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Life cycle assessment of biofuels produced by the new integrated hydropyrolysis-hydroconversion (IH^2) process

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LIFE CYCLE ASSESSMENT OF BIOFUELS PRODUCED BY THE NEW INTEGRATED HYDROPYROLYSIS-HYDROCONVERSION (IH^2) PROCESS

By

EDWIN MALECHE

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

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This thesis, “Life Cycle Assessment of Biofuels Produced by the New Integrated Hydropyrolysis-Hydroconversion (IH^2) Process,” is hereby approved in partial fulfillment of the degree of MASTER OF SCIENCE IN CHEMICAL ENGINEERING.

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List of Symbols/Abbreviations

GHG	Greenhouse Gas
LCA	Life Cycle Assessment
GTI	Gas Technology Institute
MAF	Moisture and Ash Free
mt	metric tonne (1,000 kg)
IH^2	Integrated Hydropyrolysis and Hydroconversion
psi	Pressure units (pounds per square inch)
RFS	Renewable Fuel Standards
WtW	Wood to Wheel
EAF	Energy Allocation factor
IPCC	Intergovernmental Panel for Climate Change
eGRID	Emissions & Generation Resource Integrated Database
NETL	National Energy Technology Laboratory
EPA	Environmental Protection Agency

Abstract

Biofuels are alternative fuels that have the promise of reducing reliance on imported fossil fuels and decreasing emission of greenhouse gases from energy consumption. This thesis analyses the environmental impacts focusing on the greenhouse gas (GHG) emissions associated with the production and delivery of biofuel using the new Integrated Hydropyrolysis and Hydroconversion (IH^2) process. The IH^2 process is an innovative process for the conversion of woody biomass into hydrocarbon liquid transportation fuels in the range of gasoline and diesel.

A cradle-to-grave life cycle assessment (LCA) was used to calculate the greenhouse gas emissions associated with diverse feedstocks production systems and delivery to the IH^2 facility plus producing and using these new renewable liquid fuels. The biomass feedstocks analyzed include algae (microalgae), bagasse from a sugar cane-producing locations such as Brazil or extreme southern US, corn stover from Midwest US locations, and forest feedstocks from a northern Wisconsin location.

The life cycle greenhouse gas (GHG) emissions savings of 58%–98% were calculated for IH^2 gasoline and diesel production and combustion use in vehicles compared to fossil fuels. The range of savings is due to different biomass feedstocks and transportation modes and distances. Different scenarios were conducted to understand the uncertainties in certain input data to the LCA model, particularly in the feedstock production section, the IH^2 biofuel production section, and transportation sections.

Keywords

- Life cycle assessment
- $IH^{2,}$ Integrated Hydropyrolysis and Hydroconversion process;
- Biomass
- Greenhouse gas emission
- System Boundary
- Intergovernmental Panel on Climate Change

1. Introduction

Gas Technology Institute (GTI) has developed an innovative process for the conversion of woody biomass into hydrocarbon liquid transportation fuels in the range of gasoline and diesel. The process for this conversion is referred to as "Integrated Hydropyrolysis and Hydroconversion, IH^2". The environmental impacts of producing and using these new renewable liquid fuels are largely unknown, and therefore, MTU was contracted to conduct a cradle-to-grave Life Cycle Assessment (LCA) of these new biofuel products. In addition, several biomass feedstocks were included in the scope of the requested LCA, because it is anticipated that the IH^2 will be able to accommodate a variety of biomass feedstocks. The biomass feedstocks include algae (microalgae), sugar cane bagasse, corn stover, and forest feedstocks from a location in the Upper Midwest (Wisconsin). This report contains a preliminary LCA of IH^2 biofuels based on input data for the production and delivery of biomass feedstocks to a future biofuel facility, and also based on inputs for the IH^2 process provided by GTI.

1.1 Background on the IH^2 Process

A process flow diagram of the IH^2 process is shown in Figure 1.1. A detailed description of the IH^2 process can be found in GTI publications such as in (Marker et al. 2009). The process is carried out in two sequential yet integrated stages at moderate pressure (250-500 psi); hydropyrolysis and hydroconversion. Briefly, the process is carried out in two integrated steps: hydropyrolysis and hydroconversion. The first step is an exothermic catalytic fast hydropyrolysis reaction carried out in a fluid bed reactor at moderate hydrogen pressure. The product vapors from the first step are carried to the second conversion step, a hydrodeoxygenation reactor operating at essentially the same pressure as the first hydropyrolysis reactor. The hydrogen required for the IH^2 process is produced in a reformer using C1-C3 co-products, and therefore no external hydrogen source is needed, such as H^2 from steam reforming of methane. Other by-products of the process

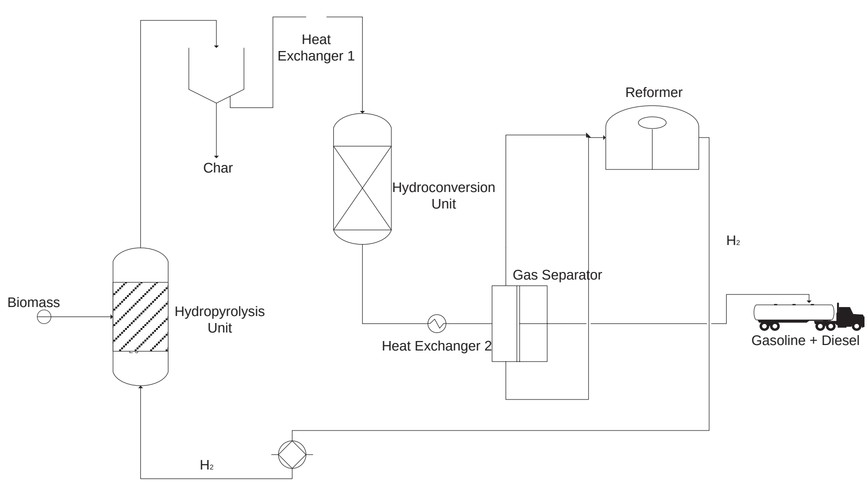

Figure 1.1 Process flow diagram of IH^2 process (Marker et al. 2009)

are char, high pressure steam, and ammonia / ammonium sulfate (not shown in Figure 1.1). Ammonia and hydrogen sulfide in the process condensate are stripped and oxidized to make ammonium sulfate which can be used as a fertilizer. More detailed diagram is shown in the appendix G.

1.2 Background on Feedstocks

Biomass types for this LCA were diverse representing feedstocks from forest, agricultural, and aquatic environments. These biomass types include algae (microalgae), bagasse from a sugar cane-producing location such as Brazil or extreme southern US, corn stover from a Midwest US location, forest feedstocks from a northern Wisconsin location. Inputs for the production, preparation, delivery, and storage of these biomass feedstocks were provided by several industrial partners in this project, as discussed later in this report. From this input data, we conducted a LCA of just the biomass production system from the "field" to the input of the IH^2 process. These analyses were useful to not only compare and contrast different feedstocks for biofuel production, but also to recommend steps to reduce the environmental impacts of such feedstock production systems.

1.3 LCA Research Objectives

The main research objectives for this report are;

1. Conduct a cradle-to-gate LCA of different biomass feedstocks for IH^2 biofuel production.
2. Conduct a cradle-to-grave LCA of IH^2 biofuels produced from different biomass feedstocks.
3. Investigate uncertainties in LCA inputs through scenario analyses.

The following sections of this report will provide details on the LCA methods used, on the input data included in the analysis, and on the greenhouse gas emissions of IH^2 biofuels. Comparisons will be made to petroleum fuels with respect to savings of GHG emissions over the IH^2 biofuel life cycle.

2. LCA Methods

LCA is mainly used to determine the environmental effects and performance of a product over its full life cycle. Motivation for using LCA in this current MS thesis is to not only satisfy the demands of the research sponsor (GTI), but also to enumerate the greenhouse gas emissions according to methodology from regulatory agencies such as the Environmental Protection Agency. LCA identifies the emissions and energy savings and aids in research and development. The LCA approach is chosen for this project, because it easily avoids having a narrow environmental concern outlook.

