external combustion devices such as heaters and boilers (sheet AD and sheet N). Sheet J has also been expanded so that the emissions from the production of electricity in a turbine system can be modelled.

3. A pathway that converts the pyrolysis oils to blending stock for gasoline and diesel fuel has also been added to the model. Some information on the process is available in the public domain as a result of work at the National Renewable Energy Laboratory (NREL), the Pacific Northwest National Laboratory (PNNL) and publicly funded work undertaken by UOP in the United States.

All of the existing functionality, e.g. sensitivity solver, Monte Carlo tool, etc, in GHGenius has been maintained. The version of GHGenius that accompanies this report is GHGenius version 3.20. A large number of upgrades are included in this version of the model but the other upgrades are described in separate reports.

2. FEEDSTOCKS

Two feedstock families have been included for this work, wood and agricultural lignocellulosic material. In each case, there are feedstocks that are waste products and feedstocks that are purpose grown in the family. Following normal LCA practice, waste feedstocks are deemed to be environmental burden free at the point of generation. This system boundary is discussed below for each of the feedstocks.

There are separate pathways added to the model, one for pyrolysis oils produced from wood and one for pyrolysis oils made from the agriculture feedstocks. This is a slightly different treatment than the cellulosic ethanol, which uses a switch (cell B48) to choose which of the feedstock to use for the single presentation of the results.

None of the model default values have been changed for these feedstocks. All of the feedstocks are already used for other fuel production pathways such as lignocellulosic ethanol, some of them are also used for the production of mixed alcohols or FT distillate.

2.1 WOOD FEEDSTOCKS

GHGenius can model three different wood feedstock scenarios, wood residues, short rotation forestry, and harvested natural timber. The default values for each scenario can be installed in the model by clicking on the appropriate default button on the Input sheet in column A, rows 110 to 120. This then sets the appropriate inputs used for the pyrolysis oil pathway. The same default values are also used for the cellulosic ethanol pathways. The user can also install their own input values for modelling.

2.1.1 Wood Residues

In the case of wood residues, it has been assumed that the wood residue is produced and consumed onsite. Following the normal LCA practice, any emissions attributable to the cutting of the tree, transporting it to a mill site, produce lumber or pulp, and generating the wood residue is attributable to the primary product being produced and not apportioned to the waste product.

Other transportation scenarios could be modelled by the user inputting the transportation distances and modes on the input sheet in column J, rows 75 to 85. This is the only change to how the model works, previous version did not allow for the wood to be utilized at a site that was different from where it was produced. Since some production systems might have to pull wood residues from multiple sites to satisfy the capacity of the production plant, this additional functionality was added to the model in this revison.

2.1.2 Short Rotation Forestry

GHGenius can also model wood production from short rotation forestry. The emissions from this resource are very dependent on the prior use of the land that the wood is grown on. This pathway does include all of the material and energy inputs that are required to grow the trees, harvest them and transport them to a plant. The version of GHGenius that has been supplied for this work has the land use emissions “zeroed out”, essentially meaning that it is assumed that the wood is grown on land that has always been used for short rotation forestry. Users can change this scenario on sheet W, row 337 by assuming a different prior use of the land.

2.1.3 Natural Timber

The harvesting of natural timber was added in 2010 ((S&T)^2, 2010). The pathway has default values for the energy required to build roads, harvest the timber, reduce the size of the wood, and the transportation of the material to the site where it is utilized. The user can also adjust any of the parameters, as they are all located on the Input sheet.

2.2 AGRICULTURAL FEEDSTOCKS

To choose which of the agricultural feedstocks are used for the production of pyrolysis oils, the user chooses the feedstock blend in row 54 on the Input sheet. Values must be entered in columns B, C and D. The model then calculates the value of the fourth option so that the sum of the four feedstocks adds up to one.

2.2.1 Wheat Straw

Wheat straw is treated as a waste product as it lies in the field. The energy that is required to collect it, bale and transported the material to the processing plant. Extra synthetic fertilizers replace the nutrients that are removed by the straw.

There are no direct land use changes calculated by the model for the default case.

2.2.2 Corn Stover

Corn stover is treated in an identical manner to wheat straw. The energy that is required to collect it, bale and transported the material to the processing plant. Extra synthetic fertilizers replace the nutrients that are removed by the straw.

There are no direct land use changes calculated by the model for the default case.

2.2.3 Switchgrass

Switchgrass is treated as a purpose grown crop for energy production in the model. The emissions are higher than they are for straw or stover as the direct land use emissions are included. The energy and fertilizer requirements are all found on the Input sheet.

2.2.4 Hay

Hay is a similar feedstock to Switchgrass, it is a purpose grown feedstock and thus the emissions tend to be higher than they are for stover and straw. The energy and fertilizer requirements are all found on the Input sheet.

3. PYROLYSIS OIL PRODUCTION

Pyrolysis is thermal decomposition occurring in the absence of oxygen. It is also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the primary products.

In general, pyrolysis of organic substances produces gas and liquid products and leaves a solid residue richer in carbon content.

The process is used heavily in the chemical industry, for example, to produce charcoal, activated carbon, and other chemicals from wood, to convert ethylene dichloride into vinyl chloride to make PVC, to produce coke from coal, to convert biomass into syngas, to turn waste into safely disposable substances, and for transforming medium-weight hydrocarbons from oil into lighter ones like gasoline. These specialized uses of pyrolysis may be called various names, such as dry distillation, destructive distillation, or cracking.

Pyrolysis differs from other high-temperature processes like combustion and hydrolysis in that it does not involve reactions with oxygen, water, or any other reagents. In practice it is not possible to achieve a completely oxygen-free atmosphere. Because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs.

There are different types of pyrolysis systems with different operating conditions. Lower process temperatures and longer vapour residence times favour the production of charcoal. High temperatures and longer residence time increase the biomass conversion to gas, and moderate temperatures and short vapour residence time are optimum for producing liquids. The product distribution obtained from different modes of pyrolysis process are summarised in the table below. The characteristics of typical systems are shown in the following table.

Table 3-1 Pyrolysis System Characteristics

Mode	Conditions	Gas	Liquid	Char
		Wt %		
Fast	~500°C, vapour residence time ~ 1 sec	75	12	13
Intermediate	~500°C, vapour residence time ~ 10-30 sec	50	25	25
Slow	~400°C, vapour residence time ~ hours-days	30	35	35
Gasification	~800°C	5	10	85

Fast pyrolysis for liquids production is of particular interest currently as the liquids are transportable and storage. Fast pyrolysis occurs in a time of few seconds or less. Therefore, chemical reaction kinetics, but also heat and mass transfer processes as well as phase transition phenomena, play important roles. The critical issue is to bring the reacting biomass particle to the optimum process temperature and minimize its exposure to the intermediate (lower) temperatures that favour formation of charcoal. One way this objective can be achieved is by using small particles, for example in the fluidized bed process. Another possibility is to transfer heat very fast only to the particle surface that contacts the heat source, which is applied in ablative processes.

In fast pyrolysis, biomass decomposes to generate mostly vapours and aerosols and some charcoal. After cooling and condensation, a dark brown mobile liquid is formed which has a heating value about half that of conventional fuel oil. While it is related to the traditional pyrolysis processes for making charcoal, fast pyrolysis is an advanced process, with carefully controlled parameters to give high yields of liquid. The essential features of a fast pyrolysis process for producing liquids are:

- Very high heating and heat transfer rates at the reaction interface, which usually requires a finely ground biomass feed
- Carefully controlled pyrolysis reaction temperature of around 500?C and vapour phase temperature of 400-450?C,
- Short vapour residence times of typically less than 2 seconds
- Rapid cooling of the pyrolysis vapours to give the bio-oil product.

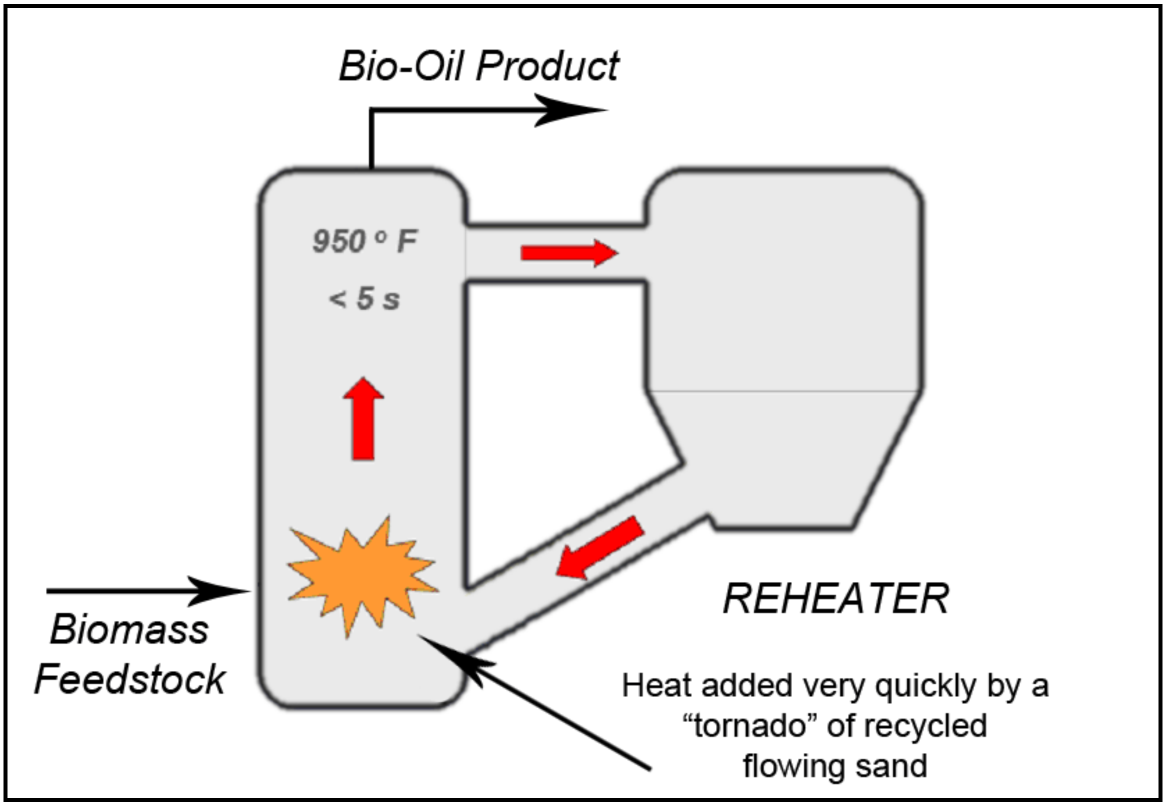
The main product, bio-oil, is obtained in yields of up to 75% wt on dry feed basis, together with by-product char and gas which are often used within the process to provide the process heat requirements so there are no waste streams other than flue gas and ash. A fast pyrolysis process includes drying the feed to typically less than 10% water in order to minimise the water in the product liquid oil (although up to 15% can be acceptable), grinding the feed (to around 2 mm in the case of fluid bed reactors) to give sufficiently small particles to ensure rapid reaction, pyrolysis reaction, separation of solids (char), quenching and collection of the liquid product (bio-oil). Virtually any form of biomass can be considered for fast pyrolysis.

One example of fast pyrolysis is Ensyn’s Rapid Thermal Processing (RTP)™ technology, the world’s only pyrolysis technology that has operated on a long-term commercial basis, converts biomass to liquid in less than two seconds.

RTP™ is a fast thermal process whereby biomass is introduced into a vessel and rapidly heated to 500ºC by a tornado of hot sand and then rapidly cooled within seconds. The process generates a relatively high yield (i.e., approx 75 wt%) of pourable, liquid “bio-oil” from residual forestry or agricultural biomass.

The process also produces by-product char and non-condensable gas, both of which can be efficiently used to provide process energy, which can then be used in the reheater to maintain the RTP™ process and/or in the dryer to condition the biomass. A simple flow scheme is shown in the following figure.

Figure 3-1 Ensyn's RTP Process



3.1 PYROLYSIS OIL PRODUCTION

If biomass is heated to high temperatures in the total absence of oxygen, it pyrolyzes to a liquid that is oxygenated, but otherwise has some similar characteristics to petroleum. This pyrolysis- or "bio-oil" can be burned to generate heat or electricity, or it can be used to provide base chemicals for biobased products.

The liquid contains varying quantities of water, which forms a stable single phase mixture, ranging from about 15 wt% to an upper limit of about 40 wt% water, depending on how it was produced and subsequently collected. It is immiscible with petroleum-derived fuels.

The density of the liquid is very high at around 1.2 kg/litre compared to light fuel oil at around 0.85 kg/ litre. This means that the liquid has about 42% of the energy content of fuel oil on a weight basis, but 61% on a volumetric basis.

The typical characteristics of bio-oil are summarized in the following table.

Table 3-2 Bio-Oil Physical Properties

Physical Properties	Typical Value	Values in GHGenius
Moisture content	15–30%	
pH	2.5	
Specific gravity	1.20	1.2
Elemental analysis, dry basis		
C	56.4%	56.4%
H	6.2%	6.2%
O (by difference)	37.3%	37.3%
N	0.1%	
Ash	0.1%	
HHV as produced (depends on moisture)	16–19 MJ/kg	17.5 MJ/kg
Viscosity (at 40ºC and 25% water)	40–100 cp	
Solids (char)	0.5%	
Distillation	max. 50% as liquid degrades	

3.1.1 Mass and Energy Balance

Ensyn have supplied mass and energy balance information on their system for the two feedstock families of interest and it is used as the basis for the default values in the model. This information is summarized below. The model is, of course, flexible and other process parameters can be modelled by changing the primary variables, all of which are located on the Input sheet, or on sheet Y (co-products).

3.1.1.1 Wood Residues

Most of the operating experience with the Ensyn system has been developed with systems that use wood as the feedstock. The pyrolysis process produces bio-oil, char, and a fuel gas form the wood feedstock. It has been assumed that the char and the fuel gas are fully utilized by the system to dry the feedstock and thus the overall system can be simplified to one that utilizes dry feedstock to produce bio-oil. The system uses some electricity and during start-up some natural gas. It has been assumed that the average energy requirements can be estimated based on 5% of the start-up values and 95% of the normal operating values. The inputs and outputs from the system are summarized in the following table.

Table 3-3 System Inputs and Outputs - Wood

	Input	Output
Dry wood, kg	1.646	
Electric Power, kWh	0.25	
Natural gas, litres	0.02	
Bio-oil, litre		1.0

The model will accept fuel gas as a co-product for the wood systems, so if a feedstock has a low moisture content and excess fuel gas is produced, it can be treated as a co-product by entering the quantity produced on the Input sheet (cells W and X 260). The fuel gas is assumed to displace natural gas and receives and energy and emissions credit on that basis.

3.1.1.2 *Agricultural Residues*

For the agricultural residue systems, it has been assumed that the char and a portion of the fuel gas are utilized by the system to dry the feedstock and thus the overall system can be simplified to one that utilizes dry feedstock to produce bio-oil and some fuel gas. The system uses some electricity and during start-up some natural gas. It has been assumed that the average energy requirements can be estimated based on 5% of the start-up values and 95% of the normal operating values. The inputs and outputs from the system are summarized in the following table.

Table 3-4 System Inputs and Outputs – Ag Residues

	Input	Output
Dry feedstock, kg	1.88	
Electric Power, kWh	0.29	
Natural gas, litres	0.029	
Bio-oil, litre		1.0
Fuel gas, kg		0.47
Fuel gas, MJ		5.5

3.1.2 Process Emissions

There are emissions from the system that can also impact the lifecycle emissions of air contaminants and GHG emissions. These result from the feedstock drying and from the pyrolysis system itself. These emissions are on sheet N in the model, columns BN and BO. The values could be changed by the user is data for a specific feedstock is available.

3.1.2.1 *Wood Feedstock*

The non-energy related process emissions are summarized in the following table. These are estimated from emission test results on the produced char when available and otherwise from estimates of wood combustion systems. In GHGenius, these emissions are reported per unit of feedstock and not per unit of feedstock combusted. In the case of the Ensyn system about 20% of the feedstock is combusted as char with much of the remained producing the bio-oil.