Alternative bio-based transportation fuels have the potential to decrease climate change emissions from vehicular transportation. The magnitude of this emission reduction can best be determined using the methods of life cycle assessment (LCA) by considering the entire life cycle of the new biofuel product from biomass cultivation through conversion to biofuel product, and use in vehicles. The methods for LCA put forth by the International Organization for Standardization (ISO 2006) were followed in this analysis. The main steps in conducting a life cycle assessment are as follow, and further details on each step will appear later in this report.

- Life cycle goal and scope and functional unit definition
- Life cycle inventory analysis
- Life cycle impact assessment
- Life cycle interpretation

2.1 Goal and Scope and Functional Unit

The main purpose of this research project is to help GTI develop a better and more sustainable biofuel manufacturing process and product. This is done by estimating the environmental burdens in the form of GHG emissions that are associated with the GTI (IH^2) biofuel production process. In satisfying this main purpose, this study will evaluate the cradle-to-grave life cycle assessment (LCA) of the Gas Technology Institute (GTI) Integrated Hydropyrolysis and Hydroconversion (IH^2) production chain, including the production of input feedstocks and use of output IH^2 biofuels. The goal is to compare environmental impacts of IH^2 biofuels to equivalent fossil fuels in order to determine savings of emissions, but along this path, intermediate results for each biomass feedstock will be generated and compared to each other. The scope of this LCA will be from cradle-to-grave and the impacts of concern are greenhouse gas emissions. The functional unit for biomass feedstocks and IH^2 biofuels will be 1 dry metric ton and 1 MJ of energy, respectively. The input data for these LCAs will be organized by the scale of production; 1 dry metric ton for biomass inputs, and for IH^2 biofuels production, 2,000 moisture and ash-free (MAF) metric tons/day facility. The LCA results for IH^2 biofuels were generated by dividing the LCA emissions by the total energy content in MJ of IH^2 biofuel produced each day from the facility. This biofuel production changed depending on the specific biomass input feedstock input to the facility, as shown in the subsequent sections.

2.2 Life Cycle Diagram and System Boundary

The life cycle diagrams describing each IH^2 biofuel production system is presented in Figure 2.1 for microalgae, sugar cane bagasse, corn stover, and forest feedstocks. Each diagram has similarities and subtle differences, especially in the feedstock production stage, the first stage on the left of each diagram. Fuels, electricity, lubricants, and grease are common inputs for each of the feedstock production stages because of the presence of machines for biomass collection and equipment for pumping algae solutions (microalgae) and for size reduction (bagasse, stover, and forest feedstocks). Fertilizers are required for stover feedstocks because this feedstock is produced from intensive agricultural practice which involved application of inorganic and organic fertilizers. When this feedstock is collected off of the land, the nutrients are removed with and must be replaced for successful subsequent crop production. At the IH^2 conversion to biofuels stage, inputs of catalysts, electricity, and other chemicals are included, and outputs of co-products steam, ammonia, and ammonium sulfate are produced. Diesel fuel for transportation of IH^2 biofuels to locations of blending into fossil fuel stocks is included, and consideration is given to transport to filling stations and also for emissions of greenhouse gases from vehicle use of the biofuels.

The next section will present tables of input data for production of biomass feedstocks and also of IH^2 biofuels produced from these feedstocks.

This analysis also considers the land use change which could both directly and indirectly affect the impact analysis. The direct land use change is where food crop land is converted to grow biofuel crops. During the land preparation step, some additional GHG emissions may occur and any carbon stock changes before and after establishment of bioenergy crops will alter the GHG analysis by contributing additional CO_2 sequestration or increasing GHG emissions. The indirect land use change is where agriculture land is converted to grow biofuel crops instead of food crops. Because food demand is "inelastic" meaning that food demand must be met as the highest priority, when agricultural lands in food production are diverted to bioenergy crop production, somewhere in the world natural wild lands will be converted to food production, with associated land use change GHG emissions.

Although land use change emissions were considered in this study, it was concluded that these effects are negligible for the following reasons. First for micro algae feedstock, this was acquired from natural ponds with runoff water from agricultural land practices, thus this had neutral effect to the land use change. Secondly for the corn stover, the feedstock was acquired from the farms as a waste within sustainable practices such as soil quality is not diminished, and therefore no extra land was required to satisfy food production, leading to having no effect to land use change. Thirdly, the bagasse feedstock was acquired as a waste from the sugar cane processing facility; therefore no land use change resulted from this use bagasse. Lastly, the forest resource biomass was considered as residue and therefore no extra land was required, leading to having no effect on land use change.

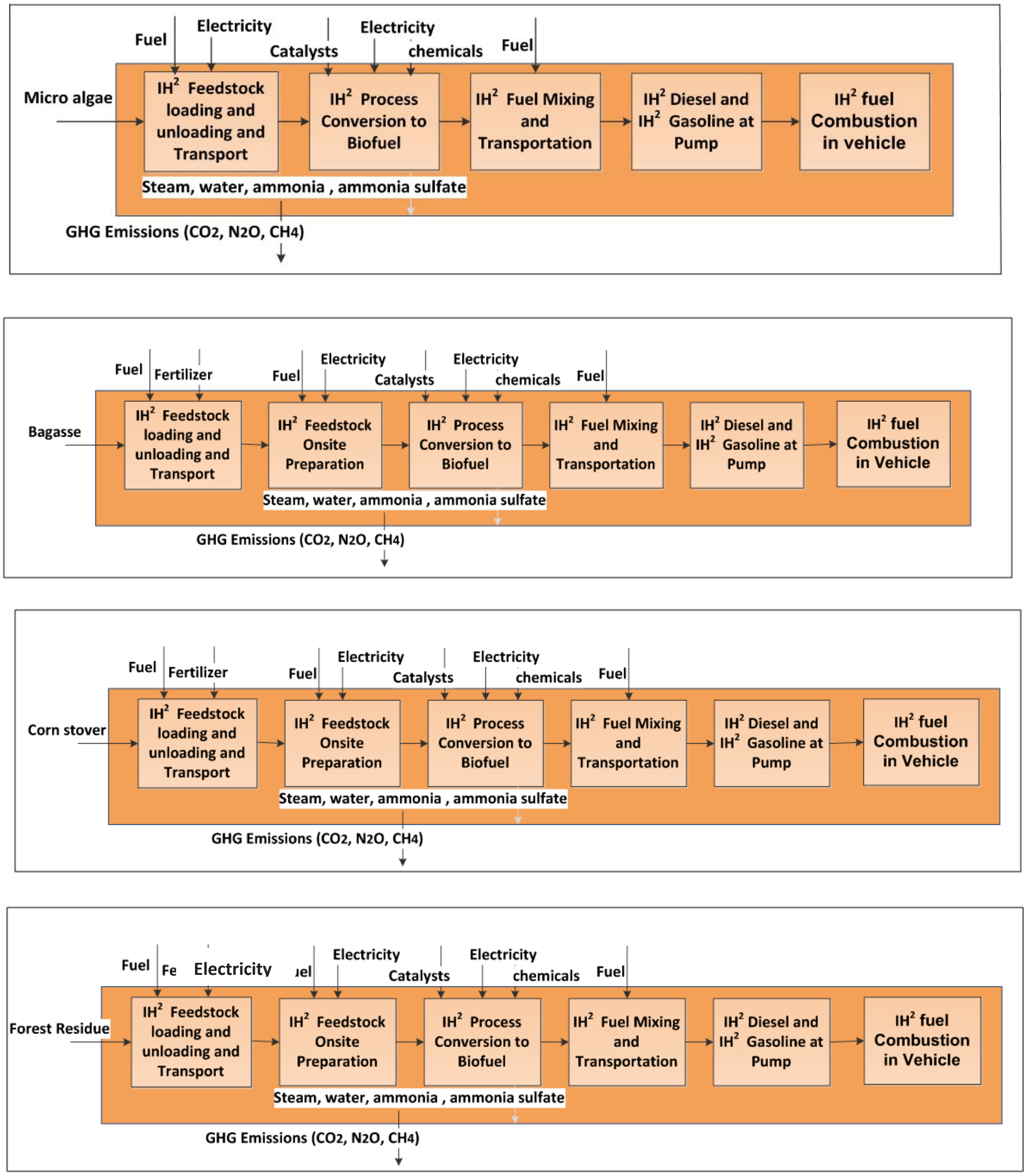

Figure 2.1 Life cycle diagrams for production of IH^2 biofuels from different biomass feedstocks.