Table 3-5 Process Emissions - Wood

Component	Emissions g/GJ of Feedstock
Aldehydes (as HCHO) exhaust	0.10
NMOC exhaust	2.00
CH_4 (exhaust)	0.40
CO	2.20
N_20	0.50
NOx (NO_2)	11.0
SOx (SO_2)	0.0
PM	5.00

3.1.2.2 Agricultural Residues

The non-energy related process emissions are summarized in the following table.

Table 3-6 Process Emissions – Agricultural Residues

Component	Emissions g/GJ of Feedstock
Aldehydes (as HCHO) exhaust	0.10
NMOC exhaust	2.00
CH_4 (exhaust)	0.40
CO	2.20
N_20	0.50
NOx (NO_2)	11.0
SOx (SO_2)	0.0
PM	5.00

3.1.3 Pyrolysis Oil Transportation

The pyrolysis oil could be consumed on the site where it is produced or it could be shipped to another site for use or upgrading. The transportation options are selected in columns K and L, rows 89 to 99 on the Input sheet.

The default values are 200 km for distance transported and the mode of transportation is by truck. The user can easily set these values to zero if the product is consumed on the same site as it is produced at.

3.2 PYROLYSIS OIL UPGRADING

A demonstration project to upgrade pyrolysis oils to transportation fuels is underway in Hawaii (US DOE, 2010). This project will process one ton per day of biomass into transportation fuels. The primary technology participants are UOP and Ensyn. The Ensyn RTP™ technology will be used for the production of pyrolysis oils and the upgrading technology is being supplier by UOP.

There are two techno-economic reports that have been released recently on the production and upgrading of pyrolysis oils to transportation fuels. A report from Pacific Northwest National Laboratory (Jones et al, 2009) and a report from the National Renewable Energy Laboratory (Wright et al, 2010). The Jones report assumed a wood feedstock and has the most complete process description and mass balance. The Wright report was based on corn stover feedstock and has a less detailed mass and energy balance. The Jones report has been used as the basis for the default values developed for the model.

The bio-oil upgrading is a two step process, the oil must first be stabilized by hydrotreating the oil to lower the acidity and then the stabilized oil is hydrocracked to produce products in the gasoline boiling range and the diesel fuel boiling range. The hydrogen required for both stages could be supplied by natural gas reforming or from increased utilization of biomass. The two process stages are shown in the following figures.

Figure 3-2 Bio-Oil Stabilization Stage

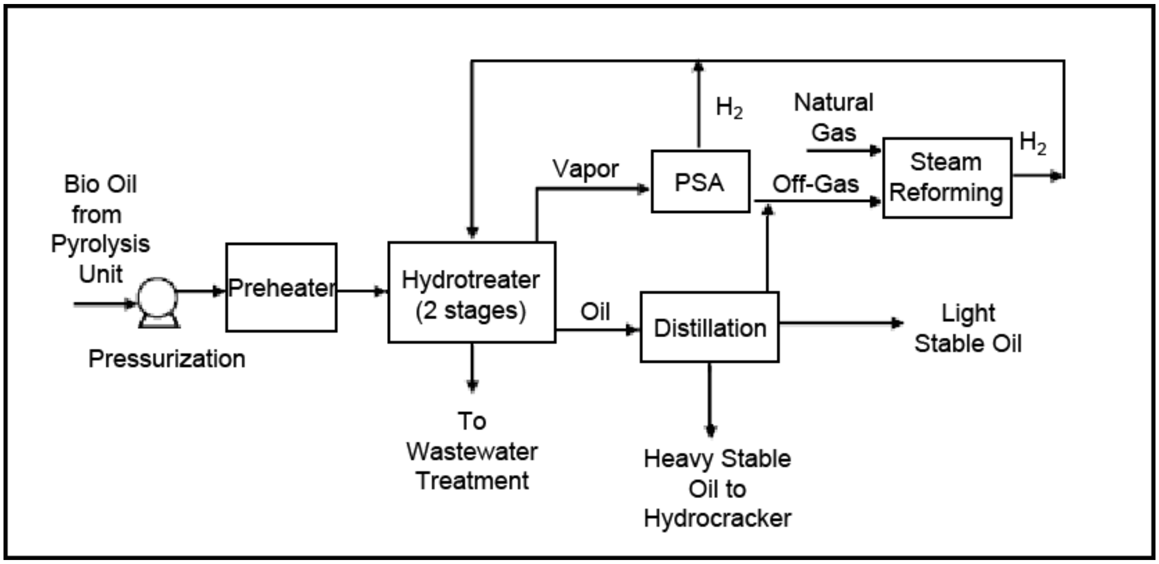
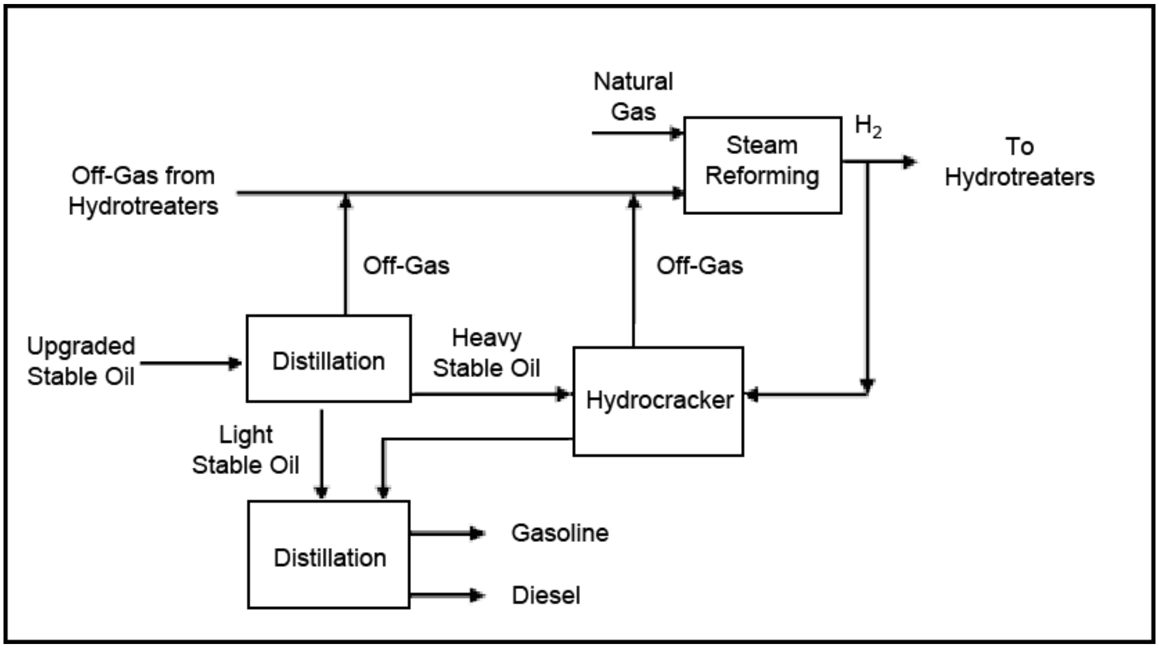


Figure 3-3 Hydrocracking Stage



The overall mass and energy balance for the two stages are summarized in the following table. The electricity consumption for the upgrading has been reduced from the Jones study by the quantity of electricity already included in the pyrolysis oil production stage.

Table 3-7 Mass and Energy Balance for Upgrading

	Input	Output
		Litre
Pyrolysis Oil, kg	1.80	
Natural gas, litres	315	
Electricity, kWh	0.56	
Gasoline Fraction		0.45
Diesel Fraction		0.55
Total transportation fuel fraction.		1.0

When this information is used in GHGenius there is more energy being produced in the final product than existed in the feedstock. This is an unlikely situation and it could be that the energy content of the pyrolysis oil used in the PNNL study was higher than that which is used in GHGenius. For the defaults value in GHGenius it will be assumed that the energy efficiency (Product energy/feedstock energy) is 0.95. This value is obtained when 2.14 kg of pyrolysis oil is used instead of the 1.8 kg as shown in the above table.

The proportion of gasoline and diesel fuel in the refined product can be adjusted by the operating conditions. These fuels are unlikely to be used directly but rather it is more likely that they will be blended with traditional fossil fuels prior to use.

Neither the NREL nor the PNNL reports have any information on process emissions from the upgrading process. The process emissions for the upgrading have been calculated based on the process emissions from a catalytic coker in a refinery as these emissions are already included on sheet G of the model. The results are found in column BP on sheet N.

3.2.1 Refined Bio Oil Transportation

The refined bio oil could be consumed on the site where it is produced or it could be shipped to another site for use. The transportation options are selected in columns M and N, rows 89 to 99 on the Input sheet.

The default values are 200 km for distance transported and the mode of transportation is by truck. The user can easily set these values to zero if the product is consumed on the same site as it is produced at.

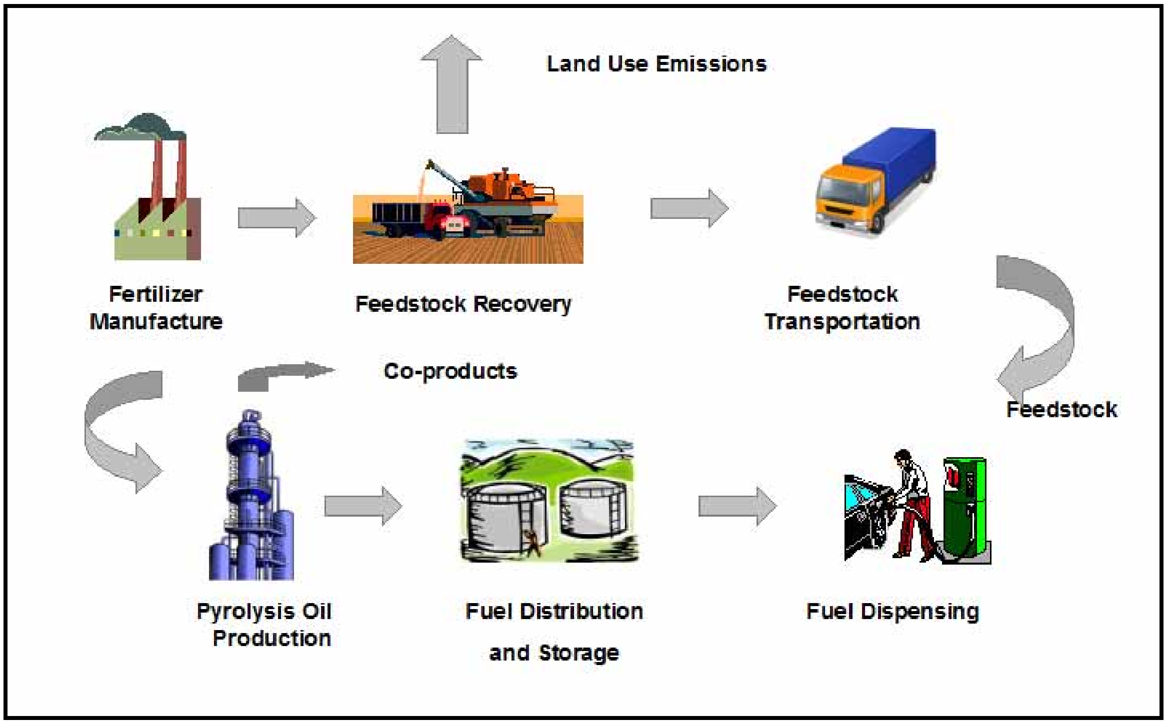
4. PYROLYSIS OIL UTILIZATION

For this work it has been assumed that the bio-oil could be used in thermal applications as a replacement for heating oil, in a turbine for the production of electric power, or it could be refined to blending components for transportation fuels.

4.1 THERMAL APPLICATIONS

The lifecycle system that is considered for the production and use of pyrolysis oils as a thermal energy source is shown in the following figure.

Figure 4-1 System for Production and Use in Thermal Applications



It will be assumed that the combustion efficiency of the bio-oil is the same as that of heating oil. The emissions from the combustion of bio-oil required for the model are summarized in the following table. These are based on emission test results supplied by Ensyn. The SOx emissions are calculated from the sulphur content of the fuel. In cases where the Ensyn results did not report results for a parameter the emissions have been estimated from the parameters that are reported and emission factors for fuel oil.

Table 4-1 Combustion Emissions – Bio-oil

Component	Emissions g/GJ of Fuel
Aldehydes (as HCHO) exhaust	0.00
Fuel evaporation or leakage	0.00
NMOC exhaust	0.10
CH_4	0.07
CO	28.56
$N_2$0	0.32
NOx (NO_2)	160.7
SOx (SO_2)	0.89
PM	23.8

4.2 ELECTRICITY PRODUCTION

The emissions from the combustion of the bio-oil in a turbine are summarized in the following table. The emission factors for CO, NOx, and SOx have been supplied by Ensyn and are based on test results. The other emission factors are based on typical results for an oil-fired turbine (EPA AP-42, and IPCC).

Table 4-2 Combustion Turbine Emissions – Bio-oil

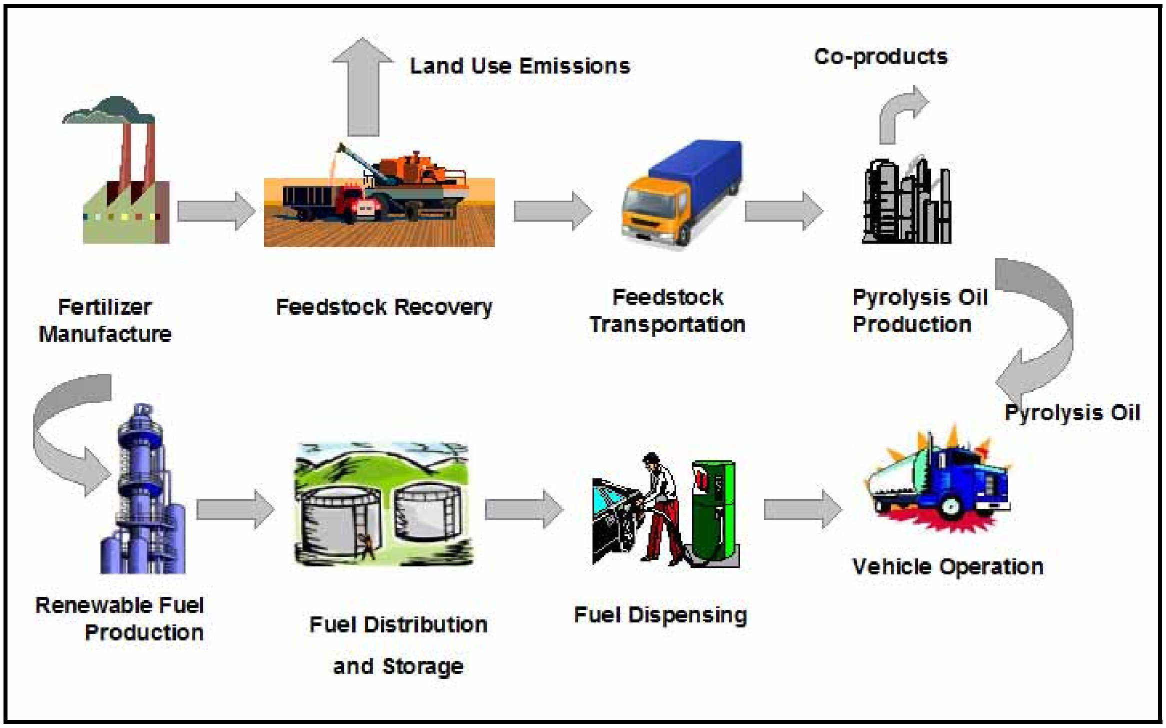
Component	Emissions g/GJ of Fuel
Aldehydes (as HCHO) exhaust	0.12
NMOC exhaust	0.43
CH_4 (exhaust)	0.1
CO	100
$N_2$0	0.3
NOx (NO_2)	120
SOx (SO_2)	4
PM	5

We have modelled a net power system efficiency of 29.6%. The user of the model can easily change this by changing the value in cell L32 on sheet J.

4.3 TRANSPORTATION FUEL USE

The gasoline fraction and the diesel fraction of the fuel produced can be blended with fossil fuels to produce fuels for light and heavy-duty applications. The system that is modelled is shown in the following figure.

Figure 4-2 System for Refined Bio-Oil



The system produces two products, a gasoline fraction and a diesel fraction. There are multiple ways that this can be modelled. One fraction could be assigned the primary product and the other a co-product, with a credit for the co-product based on the emissions displaced, or there could be some sort of allocation of the emissions between the two products on the basis of mass, energy, or some other parameter.