3. Life Cycle Inventory

The life cycle inventory is the list of emissions associate with each input to the IH^2 biofuel life cycle. The total inventory is the sum of emissions for all of the inputs. The inventory of emissions resides within input-specific ecoprofiles in the ecoinvent database in SimaPro 7.2, the LCA software tool used in this study. For example, if diesel fuel is one input to the biomass feedstock production stage, an ecoprofile in the ecoinvent database in SimaPro 7.2 has a list of emissions inventory data for the production of this diesel fuel. We created a diesel combustion emission ecoprofile with an emission factor of 3.17 kg CO_2 / kg petroleum diesel combusted based on stoichiometry. Similarly, other ecoprofiles were used for other life cycle inputs such as transport by road (includes combustion emissions of diesel fuel), for fertilizer inputs, chemicals used, and catalysts. These inventories have data for calculation of many categories of environmental impact, but in this study the primary and sole category of interest is greenhouse gas emissions and global warming. The emissions inventory of the greenhouse gases CO_2, N_2O, CH_4, refrigerants, and solvents is therefore of primary interest. This study did not include the N_2O emissions associated with nitrogen (N) fertilizers allocated to corn stover and cane bagasse production because the removal of N with these biomass feedstocks will have the effect of reducing N_2O emissions compared to the business-as-usual case (feedstocks left on the land to decompose and emit N_2O). This emissions reduction is compensated for when additional N fertilizer is applied to the subsequent corn and sugar cane crops in equal amounts. This assumption is justified based on "Tier 1" emission factors used in the Intergovernmental Panel on Climate Change (IPCC) (Eggleston et al. 2006).

3.1 Inputs for Biomass Feedstock Production

3.1.1 Inputs for Microalgae Production

Table 3.1 below shows the algae production inputs used for the life cycle assessment for the Aquaflow Bionomic Corporation (ABC). This data was obtained from a spreadsheet provided by ABC based on Blenheim site Power assuming 100 g algae/m^3 cell density. The data was then divided into different sections. The first section was the raw material section which includes use of fertilizers which are all provided by the sewage plant or natural water body. The second section is the Pump Shed, which includes the supply and the discharge pumps; 5 electric motors whose energy use is measured in kWh/kg dry algae recovered. The third section is the New Harvest Unit. This section contributes much of the energy and is a total of 6 motors. The fourth section is the De-watering process section where several activities take place including removal of excess water by draining and rising which is done using electrical motors. The other important activity that takes place in this section, is use of chemical additives to agglomerate the algae at the dewatering stage to enhance the harvesting process. Lastly is the transportation to the IH^2 processing which is assumed to be done over a 100 km distance. The moisture in the algae was taken into account for this transport step assuming 80% moisture content.

The main inputs in Table 3.1 for the LCA analysis of the GHG emission was the electricity used by the motors at the pump shed section and new harvest unit section.

Greenhouse gas emissions per kWh of electricity used were obtained from the US Environmental Protection Agency eGRID website assuming a U.S. average grid (US

Table 3.1

Data inputs for algae cultivation, harvesting, and transport for Aquaflow Bionomic Corporation. Basis is 1 dry metric ton microalgae and 100 g algae / m^3.

Life Cycle Stage	Items Used	Amounts
Raw Material Productions	Fertilizer	N/A
Harvesting of Algae		
	Electricity for separation	
	Hydraulic oil	negligible
	Lubrication oil	negligible
Pump shed	Motor(1)	10 kWh
	Motor(2)	100 kWh
	Motor (3)	500 kWh
	Motor(4)	800 kWh
	Motor(5)	100 kWh
New Harvest units	Motor(6)	100 kWh
	Motor(7)	100 kWh
	Motor(8)	40 kWh
	Motor(9)	40 kWh
	Motor(10)	20 kWh
	Motor(11)	20 kWh
De-watering	Motor(12)	80 kWh
	Motor(13)	20 kWh
0.076 ton/ton of dry algae	Chemical additives	
	Fuel	
Conveyance of Algae	Electricity	
Transport		100 km

EPA 2011) in the base case analysis. The emissions in this eGRID database are for electricity production only and do not include upstream process of production of primary energy (coal, etc.). To account for this, 10% extra emissions were added for these upstream processes. These additional emissions were arrived at after review of several electricity generation ecoprofiles in the ecoinvent database in SimaPro. The data provide by the ABC in Table 3.1 was divided by three so as to get the algae cell density of 300 g algae/m^3 because the original data was for 100 g algae/ m^3 cell density. The process flow diagram of production of micro algae is shown in appendix I.

3.1.2 Inputs for Bagasse Production

Bagasse is considered a waste from the sugar or cane ethanol production process, and in this analysis it is assumed available with no environmental burden from its production. However, environmental impacts accumulate from bagasse handling in the IH^2 biofuels production life cycle. The step wise process of bagasse handling as a feedstock includes loading, transportation, and unloading to the IH^2 facility. The first stage involves using a diesel powered front loader to transfer bagasse into trucks for transport. The second stage is the transportation stage, where the bagasse is transported using a 16-32 ton truck to be delivered to the IH^2 facility. The third stage is the unloading of the bagasse to IH^2 facility storage, and finally loading into the IH^2 facility.

The main inputs in Table 3.2 are for loading/unloading and for transportation, which involves the use of 16-32 ton trucks to the IH^2 facility. The bagasse may be ground to decrease the size so as to have the desirable size for the IH^2 processing. The first stage is the loading of unbaled bagasse using front loaders directly from the bagasse piles at sugar milling factory onto trucks. There are three such loading/unloading steps and this is the cause of the factor of 3 in the inputs of Table 3.2 for diesel fuel. The factor of 1.1 converts from short tons, the basis for the input data from (Morey et al. 2010), to metric tons, and the factor of 1.45 accounts for the field moisture content of the bagasse, assumed to be 45%. The (Morey et al.2010) study was on corn stover, but the steps in the feedstock supply chain and equipment used are very similar to the bagasse supply chain, and therefore the use of this source of input data is justified. Drying of bagasse prior to entering IH^2 reactors is not included in this input data, but is included in the IH^2 process analysis section. There is not factor of 3 for lubricating oils because the input value includes this already. Emissions for combustion of diesel fuel is included in the analysis for loading / unloading steps using stoichiometric factor of 3.17 kg CO_2 / kg diesel combusted. Diesel volume in gallons was converted to kg by using a density of 0.85 kg diesel / L diesel and converting between gallons and liters.

Table 3.2

Inventory data for bagasse loading, transportation, and unloading on a basis of 1 dry metric ton of feedstock.

Life Cycle Stage	Inputs	Units
Loading and unloading		
Diesel fuel	0.04625*3*1.1*1.45	gallons/ton
Lubricating oil	0.00089*1.1*1.45	gallons/ton
Transportation (assume 100 km distance)		
Transport, lorry 16-32t, EURO3/RER S	100	tkm

3.1.3 Inputs for Corn Stover Production

Corn stover feedstock production includes collection from the fields, loading, transportation, unloading, and fertilizer replacement to the fields to compensate for nutrients removed with the stover. We assume that there will be no change in soil organic carbon due to removal of some, but not all, of the stover from the field, and therefore no emissions of CO_2 from C stock change. The first stage in Figure 1 involves diesel-powered stalk shredder equipment used for shredding of the corn stover. Then the stover is collected, which involves raking and baling, and processed into round bales. Next is stover loading, where the round bales are lifted and moved using a front loader onto trucks for transportation. Then, the corn stover is transported and delivered to the IH^2 facility, and then finally unloaded to the storage area.