The approach taken here is that effectively a single product, transportation fuel blending stock, is produced and it can be blended into either gasoline or diesel fuel. This effectively does an allocation based on the energy content of the fuel.

The user enters the volumetric fuel volume ratio on the Input sheet (cell F35) for either the gasoline or diesel fuel blend and looks for the lifecycle emission results on the Upstream Emissions sheet.

5. BIO-OIL RESULTS

The energy balance results and the lifecycle GHG emissions for the various scenarios modelled are presented in this section along with values for some fossil energy equivalents for comparison. The GHGenius model is set to 2011 and for the average of Canada.

5.1 ENERGY BALANCE

GHGenius can calculate the total energy balance for a pathway or the fossil energy balance. These balances include all of the energy used to make the various secondary energy sources used in a process.

5.1.1 Wood Feedstock

In the following table the total energy balance for wood residues and short rotation forestry are compared to the energy balance for heating oil.

Table 5-1 Total Energy Balance – Wood Feedstocks

Fuel	Heating oil	Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	Joules Consumed/Joule Delivered			
Fuel dispensing	0.0024	0.0063	0.0063	0.0063
Fuel distribution, storage	0.0069	0.0040	0.0040	0.0040
Fuel production	0.1170	0.5747	0.5977	0.5904
Feedstock transmission	0.0117	0.0000	0.0202	0.0202
Feedstock recovery	0.1237	0.0000	0.0357	0.0359
Feedstock Upgrading				
Ag. chemical manufacture	0.0000	0.0000	0.0241	0.0000
Co-product credits	-0.0011	0.0000	0.0000	0.0000
Total	**0.2606**	**0.5850**	**0.6881**	**0.6569**
Net Energy Ratio (J delivered/J consumed)	**3.8373**	**1.7093**	**1.4533**	**1.5224**

The bio-oil systems do require more total energy to produce a unit of energy than producing heating oil does. This situation changes when the fossil energy requirements are considered as shown in the following table. The energy balance for the bio-oil produced from wood residues is quite significant.

Table 5-2 Fossil Energy Balance– Wood Feedstocks

Fuel	Heating oil	Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	Joules Consumed/Joule Delivered			
Fuel dispensing	0.0005	0.0014	0.0014	0.0014
Fuel distribution, storage	0.0056	0.0031	0.0031	0.0031
Fuel production	0.1099	0.0122	0.0122	0.0122
Feedstock transmission	0.0088	0.0000	0.0200	0.0200
Feedstock recovery	0.1111	0.0000	0.0336	0.0354
Feedstock Upgrading				
Ag. chemical manufacture	0.0000	0.0000	0.0227	0.0000
Co-product credits	-0.0010	0.0000	0.0000	0.0000
Total	**0.2350**	**0.0168**	**0.0931**	**0.0722**
Net Energy Ratio (J delivered/J consumed)	**4.2556**	**59.5705**	**10.7406**	**13.8574**

5.1.2 Agricultural Residue Feedstock

The energy balance results for the agricultural feedstocks are presented in the following tables. Two examples are presented, wheat straw and switchgrass.

Table 5-3 Total Energy Balance – Agricultural Feedstocks

Fuel	Heating oil	Bio-oil	
Feedstock	Crude Oil	Wheat Straw	Switchgrass
	Joules Consumed/Joule Delivered		
Fuel dispensing	0.0024	0.0063	0.0063
Fuel distribution, storage	0.0069	0.0040	0.0040
Fuel production	0.1170	0.6285	0.6455
Feedstock transmission	0.0117	0.0178	0.0178
Feedstock recovery	0.1237	0.0068	0.0307
Feedstock Upgrading			
Ag. chemical manufacture	0.0000	0.0325	0.0414
Co-product credits	-0.0011	-0.2842	-0.2842
Total	**0.2606**	**0.4116**	**0.4614**
Net Energy Ratio (J delivered/J consumed)	**3.8373**	**2.4295**	**2.1672**

The fossil energy balances for the reference system and the two agricultural feedstocks are shown in the following table. The excess fuel gas, that is assumed to displace natural gas, results in a negative energy balance. That is, the co-products displace more fossil energy than was used in all of the rest of lifecycle.

Table 5-4 Fossil Energy Balance – Agricultural Feedstocks

Fuel	Heating oil	Bio-oil	
Feedstock	Crude Oil	Wheat Straw	Switchgrass
	Joules Consumed/Joule Delivered		
Fuel dispensing	0.0024	0.0014	0.0014
Fuel distribution, storage	0.0069	0.0031	0.0031
Fuel production	0.1170	0.0147	0.0147
Feedstock transmission	0.0117	0.0175	0.0175
Feedstock recovery	0.1237	0.0067	0.0303
Feedstock Upgrading			
Ag. chemical manufacture	0.0000	0.0303	0.0390
Co-product credits	-0.0011	-0.2798	-0.2798
Total	**0.2606**	**-0.2061**	**-0.1738**
Net Energy Ratio (J delivered/J consumed)	**3.8373**	**-4.8520**	**-5.7548**

5.2 GHG EMISSIONS

The GHG emissions for the production and use of bio-oil in a thermal application are calculated by GHGenius for each stage in the production process.

5.2.1 Wood Feedstock

The GHG emissions for the three wood feedstocks is presented in the following table and compared to those of diesel fuel. Since the primary source of the GHG emissions is the electric power that is required for the system the emissions will vary by province depending on the carbon intensity of the electric power in each region.

Table 5-5 GHG Emissions – Wood Feedstock

Fuel	Heating oil	Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	g CO_2eq/GJ (HHV)			
Fuel dispensing	114	299	301	300
Fuel distribution and storage	478	219	219	219
Fuel production	8,444	2,826	2,844	2,835
Feedstock transmission	902	0	1,567	1,567
Feedstock recovery	8,913	0	2,943	3,116
Feedstock Upgrading				
Land-use changes, cultivation	222	0	3,350	10
Fertilizer manufacture	0	0	1,477	0
Gas leaks and flares	1,773	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-240	0	0	0
Sub-Total Fuel production	20,607	3,344	12,702	8,047
Fuel Combustion	68,717	97	97	97
Grand Total	**89,324**	**3,441**	**12,799**	**8,144**
% Change				

5.2.2 Agricultural Residues Feedstock

The GHG emissions for the production of bio oil from agricultural feedstocks are shown in the following table. The lower feedstock drying requirements of these feedstocks and the availability of excess fuel gas to displace natural gas has a significant impact on the GHG emissions.

Table 5-6 GHG Emissions – Agricultural Residues Feedstock

Fuel	Heating oil	Bio-oil	
Feedstock	Crude Oil	Wheat Straw	Switchgrass
	g CO_2eq/GJ (HHV)		
Fuel dispensing	114	300	300
Fuel distribution and storage	478	219	219
Fuel production	8,444	3,361	3,361
Feedstock transmission	902	1,375	1,375
Feedstock recovery	8,913	587	2,665
Feedstock Upgrading			
Land-use changes, cultivation	222	0	3,875
Fertilizer manufacture	0	2,048	2,602
Gas leaks and flares	1,773	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-240	-14,985	-14,985
Sub-Total Fuel production	20,607	-7,095	-589
Fuel Combustion	68,717	97	97
Grand Total	**89,324**	**6,998**	**-486**
% Change			

6. ELECTRICITY RESULTS

The bio-oil produced can be combusted in a turbine generator set to produce electric power and the emissions intensity of this pathway is compared to other thermal generation options in this section.

The use of bio-oil to power an oil turbine generator set has been added to sheet J, in columns L and M. The user can adjust the turbine generator system efficiency, the default value of 29.6% has been used for these calculations.

6.1 POWER GENERATION EMISSIONS

The wood to bio-oil to electric power pathway GHG emissions are summarized in the following table. The wood scenarios have an emission intensity 83 to 95% less than a coal fired power plant depending on the source of the wood feedstock.