This analysis assumes 70% corn stover removal per unit land area with collection every other year that corn is grown, resulting in an average stover removal of 35% of area per year. This leads to more efficient, and less costly collection process and less soil compaction than harvesting of 35% of the corn stover each year. Lastly this analysis assumes that there is nutrient replacement to the corn stover harvested fields. Fertilizers rich in nitrogen, phosphate and potassium are used to replenish the nutrients lost from the field so as to have adequate nutrients for the growth of the next corn crop.

Table 3.3 shows LCA inputs for corn stover handling from the corn field to the IH^2 process as obtained from a recent research article (Morey et al.2010) and (Maleche et al. 2011). One of the key inputs is the nutrient replacement. The replacement fertilizers used are diammonium phosphate, ammonia solution, and potassium sulfate. The main diesel input in this process is during the stover collection stage, which involves stalk shredding, raking and baling. The stalk shredding occurs after harvesting of the corn and involves decreasing the size of the stalks by use of a mechanical shredder, which is diesel powered. The shredding is done so as to increase the volume of harvested corn stover and facilitate drying to the target moisture content of 15-20%. The shredded corn stover is then raked using a diesel powered machine. Lastly the stover is baled into round bales for easy handling and transport. The collection stage is the most critical step due to finding the suitable time period for the shredding, racking and round bailing of the corn stover with 15-20% moisture. The third main stage is the transportation stage, in this stage the stover in the form of round bales is loaded onto and transported by truck (25-ton). The last stage in this process is the unloading of stover bales to storage, and then loading of stored stover into the IH^2 process. Transport distance by truck to the IH^2 facility from the field is on average 30 miles (Morey et al. 2010).

Table 3.3

Inventory data for the corn stover with a basis of 1 dry metric ton of feedstock. Each fuel and lubricant entry in this table is divided by 0.85 to convert to dry basis.

Life Cycle Stage	Inputs	Units
Collection		
Stalk Shredding		
Lubricating oil	1.29E-03	gallons
Diesel fuel	0.222	gallons
Raking		
Lubricating oil	3.53E-04	gallons
Diesel fuel	0.053	gallons
Baling		
Lubricating oil	1.29E-03	gallons
Diesel fuel	0.225	gallons
Bale moving		
Lubricating oil	2.35E-03	gallons
Diesel fuel	0.424	gallons
Loading		
Diesel fuel	0.134	gallons
Lubricating oil	1.53E-03	gallons
Transportation		
Diesel	0.408	gallons
Lubricating oil	2.47E-03	gallons
Unloading		
Diesel fuel	0.134	gallons
Lubricating oil	1.53E-03	gallons
Nutrients Replacement		
Ammonia	9.42	kg
Diammonium phosphate	2.9	kg
Potassium sulfate	12.7	kg

3.1.4 Inputs for Timber Resources Production

Mr. John Gephardt has developed a model of timber resource procurement for northern Wisconsin on behalf of Johnson Timber Company (JTC) and provided information on the quantities of fuel, lubricants, and electricity based on the amount of feedstock delivered per day. This model was based on a wide range of available woody feedstock that were identified around a site located in Park Falls, Wisconsin. Types of feedstock included are: logging residues; un-merchantable timber; un-marketable timber; marketable timber; and mill residues. Each feedstock type has unique requirements in their collection, transport, and processing needs. Within any one type, quantities were available at differing distances to Park Falls. Based on the delivered costs for each feedstock the JTC model selects a blend of feedstock which would result in the lowest possible total costs for each plant size that was evaluated. The price of diesel fuel was included as a variable in the model. This allowed the model to take into account how the blend of feedstock in the output would be influenced as diesel prices change.

The stepwise process of wood and forest residue production in JohnsonTimber Company is illustrated in the flow sheet below in Figure 3.1. The first stage is the collection of resources from the forest. The processes involved in this stage include skidding and cutting of the biomass from the forest to the required length for transportation, roadside chipping and debarking, and loading of the round wood, slabs and chips using a log loader and chip dumps. The second stage is road transport in which the round wood, bark, sawdust, slabs, fuel rods, and woodchips are transported for processing to the IH^2 facility. The last stage is the processing stage. In this stage size reduction occurs whereby there is conversion of the round wood and other sized biomass into chips small enough for the IH^2 process. This stage also includes the use of grinders which can be either stationary (electrical powered) or mobile (diesel powered). In this analysis the grinders are assumed to be either stationary or mobile and are electric-powered according to information from Mr. Gephardt. In the last stage we have the mixing loaders which are used to blend the various types of feed stock which use screens to remove the oversized materials to the IH^2 process.

The JTC model was used to evaluate biomass inputs rates ranging from 50 to1,750 dry short tons/day. Figure 3.2 shown below illustrates how the percentages of hardwoods and softwoods changed with increasing plant size. Within the supply area, hardwoods comprise approximately 70% and softwoods 30% of the available feedstock. The higher percentage of hardwood at the smaller plant sizes is the result of low valued hardwood residues available from an adjacent pulp and paper mill. For the study plant sizes of 500 dry short tons/day and 1,000 dry short tons/day of feedstock were selected for evaluation. The feedstock selected for each plant sized was values were chosen from an economic stand point. Figure 3.3 shows the distribution of total diesel fuel among feedstock collection, transportation, and processing (chipping). Above 1,000 dry short tons/day, there is not much change in total diesel consumption per dry short ton.

Table 3.4 and 3.5 show the wood and forest residue production inputs used for the life cycle assessment for the Johnson's Timber Company. This data was based on an assumption of $3.00 and $6.00 per gallon of diesel fuel in two separate scenarios. This data was divided into different sections. The first section involved the raw material collection which includes the use of lubricants, fuel, grease, hydraulic fluid, and gasoline. The second main section is the transportation which includes the use of lubricants and fuel. The third main section is the yard processing section. In this section several activities take place including wood chipping, screening, and conveying. These inputs include electricity for running the motors, and fuel and lubricants inputs for the different yard equipment.

The main data inputs in Table 3.4 and 3.5 are the diesel used for the collection and transportation of the wood to the IH^2 processing plant. Lubricants and hydraulic oil values were assumed based upon the diesel consumption estimates provided by Mr. Gephardt on behalf of JTC. The fertilizer and other additives are assumed to be negligible because no use of these inputs occurs for timber cultivation. The main biomass feed stock inputs are underutilized round wood sources and the non-commercial tree species, since they are undesirable in the manufacturing of traditional forest products**.** Lastly the other main biomass feedstock inputs are forest residues which include tops, limbs and fuel rods. The fuel rods are defined as the round woods that do not meet the size and quality standards for traditional forest products and examples of this are the oversized and undersized stems from saleable and unsaleable trees.

In this inventory the second major input is the electricity used for the size reduction which is used in the electric motors of the stationary chipper. The materials which require high energy for size reduction are the sawmill slabs, fuel rods, and round woods which go through extensive processing for the size reduction. The main equipment used in the yard is the stationary chipper, conveyor system, over size screen, secondary hog and chip dumps. On the other hand, there are materials which do not require a lot of energy for size reduction due to be ready to use or being available in fairly small size particles.

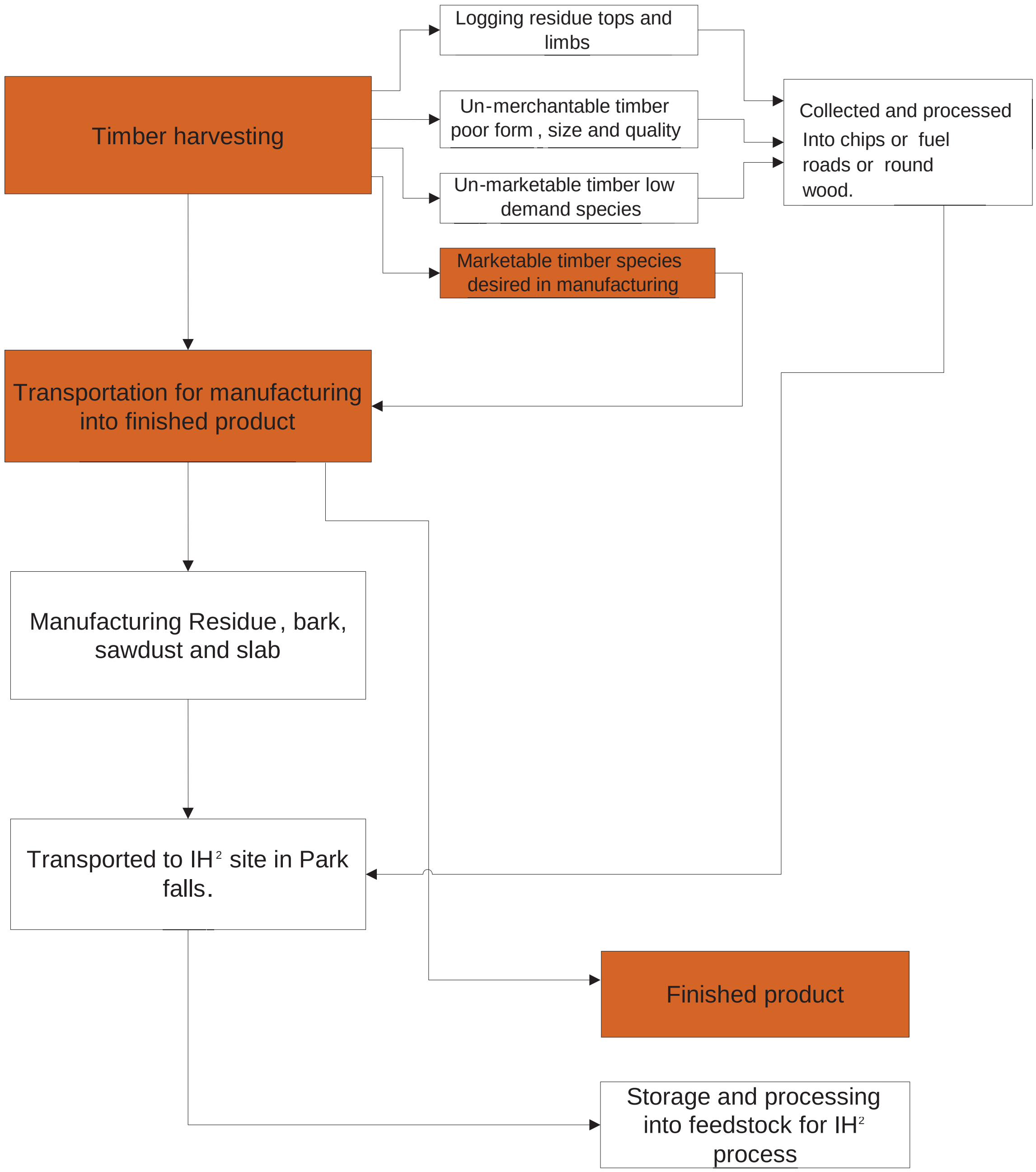

Figure 3.1 Process flow diagram for wood and forest residue production from Johnson Timber Company. The shaded boxes represent steps which are not included in the analysis presented here.

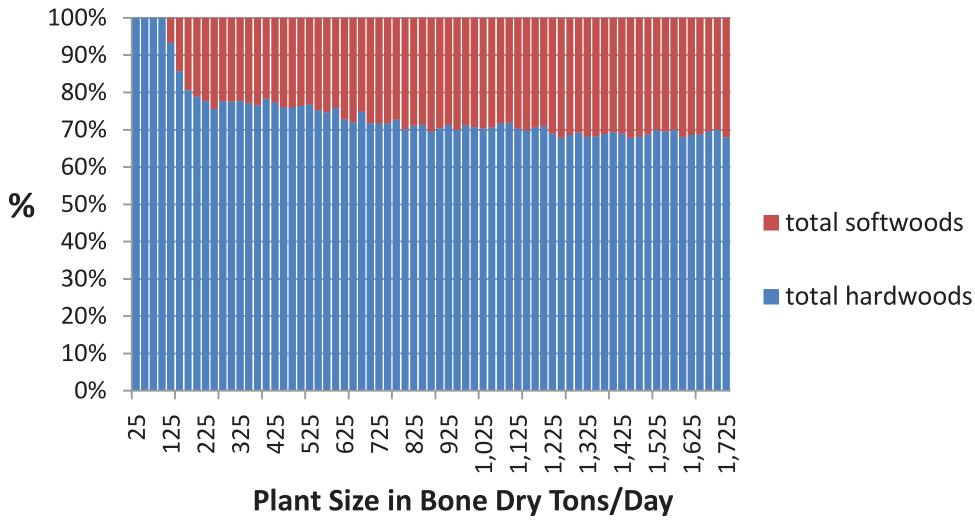

Figure 3.2 The percentages of hard wood and soft wood used as the feed stock input with varying plant size.

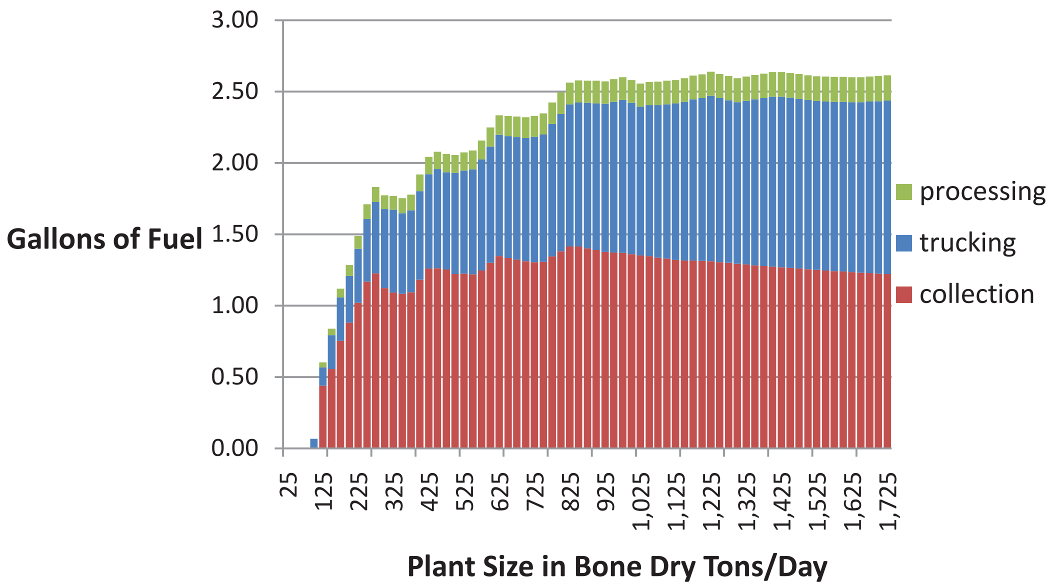

Figure 3.3 Diesel fuel consumption for collection, trucking, and processing as a function of biomass input rate.

Table 3.4
Data inputs for wood and forest residue raw material collection, transportation and yard processing based on 1 dry short ton biomass with an assumption of $3 per gallon of diesel fuel.