Table 6-1 GHG Emissions from Power Generation - Wood

	Coal	Fuel oil	NG/boiler	NG turbine	Bio-oil	
					Wood Residues	Wood SRF
	g/GJ-input					
Aldehydes	0.05	0.12	0.00	0.00	0.41	0.41
NMOC	1.31	2.18	3.69	0.65	1.45	1.45
Ozone-weighted NMOC	0.85	1.09	1.47	0.26	0.73	0.73
CH_4	0.88	0.80	0.97	3.70	0.34	0.34
CO	10.94	14.37	35.58	35.29	337.84	337.84
N_2O	0.04	0.01	0.04	1.29	1.01	1.01
NOx as NO_2	231.83	63.15	57.90	67.22	405.41	405.41
SOx	479.09	214.69	0.62	0.62	13.51	13.51
PM	20.88	12.05	3.22	2.84	16.89	16.89
CO_2 from combustion	90,545	71,102	50,066	50,069	0	0
All other gases from combustion	36	31	46	479	315	313
Subtotal from combustion	90,581	71,133	50,112	50,548	315	313
Upstream fuel cycle emissions	6,900	15,516	5,735	5,735	3,344	11,458
Total fuel cycle emissions						
g-CO_2-eq/GJ-generated	295,699	275,224	153,528	125,074	12,361	43,978
Distribution efficiency	0.92	0.92	0.92	0.92	0.92	0.92
g-N_2O/kWh-delivered	0	0	0	0	0	0
g-CO_2-eq of SF6/GJ-generated	561	561	561	561	561	561
g-CO_2-eq/GJ-delivered	322,535	300,304	168,169	137,274	14,892	49,222
g-CO_2-eq/kWh-delivered	1161.1	1081.1	605.4	494.2	53.6	177.2
% change vs. coal plant	n.a.	-6.9%	-47.9%	-57.4%	-95.4%	-84.7%

The use of agricultural feedstocks for the production of bio oil and electric power is summarized in the following table. The availability of the excess fuel gas provides benefits here and the wheat straw feedstock results in negative emissions, when the benefits from displacing natural gas are considered.

Table 6-2 GHG Emissions from Power Generation – Agricultural Feedstocks

	Coal	Fuel oil	NG/boiler	NG turbine	Bio-oil	
					Wheat Straw	Switch grass
	g/GJ-input					
Aldehydes	0.05	0.12	0.00	0.00	0.41	0.41
NMOC	1.31	2.18	3.69	0.65	1.45	1.45
Ozone-weighted NMOC	0.85	1.09	1.47	0.26	0.73	0.73
CH_4	0.88	0.80	0.97	3.70	0.34	0.34
CO	10.94	14.37	35.58	35.29	337.84	337.84
N_2O	0.04	0.01	0.04	1.29	1.01	1.01
NOx as NO_2	231.83	63.15	57.90	67.22	405.41	405.41
SOx	479.09	214.69	0.62	0.62	13.51	13.51
PM	20.88	12.05	3.22	2.84	16.89	16.89
CO_2 from combustion	90,545	71,102	50,066	50,069	0	0
All other gases from combustion	36	31	46	479	315	315
Subtotal from combustion	90,581	71,133	50,112	50,548	315	315
Upstream fuelcycle emissions	6,900	15,516	5,735	5,735	-7,083	-576
Total fuelcycle emissions						
g-CO_2-eq/GJ-generated	295,699	275,224	153,528	125,074	-22,864	-881
Distribution efficiency	0.92	0.92	0.92	0.92	0.92	0.92
g-N_2O/kWh-delivered	0	0	0	0	0	0
g-CO_2-eq of SF6/GJ-generated	561	561	561	561	561	561
g-CO_2-eq/GJ-delivered	322,535	300,304	168,169	137,274	-23,354	515
g-CO_2-eq/kWh-delivered	1161.1	1081.1	605.4	494.2	-84.1	1.9
% change vs. coal plant	n.a.	-6.9%	-47.9%	-57.4%	-107.2%	-99.8%

7. REFINED BIO OIL RESULTS

The pyrolysis oils can be refined to transportation fuel components are discussed in the previous sections of the report. These fuel components can then be blended with gasoline or diesel fuel. The fuel components are completely interchangeable with the traditional fossil fuel components. There is no blend limit, since they do not contain oxygen, and there is no impact on the engine efficiency or exhaust emissions arising from the use of the fuel.

7.1 ENERGY BALANCE

The total and fossil energy balances of the various fuel pathways are calculated by the model and the results for the default assumptions are shown in this section.

7.1.1 Wood Feedstocks

In the following table the total energy balance for wood residues and short rotation forestry are compared to the energy balance for diesel. The total energy balance is not as good as diesel fuel produced from crude oil, as one might expect given the amount of cracking of the molecules.

Table 7-1 Total Energy Balance –Refined Bio Oil - Wood Feedstocks

Fuel	Diesel Fuel	Refined Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	Joules Consumed/Joule Delivered			
Fuel dispensing	0.0024	0.0024	0.0024	0.0024
Fuel distribution, storage	0.0069	0.0120	0.0120	0.0120
Fuel production	0.1170	0.4363	0.4363	0.4363
Feedstock transmission	0.0117	0.0087	0.0266	0.0266
Feedstock recovery	0.1237	0.0000	0.0316	0.0318
Feedstock Upgrading				
Ag. chemical manufacture	0.0000	0.0000	0.0213	0.0000
Co-product credits	-0.0011	0.0000	0.0000	0.0000
Total	**0.2606**	**0.4594**	**0.5303**	**0.5092**
Net Energy Ratio (J delivered/J consumed)	**3.8373**	**2.1768**	**1.8858**	**1.9641**

This situation changes when the fossil energy requirements are considered as shown in the following table. The change is not as significant as it was for the production of pyrolysis oils as a significant quantity of natural gas is used to produce the hydrogen that is consumed in the process.

Table 7-2 Fossil Energy Balance – Refined Bio Oil – Wood Feedstocks

Fuel	Diesel Fuel	Refined Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	Joules Consumed/Joule Delivered			
Fuel dispensing	0.0005	0.0005	0.0005	0.0005
Fuel distribution, storage	0.0056	0.0114	0.0114	0.0114
Fuel production	0.1099	0.3729	0.3729	0.3729
Feedstock transmission	0.0088	0.0086	0.0263	0.0263
Feedstock recovery	0.1111	0.0000	0.0298	0.0314
Feedstock Upgrading				
Ag. chemical manufacture	0.0000	0.0000	0.0201	0.0000
Co-product credits	-0.0010	0.0000	0.0000	0.0000
Total	**0.2350**	**0.3933**	**0.4609**	**0.4424**
Net Energy Ratio (J delivered/J consumed)	**4.2556**	**2.5423**	**2.1696**	**2.2605**

7.1.2 Agricultural Residue Feedstock

The energy balance results for the agricultural feedstocks are presented in the following tables. Two examples are presented, wheat straw and switchgrass. In total they are very similar to the diesel fuel produced from crude oil, although there are large differences in the individual stages.

Table 7-3 Total Energy Balance – Refined Bio Oil – Agricultural Feedstocks

Fuel	Diesel Fuel	Bio-oil	
Feedstock	Crude Oil	Wheat Straw	Switchgrass
	Joules Consumed/Joule Delivered		
Fuel dispensing	0.0024	0.0024	0.0024
Fuel distribution, storage	0.0069	0.0120	0.0120
Fuel production	0.1170	0.4363	0.4363
Feedstock transmission	0.0117	0.0244	0.0244
Feedstock recovery	0.1237	0.0060	0.0272
Feedstock Upgrading			
Ag. chemical manufacture	0.0000	0.0288	0.0367
Co-product credits	-0.0011	-0.2517	-0.2517
Total	**0.2606**	**0.2582**	**0.2873**
Net Energy Ratio (J delivered/J consumed)	**3.8373**	**3.8733**	**3.4806**

The fossil energy balances for the reference system and the two agricultural feedstocks are shown in the following table. The excess fuel gas, that is assumed to displace natural gas, offsets most of the natural gas that is consumed to produce the hydrogen. The fossil energy balances are quite similar to diesel fuel produced from crude oil.