Life Cycle Stage	Items Used	Amounts 500 dry tons/day	Amounts 1000 dry tons/day
Collection (Raw material Inputs)	Diesel	1.220 gallons	1.360 gallons
	Lubricating oil	0.014 gallons	0.018 gallons
	Grease	0.038 gallons	0.048 gallons
	Hydraulic fluids	0.014 gallons	0.018 gallons
	Gasoline	0.039 gallons	0.050 gallons
Transportation	Diesel	0.707 gallons	1.059 gallons
	Lubricating oil	0.014 gallons	0.017 gallons
	Hydraulic fluids	0.014 gallons	0.018 gallons
	Tubes of grease	0.038 gallons	0.048 gallons
Yard processing	Diesel	0.126 gallons	0.160 gallons
	Lubricating oil	0.016 gallons	0.016 gallons
	Hydraulic oil	0.016 gallons	0.016 gallons
	Tubes of grease	0.043 gallons	0.043 gallons
(note: US average grid)	Electricity	29.8 kWh	29.8 kWh

3.2 Inputs for IH^2 Biofuels Production

3.2.1 Inputs for Microalgae IH^2 Biofuels Production

Table 3.6 shows the IH^2 facility inputs and outputs provided for the life cycle assessment. The data was obtained from Terry Marker (GTI) and was based on a 2,000 dry metric ton/day plant. The accuracy of input data was verified by carrying out a mass and energy balance as shown in appendix A. This data was based on an assumption of 20% moisture content of the microalgae biomass feedstock that enters the IH^2 process after being dried from 80% moisture. The data was divided into different sections. The first section includes product yields in which the two main products were the IH^2 renewable diesel and gasoline. The second main section is the raw materials which encompassed the dry biomass and total catalyst which includes the catalyst used for hydropyrolysis and hydroconversion. This catalyst is used for removing all oxygen. Other inputs in this section are the cooling water chemicals plus the boiler feed water chemicals (BFW). The third main section is the utilities section electricity used to run the IH^2 process and natural gas used for drying of the algae. The fourth section is the waste products section which has CO_2 in exhaust that is produced from the reformer. Lastly there is the co-product section which includes water produced from the IH^2 processes, ammonia and ammonia sulfate, which are all mixed in specific ratios so as to produce fertilizers for sale. These co-products results in a GHG reduction credit for the IH^2 life cycle using a displacement allocation. Input tables are similarly organized for other feedstock-specific IH^2 inputs below. The simplified process flow diagram is shown in appendix H.

The inventory data from Table 3.6 was input to SimaPro, the LCA software tool used for this evaluation. This input data is shown in Table 3.6, organized by major life cycle stage. In the results section, GHG emissions will be reported for each of the major life cycle stages. Each of the inputs shown in Table 3.6 was multiplied by an energy allocation factor (EAF) which was calculated to be 1 so that the inventory would be apportioned to the main products (renewable diesel and gasoline) as well as the co-products, steam exported from the IH^2 process. The energy allocation factor was calculated using a methodology to be presented next. GHG emissions for the electricity used in the IH^2 process were the US average grid (eGRID 2011) using an ecoprofile in the ecoinvent™ database in SimaPro. The eGRID emissions are from the site of the power plant only, and do not include upstream and transmission loss effects. In order to compensate for this, the eGRID emissions were multiplied by a factor of 1.1 twice; once for upstream processes (10% additional inventory) and a second time for transmission losses (10% loss assumed).

Table 3.5

Data inputs for wood and forest residue raw material collection, transportation and yard processing based on 1 dry short ton biomass with an assumption of $6 per gallon of diesel fuel.

Life Cycle Stage	Items Used	Amounts 500 dry tons/day	Amounts 1000 dry tons/day
Collection (Raw material Inputs)	Diesel	1.047 gallons	1.197 gallons
	Lubricating oil	0.013 gallons	0.017 gallons
	Grease	0.038 gallons	0.048 gallons
	Hydraulic fluids	0.014 gallons	0.018 gallons
	Gasoline	0.039 gallons	0.050 gallons
Transportation	Diesel	0.678 gallons	0.914 gallons
	Lubricating oil	0.014 gallons	0.017 gallons
	Hydraulic fluids	0.014 gallons	0.018 gallons
	Tubes of grease	0.038 gallons	0.048 gallons
Yard processing	Diesel	0.122 gallons	0.160 gallons
	Lubricating oil	0.016 gallons	0.016 gallons
	Hydraulic oil	0.016 gallons	0.016 gallons
	Tubes of grease	0.043 gallons	0.043 gallons
(note: US average grid)	Electricity	29.8 kWh	29.8 kWh

Table 3.6

Aquaflow Bionomic IH^2 inputs and outputs inventory for 80% moisture microalgae feedstock reduced to 20% moisture. Basis: 1 day operation of 2,000 MAF metric ton/day feedstock plant operation.

Feed stock type	Units	Amounts
Product yields		
IH^2 Gasoline	mt/day	448
IH^2 Diesel	mt/day	448
Raw material		
Dry Biomass (MAF)	mt/day	2000
Total catalysts used	mt/day	0.35
BFW chemicals	mt/day	0.04
MDEA makeup	mt/day	0.002
Utilities		
Electricity required	kWh	256*24
Natural gas for drier (to decrease algae moisture)	mt/day	538
Waste products		
Char +ash	mt/day	274
CO_2 exhaust	mt/day	1030
Co-products(credits)		
Water	mt/day	8830
Ammonia	mt/day	168
Ammonium sulfate	mt/day	48

3.2.2 Inputs for Bagasse IH^2 Biofuels Production

Table 3.7 shows the IH^2 facility inputs and outputs for the life cycle inventory of bagasse biofuels. The data was provided by Terry Marker (GTI) and was based on a 2,000 metric ton (MAF) of bagasse input/day plant with feedstock moisture of 45%. The accuracy of the input data was verified by carrying out a mass and energy balance as shown in appendix B. The data was divided into different sections, similar to those described in section 3.2.1. The factor of 2 appearing converts inputs to the basis of 2,000 MAF mt/day from the original set of data for a 1,000 mt/day facility.

The export steam was calculated in two different scenarios

i) Char is burned to produce steam.

ii) Char is a co-product and exported from the product system.

Both of these scenarios affect the energy allocation calculation as shown below in section 4.2.

The bagasse was dried from 45% moisture to 20% moisture to enhance size reduction and IH^2 conversion. The energy for drying was supplied by steam generated by the exothermic reactions occurring in the hydropyrolysis and hydroconversion reactions and was accounted for in the energy balance calculations which yielded the net steam exported (provided by GTI).

The input data from Table 3.7 was entered into SimaPro 7.2, the LCA software tool used for this evaluation. Each of the inputs shown in Table 3.7 was multiplied by an energy allocation factor (EAF) which was 0.897 in the scenario where char is burned and 0.724 in the scenario which char is considered as a co-product. The inventory is allocated to the main products (IH^2 diesel and gasoline), and the co-products, ammonia and ammonium sulfate, provide an environmental impact credit in this analysis. The energy allocation factor was calculated using a methodology to be presented in section 4.2.

Table 3.7

IH^2 inputs and outputs for the 45% moisture bagasse feedstock. Basis is 1 day operation of 2,000 moisture and ash free (MAF) metric ton/day plant operation.

Feed stock type	Units	Amounts
Product yields		
IH^2 Gasoline	mt/day	216*2
IH^2 Diesel	mt/day	70*2
Raw material		
Dry Biomass (MAF)	mt/day	2000
Total catalysts used	mt/day	0.35
BFW chemicals	mt/day	0.04
MDEA makeup	mt/day	0.002
Utilities		
Electricity required (US average grid)	kWh	256*24
Diesel fuel (used by Vermeer HG 200grinder)	mt/day	11.9
Waste products		
Char +ash	mt/day	167*2
CO_2+ hydrogen exhaust	mt/day	785*2
Co-products(credits)		
Water	mt/day	1640
Ammonia	mt/day	3.3*2
Ammonium sulfate	mt/day	3.3*2
Boiler feed water*	mt/day	1.3
export steam(steam driven compressor)char product made	mt/day	313.3
export steam(steam driven compressor)char burned	mt/day	1462.6

3.2.3 Inputs for Corn Stover IH^2 Biofuels Production

Table 3.8 shows the IH^2 facility inputs and outputs provided for the life cycle assessment. The data was obtained from Terry Marker (GTI) and Eric Tan (NREL) and was based on a 2,000 dry metric ton/day plant based on an assumption of 20% moisture content of the corn stover biomass feedstock. The accuracy of input data was verified by carrying out a mass and energy balance as shown in appendix C. The data was divided into different sections as shown previously.

The input data from Table 3.8 was entered to SimaPro 7.2, the LCA software tool used for this evaluation. Each of the inputs shown in Table 3.8 was multiplied by an energy allocation factor (EA factor) which was calculated to be 0.755 so that the inventory would be apportioned to the main products (renewable diesel and gasoline) as well as the co-products, steam exported from the IH^2 process.

Table 3.8

IH^2 inputs and outputs inventory for the 20% moisture corn stover feedstock. Basis is 1 day operation of 2,000 moisture and ash free (MAF) metric ton/day plant operation.

Feed stock type	**Units**	**Amounts**
Product yields		
IH^2 Gasoline	mt/day	320
IH^2 Diesel	mt/day	200
Raw material		
Dry Biomass (MAF)	mt/day	2000
Total catalysts used	mt/day	0.35
BFW chemicals	mt/day	0.0194
MDEA makeup	mt/day	0.0007
Utilities		
Electricity required (US average grid)	kWh	25624
Diesel fuel (used by Vermeer HG 200grinder)	mt/day	11.9
Waste products		
Char +ash	mt/day	260
CO2 exhaust	mt/day	1107.2
Co-products(credits)		
Water	mt/day	160
Ammonia	mt/day	15.6
Ammonium sulfate	mt/day	9.8
Boiler feed water*	mt/day	2,841
export steam(steam driven compressor)600psi,700	mt/day	3,734

Table 3.9

Forest resources IH^2 inputs and outputs inventory for the 30% moisture and 50% moisture feedstock. Basis: 1 day of operation of 2,000 dry metric ton/day facility.

Inputs	Units	Amounts
Product yields		
IH^2Gasoline	mt/day	319.9
IH^2 diesel	mt/day	199.9
Raw material		
Dry Biomass	mt/day	2000
Total catalysts	mt/day	0.35
Cooling Tower chemicals	mt/day	0.007
BFW chemicals	mt/day	0.019
Utilities		
Electricity (US average grid)	kWh	6240
Electricity for feedstock sizing (US average grid)	kWh	5537. 8
Diesel fuel (assumed rate 10 gal/hr)	mt/day	0.1
Waste products		
Hydrogen	mt/day	16.4
Co-Products (credits, or allocation)		
Water	mt/day	159.9
$CO_2 + H_2$	mt/day	43.4
Ammonia (credit)	mt/day	14.6
Ammonium sulfate (credit)	mt/day	3.2
Export steam driven compressors (30%moisture) (allocation)	mt/day	2917.1
Export steam driven compressors (50% moisture) (allocation)	mt/day	1447.8

3.2.4 Inputs for Forest Resources IH^2 Biofuels Production

Table 3.9 shows the IH^2 facility inputs and outputs provided for the life cycle assessment for the Johnson Timber Company's forest feedstock. The inventory data was obtained from Terry Marker (GTI) and Eric Tan (NREL) and was based on a 2,000 dry metric ton/day IH^2 plant with feedstock dried to moisture of 10%. This data was based on an assumption of 30% and 50% feedstock moisture for two separate scenarios. The accuracy of the input data was verified by carrying out a mass and energy balance as shown in appendix D. This data was divided into different sections, similar to Table 3.3 in section 3.2.1.

The inventory data from Table 3.9 was input to SimaPro, the LCA software tool used for this evaluation. In the results section, GHG emissions will be reported for each of the major life cycle stages. Each of the inputs shown in Table 3.9 was multiplied by an energy allocation factor (EAF) so that the inventory would be apportioned to the main products (IH^2 diesel and gasoline) as well as the co-products, ammonia and ammonium sulfate. The energy allocation factor was calculated using a methodology to be presented next. GHG emissions for the electricity used for the grinding and the IH^2 process were the US average grid. The original data was obtained from the table in appendix F.

4. Energy Allocation

Energy allocation (EA) was applied in order to distribute the system environmental burdens among all products and co-products in the IH^2 biofuel production chain. The EA method includes an energy balance utilizing material flows and lower heating values (LHV) for each co-product from the IH^2 biofuel conversion stage. No co-products were generated in any other stage for all of the feedstocks considered in this study. The following sections describe the calculations made to determine energy allocation factors (EA factor) to be applied to allocate environmental impact to the main IH^2 biofuel products. The EA factor was applied to all inputs in every life cycle stage to the IH^2 biofuels production system. Energy allocation is an energy balance around the IH^2 process where co-products are produced. We wish to know what fraction of total output of energy from the process is contained in IH^2 biofuels. Energy can be carried out of the process in various forms; IH^2 biofuels, steam, and char co-product. As a quality check on these energy balance calculations, we also attempted to balance the total input energy from the input biomass to the IH^2 conversion process, with all output energy streams. Our attempts to do this from the data provided by GTI yielded energy balances that did not close perfectly, but the output energy was lower than the input energy by 5-20% for most feedstocks. Although this is not perfect data quality, such a result is consistent with energy losses from the process in the form of waste heat which was not quantified. In summary, we feel that the data quality was of sufficiently high quality to proceed with the final analyses.

The (EA) factor was obtained by using the equations below whereby the denominator represents the total energy out from all products and numerator is energy content of the IH^2 gasoline and IH^2diesel.

$$EA_{Biomass\ \ Feedstock} = \frac{Energy\ \ Out\ (\ gasoline+diesel)}{Total\ Energy\ out}$$

4.1 Microalgae IH^2 Biofuels

When the individual inputs are included the above equation transforms into;

20% Moisture Content Micro algae

$$EAF = \frac{\overbrace{\left(44\frac{MJ}{kg}*4.48\times10^5\frac{kg}{day}\right)}^{gasoline}+\overbrace{\left(44\frac{MJ}{kg}*4.48\times10^5\frac{kg}{day}\right)}^{diesel}}{\underbrace{\left(44\frac{MJ}{kg}*4.48\times10^5\frac{kg}{day}\right)}_{gasoline}+\underbrace{\left(44\frac{MJ}{kg}*4.48\times10^5\frac{kg}{d\ ay}\right)}_{diesel}} = 1$$

4.2 Bagasse IH² Biofuels

When the individual inputs are included the above equation transforms into;

20% moisture content bagasse with char as a product

$$EAF = \frac{\overbrace{\left(44\frac{MJ}{kg}*432981.82\frac{kg}{day}\right)}^{gasoline}+\overbrace{\left(44\frac{MJ}{kg}*140318.18\frac{kg}{day}\right)}^{diesel}}{\underbrace{\left(44\frac{MJ}{kg}*432981.82\frac{kg}{day}\right)}_{gasoline}+\underbrace{\left(44\frac{MJ}{kg}*140318.18\frac{kg}{day}\right)}_{diesel}+\underbrace{\left(26.8\frac{MJ}{kg\ char}*334759\frac{kg}{day}\right)}_{char}\underbrace{\left(1.9845\frac{MJ}{kg\ steam}*313985\frac{kg}{day}\right)}_{steam}} =$$

$$0.724$$

20% moisture content bagasse with char burned

$$EAF = \frac{\overbrace{\left(44\frac{MJ}{kg}*432981.82\frac{kg}{day}\right)}^{gasoline}+\overbrace{\left(44\frac{MJ}{kg}*140318.18\frac{kg}{day}\right)}^{diesel}}{\underbrace{\left(44\frac{MJ}{kg}*432981.82\frac{kg}{day}\right)}_{gasoline}+\underbrace{\left(44\frac{MJ}{kg}*140318.18\frac{kg}{d\ ay}\right)}_{diesel}+\underbrace{\left(1.9845\frac{MJ}{kg\ steam}*1465964\frac{kg}{day}\right)}_{steam}} = 0.897$$

The lower heating values (LHV) of the fuels, steam, and char were obtained from existing databases in the MTU LCA group.