Table 7-4 Fossil Energy Balance – Refined Bio Oil – Agricultural Feedstocks

Fuel	Diesel Fuel	Bio-oil	
Feedstock	Crude Oil	Wheat Straw	Switchgrass
	Joules Consumed/Joule Delivered		
Fuel dispensing	0.0005	0.0005	0.0005
Fuel distribution, storage	0.0056	0.0114	0.0114
Fuel production	0.1099	0.3729	0.3729
Feedstock transmission	0.0088	0.0241	0.0241
Feedstock recovery	0.1111	0.0059	0.0268
Feedstock Upgrading			
Ag. chemical manufacture	0.0000	0.0268	0.0345
Co-product credits	-0.0010	-0.2478	-0.2478
Total	**0.2350**	**0.1938**	**0.2224**
Net Energy Ratio (J delivered/J consumed)	**4.2556**	**5.1604**	**4.4960**

7.2 UPSTREAM EMISSIONS

The GHG emissions for the production and use of refined bio-oil are calculated by GHGenius for each stage in the production process.

7.2.1 Wood Feedstock

The GHG emissions for the three wood feedstocks is presented in the following table and compared to those of diesel fuel. Since the primary source of the GHG emissions is the electric power that is required for the system the emissions will vary by province depending on the carbon intensity of the electric power in each region.

Table 7-5 GHG Emissions – Refined Bio Oil - Wood Feedstock

Fuel	Diesel Fuel	Refined Bio-oil		
Feedstock	Crude Oil	Wood residues	Short Rotation Forestry	Standing Timber
	g CO_2eq/GJ (HHV)			
Fuel dispensing	114	114	114	114
Fuel distribution and storage	478	931	931	931
Fuel production	8,444	25,027	25,069	25,048
Feedstock transmission	902	674	3,449	3,449
Feedstock recovery	8,913	0	2,606	2,760
Feedstock Upgrading				
Land-use changes, cultivation	222	0	2,967	9
Fertilizer manufacture	0	0	1,308	0
Gas leaks and flares	1,773	0	0	0
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-240	0	0	0
Sub-Total Fuel production	20,607	26,746	36,446	32,311
Fuel Combustion	70,276	1,738	1,738	1,738
Grand Total	90,883	28,484	38,184	34,049
% Reduction		68.7%	58.0%	62.5%

7.2.2 Agricultural Residues Feedstock

The GHG emissions for the production of refined bio oil from agricultural feedstocks are shown in the following table. The lower feedstock drying requirements of these feedstocks and the availability of excess fuel gas to displace natural gas has a significant impact on the GHG emissions.

Table 7-6 GHG Emissions – Refined Bio Oil - Agricultural Residues Feedstock

Fuel	Diesel Fuel	Refined Bio-oil	
Feedstock	Crude Oil	Wheat Straw	Switchgrass
	g CO_2eq/GJ (HHV)		
Fuel dispensing	114	114	114
Fuel distribution and storage	478	931	931
Fuel production	8,444	25,514	25,514
Feedstock transmission	902	3,109	3,109
Feedstock recovery	8,913	520	2,360
Feedstock Upgrading			
Land-use changes, cultivation	222	0	3,431
Fertilizer manufacture	0	1,813	2,304
Gas leaks and flares	1,773	0	0
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	-240	-13,270	-13,270
Sub-Total Fuel production	20,607	18,731	24,494
Fuel Combustion	70,276	1,738	1,738
Grand Total	90,883	20,469	26,232
% Change		77.5%	71.1%

7.3 LIFECYCLE EMISSIONS

The refined bio oil can be distilled and the fractions blended into gasoline and diesel fuel. The lifecycle emission results for a 10% blend are compared to gasoline and diesel fuel produced from crude oil in this section.

7.3.1 Wood Feedstocks

The lifecycle GHG emissions for the gasoline fraction of refined bio oil blended at the 10% level is shown in the following table and compared to gasoline. These are for the default light duty vehicle in GHGenius. The source of the feedstock has some impact on the GHG emissions but the range of reductions is from 5 to 6% for the 10% blend.

Table 7-7 Lifecycle GHG Emissions Gasoline Fraction Refined Bio Oil

General fuel	Gasoline	Refined Bio-Oil		
Fuel specification	RFG30ppm S	RBO10	RBO10	RBO10
Feedstock	crude oil	Wood Residues	Short Rotation Forestry	Standing Timber
	g CO_2eq/km			
Vehicle operation	211.1	211.1	211.1	211.1
C in end-use fuel from CO_2 in air	0.0	-20.5	-20.5	-20.5
Net Vehicle Operation	211.1	190.6	190.6	190.6
Fuel dispensing	0.4	0.4	0.4	0.4
Fuel storage and distribution	1.5	1.7	1.7	1.7
Fuel production	40.8	45.1	45.2	45.2
Feedstock transport	2.9	2.9	3.8	3.8
Feedstock recovery	28.9	25.9	26.8	26.9
Feedstock Upgrading		0.0	0.0	0.0
Land-use changes, cultivation	0.7	0.7	1.7	0.7
Fertilizer manufacture	0.0	0.0	0.4	0.0
Gas leaks and flares	5.9	5.3	5.3	5.3
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0
Emissions displaced by co-products	-0.8	-0.7	-0.7	-0.7
Sub total (fuel cycle)	291.5	271.8	275.2	273.7
% changes (fuel cycle)	0.0	-6.9	-5.8	-6.3
Vehicle assembly and transport	*2.8*	*2.8*	*2.8*	*2.8*
Materials in vehicles (incl. Storage) and lube oil production/use	*27.6*	*27.6*	*27.6*	*27.6*
Grand total	322.0	302.3	305.7	304.2
% changes to CG (grand total)	-0.2	-6.3	-5.2	-5.7
% changes to RFG (grand total)	0.0	-6.1	-5.1	-5.5

The lifecycle emissions for the diesel fraction blended at 10% (vol.) and used in heavy duty vehicles is shown in the following table. The GHG emissions for the fuel blended into diesel fuel are slightly higher on a % basis due to the higher emissions for diesel fuel compared to gasoline.

Table 7-8 Lifecycle GHG Emissions Diesel Fraction Refined Bio Oil

General fuel	Diesel	Refined Bio-Oil		
Fuel specification	15 ppm S	RBO10	RBO10	RBO10
Feedstock	crude oil	Wood Residues	Short Rotation Forestry	Standing Timber
	g CO_2eq/km			
Vehicle operation	1,077.8	1,077.8	1,077.8	1,077.8
C in end-use fuel from CO_2 in air	0.0	-105.1	-105.1	-105.1
Net Vehicle Operation	1,077.8	972.7	972.7	972.7
Fuel dispensing	1.8	1.7	1.8	1.8
Fuel storage and distribution	7.3	8.0	8.0	8.0
Fuel production	129.5	155.5	155.6	155.6
Feedstock transport	13.8	13.5	17.9	17.8
Feedstock recovery	136.7	122.7	126.9	127.1
Feedstock Upgrading		0.0	0.0	0.0
Land-use changes, cultivation	3.4	3.1	7.7	3.1
Fertilizer manufacture	0.0	0.0	2.1	0.0
Gas leaks and flares	27.2	24.4	24.4	24.4
CO_2, H_2S removed from NG	0.0	0.0	0.0	0.0
Emissions displaced by co-products	-3.7	-3.3	-3.3	-3.3
Sub total (fuel cycle)	1,393.9	1,298.3	1,313.7	1,307.1
% changes (fuel cycle)	--	-6.9	-5.8	-6.2
Vehicle assembly and transport	*5.4*	*5.4*	*5.4*	*5.4*
Materials in vehicles (incl. Storage) and lube oil production/use	*31.1*	*31.1*	*31.1*	*31.1*
Grand total	1,430.4	1,334.8	1,350.2	1,343.7
% changes to Diesel (grand total)	--	-6.7	-5.6	-6.1

7.3.2 Agricultural Feedstocks

The same GHG emission information is available for agricultural feedstocks and is presented in the following tables. Lifecycle GHG emissions for the gasoline fraction of refined bio oil produced from agricultural feedstocks and blended at the 10% level is shown in the following table and compared to gasoline. These are for the default light duty vehicle in GHGenius.

Table 7-9 Lifecycle GHG Emissions Gasoline Fraction Refined Bio Oil

General fuel	Gasoline	Refined Bio-Oil	
Fuel specification	RFG30ppm S	RBO10	RBO10
Feedstock	crude oil	Wheat Straw	Switchgrass
	g CO_2eq/km		
Vehicle operation	211.1	211.1	211.1
C in end-use fuel from CO_2 in air	0.0	-20.5	-20.5
Net Vehicle Operation	211.1	190.6	190.6
Fuel dispensing	0.4	0.4	0.4
Fuel storage and distribution	1.5	1.7	1.7
Fuel production	40.8	44.9	44.9
Feedstock transport	2.9	3.6	3.6
Feedstock recovery	28.9	26.4	26.9
Feedstock Upgrading		0.0	0.0
Land-use changes, cultivation	0.7	0.7	1.7
Fertilizer manufacture	0.0	0.6	0.7
Gas leaks and flares	5.9	5.3	5.3
CO_2, H_2S removed from NG	0.0	0.0	0.0
Emissions displaced by co-products	-0.8	-4.8	-4.8
Sub total (fuel cycle)	291.5	269.3	271.1
% changes (fuel cycle)	0.0	-7.8	-7.2
Vehicle assembly and transport	*2.8*	*2.8*	*2.8*
Materials in vehicles (incl. Storage) and lube oil production/use	*27.6*	*27.6*	*27.6*
Grand total	322.0	299.8	301.5
% changes to CG (grand total)	-0.2	-7.0	-6.5
% changes to RFG (grand total)	0.0	-6.9	-6.3

The lifecycle emissions for the diesel fraction produced from agricultural feedstocks and blended at 10% (vol.) and used in heavy duty vehicles is shown in the following table.

Table 7-10 Lifecycle GHG Emissions Diesel Fraction Refined Bio Oil

General fuel	Diesel	Refined Bio-Oil	
Fuel specification	15 ppm S	RBO10	RBO10
Feedstock	crude oil	Wheat Straw	Switchgrass
	g CO_2eq/km		
Vehicle operation	1,077.8	1,077.8	1,077.8
C in end-use fuel from CO_2 in air	0.0	-105.1	-105.1
Net Vehicle Operation	1,077.8	972.7	972.7
Fuel dispensing	1.8	1.7	1.7
Fuel storage and distribution	7.3	8.0	8.0
Fuel production	129.5	153.8	153.8
Feedstock transport	13.8	17.0	17.0
Feedstock recovery	136.7	124.8	127.4
Feedstock Upgrading		0.0	0.0
Land-use changes, cultivation	3.4	3.1	8.0
Fertilizer manufacture	0.0	2.6	3.3
Gas leaks and flares	27.2	24.7	24.7
CO_2, H_2S removed from NG	0.0	0.0	0.0
Emissions displaced by co-products	-3.7	-22.2	-22.2
Sub total (fuel cycle)	1,393.9	1,286.0	1,294.2
% changes (fuel cycle)	--	-7.7	-7.1
Vehicle assembly and transport	*5.4*	*5.4*	*5.4*
Materials in vehicles (incl. Storage) and lube oil production/use	*31.1*	*31.1*	*31.1*
Grand total	1,430.4	1,322.5	1,330.7
% changes to Diesel (grand total)	--	-7.5	-7.0

8. DISCUSSION

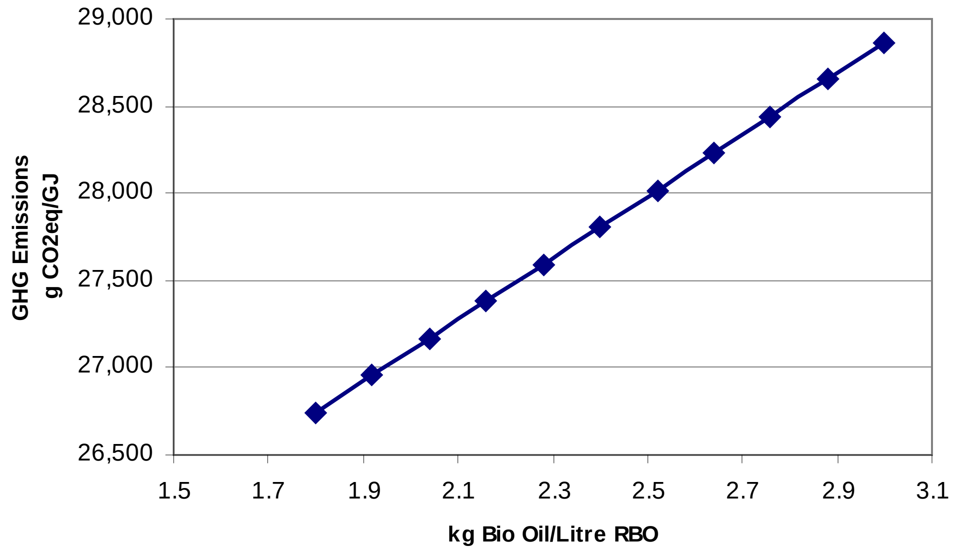
The production of pyrolysis oil from biomass is one way to produce a liquid fuel from solid materials. The process is relatively well understood and has been demonstrated on a reasonable scale at a number of locations. The bio oil that is produced is suitable for external combustion activities such as use in a boiler, a heater, or in a combustion turbine which can be attached to an electrical generator. The systems described provide a very good GHG emissions profile for most biomass feedstocks. Feedstocks that have naturally low moisture content can have extremely low GHG emissions as not only is bio oil produced but also significant quantities of fuel gas are produced.

The refining of pyrolysis oils to produce transportation fuels is less well developed but it is attracting significant attention. One of the drivers of this interest is the fact that the products that are produced are “drop in “ fuels. They can be blended at essentially any level and present no issues with the existing transportation fuel infrastructure. The fact that this process is less well developed means that there is greater uncertainty regarding the modelling results.

Two areas where there is some uncertainty is the yield of refined bio oil from the pyrolysis oil and the hydrogen consumption. The sensitivity solver in GHGenius can be used to address this uncertainty.

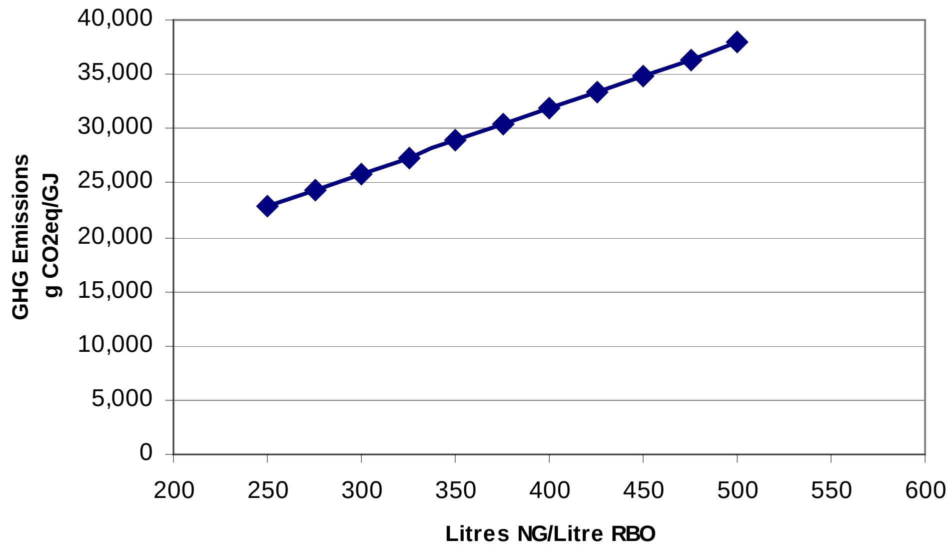
In the following figure the upstream GHG emissions from the refining of pyrolysis oil produced from wood residues is shown as a function of the yield (expressed as kg pyrolysis oils per litre of blending stock produced). The default yield is 1.8 kg of pyrolysis oil per litre of transportation fuel produced.

Figure 8-1 Sensitivity to Product Yield



Another area of uncertainty is the consumption of hydrogen in the process. In the model natural gas is consumed to produce the hydrogen. The sensitivity of the upstream GHG emissions to natural gas use is shown in the following figure. The default consumption is 315 litres of natural gas per litre of transportation fuel produced.

Figure 8-2 Sensitivity to Natural Gas Consumption



The GHGenius model has been update with a comprehensive and flexible pyrolysis oil pathway. The oil can be produced from wood and agricultural feedstocks, it can be used as a boiler fuel, a fuel to produce electricity though a turbine generator set, or it can be refined into transportation fuel components for blending with gasoline or diesel fuel.

9. REFERENCES

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