4.3 Corn Stover IH² Biofuels

When the individual inputs are included the above equation transforms into;

20% moisture content corn stover with char burned

$$EAF = \frac{\overbrace{\left(44\frac{MJ}{kg}*5.64\times10^5\frac{kg}{day}\right)}^{gasoline}+\overbrace{\left(44\frac{MJ}{kg}*2.0\times10^5\frac{kg}{day}\right)}^{diesel}}{\underbrace{\left(44\frac{MJ}{kg}*5.64\times10^5\frac{kg}{day}\right)}_{gasoline}+\underbrace{\left(44\frac{MJ}{kg}*2.0\times10^5\frac{kg}{d\ ay}\right)}_{diesel}+\underbrace{\left(1.9845\frac{MJ}{kg\ steam}*3.734\times10^5\frac{kg}{day}\right)}_{steam}} = 0.755$$

4.4 Forest Resources IH² Biofuels

For the two different feedstock moisture scenarios, the energy allocation factor equations are as seen in the equations below. The Low Heating Value of the hydrogen was obtained from literature (Grohmann et al. 1984), while the LHV for the wood biomass was obtained from other literature.

30%moisture feedstock

$$EA\ factor\ = \frac{\overbrace{\left(44\frac{MJ}{kg}*3.2\times10^5\frac{kg}{day}\right)}^{gasoline}+\overbrace{\left(44\frac{MJ}{kg}*1.99\times10^5\frac{kg}{day}\right)}^{diesel}}{\underbrace{\left(44\frac{MJ}{kg}*3.2\times10^5\frac{kg}{day}\right)}_{gasoline}+\underbrace{\left(44\frac{MJ}{kg}*1.99\times10^5\frac{kg}{d\ ay}\right)}_{diesel}+\underbrace{\left(1.9845\frac{MJ}{kg\ steam}*2.92\times10^5\frac{kg}{day}\right)}_{steam}} = 0.798$$

50% moisture feedstock

$$\text{EA factor}\ = \frac{\overbrace{\left(44\frac{\text{MJ}}{\text{kg}}*3.2\times10^5\frac{\text{kg}}{\text{day}}\right)}^{\text{gasoline}}+\overbrace{\left(44\frac{\text{MJ}}{\text{kg}}*1.99\times10^5\frac{\text{kg}}{\text{day}}\right)}^{\text{diesel}}}{\underbrace{\left(44\frac{\text{MJ}}{\text{kg}}*3.2\times10^5\frac{\text{kg}}{\text{day}}\right)}_{\text{gasoline}}+\underbrace{\left(44\frac{\text{MJ}}{\text{kg}}*2.0\times10^5\frac{\text{kg}}{\text{d ay}}\right)}_{\text{diesel}}+\underbrace{\left(1.9845\frac{\text{MJ}}{\text{kg steam}}*1.45\times10^5\frac{\text{kg}}{\text{day}}\right)}_{\text{steam}}} = 0.888$$

5. Life Cycle Impact Assessment

The inventory data were converted to greenhouse gas impacts using the IPCC GWP 100a method in SimaPro 7.2. This method converts emissions of greenhouse gases into equivalent emissions of CO_2 by employing global warming potentials (GWP). The GWP of CO_2 is 1, for CH_4 = 25, and for N_2O is 298. Other greenhouse gases are also included in this analysis, including solvents and refrigerants that accompany ecoprofiles resident in SimaPro and called into the analysis with the material and energy inputs. In this study, CO_2 emissions from (or sequestration into) biogenic carbon were not counted in the GHG analysis, only fossil derived CO_2 emissions. The reason for this distinction between biogenic and fossil carbon is because when biomass grows, CO_2 is sequestered from the atmosphere into biomass, and upon conversion and combustion of biofuels, the CO_2 is returned to the atmosphere again in a closed cycle. We did not take a consequential view of the fate of biogenic carbon in the IH^2 pathway, for example if CH_4 emissions would be a result of changes in biogenic carbon throughout the life cycle. As of this writing, field data was lacking to provide such data, and we believe that is will be a minor contributor to the life cycle. The inputs for corn stover production were acquired from the farms as a waste and this was done within the sustainable limit by only taking what we required and left some of the of the crops in the soil to degrade and replenish some of the lost nutrients and soil organic matter for the next crop.

5.1 Microalgae IH^2 Biofuel

The results from the SimaPro analysis were arrived at by dividing the 1-day impact results by the total energy content of the IH^2 biofuels produced (39,424,000 MJ/day), or multiplying by the reciprocal which was 2.54E-8 of a day/MJ. This calculation is shown equations below.

$$\frac{1}{IH^2\ gasoline + IH^2\ diesel}$$

$$\frac{1}{(19{,}712{,}000\ MJ/day) + (19{,}712{,}000\ MJ/day)} = 2.54E - 8\ day/MJ$$

Doing this converted the GHG emissions from a 1 day basis to 1 MJ IH^2 biofuel basis.

5.2 Bagasse IH^2 Biofuels

The results from the SimaPro analysis were arrived at by dividing the 1-day impact results by the total energy content of the IH^2 biofuels produced (25,225,200 MJ/day), or multiplying by the reciprocal which was 3.96E-8 of a day/MJ. This calculation is shown equations below.

$$\frac{1}{IH^2\ gasoline + IH^2\ diesel}$$

$$\frac{1}{(19{,}051{,}200\ MJ/day) + (6{,}174{,}000\ MJ/day)} = 3.96E - 8\ day/MJ$$

Doing this converted the GHG emissions from a 1 day basis to 1 MJ IH^2 biofuel basis. A comparison of the GHG results for IH^2 biofuels is compared to the life cycle GHG emission for petroleum gasoline, diesel, and aviation fuel.

5.3 Corn Stover IH^2 Biofuels

The results from the SimaPro analysis were arrived at by dividing the 1-day impact results by the total energy content of the IH^2 biofuels produced (22,880,000 MJ/day), or multiplying by the reciprocal which was 4.37E-8 day/MJ. This calculation is shown equations below.

$$\frac{1}{IH^2\ gasoline + IH^2\ diesel}$$

$$\frac{1}{(14{,}080{,}000\ MJ/day) + (8{,}800{,}000\ MJ/day)} = 4.37E - 8\ day/MJ$$

5.4 Forest Feedstocks IH^2 Biofuels

The results from the SimaPro analysis were arrived at by dividing the 1-day impact results by the total energy content of the IH^2 biofuels produced (22,880,000 MJ/day), or multiplying by the reciprocal which was 4.37E-8 day/MJ. This calculation is shown equations below.

$$\frac{1}{IH^2\ gasoline + IH^2\ diesel}$$

$$\frac{1}{(14{,}080{,}000\ MJ/day) + (8{,}800{,}000\ MJ/day)} = 4.37E - 8\ day/MJ$$

6. Life Cycle Assessment Results

6.1 Microalgae Biomass and IH^2 Biofuel Results

6.1.1 Microalgae Biomass Production

The results obtained from this analysis are grouped into four main sections: i. Algae Production Pump Shed ii. Algae Production New Harvest Units, iii. Algae Production Dewatering, and iv. Algae Transport. Figure 6.1 shows the GHG emissions per dry metric ton algae produced assuming 300 g algae/m^3 cell density. The Pump Shed stage emits the largest amount of emissions, followed by Algae Production Dewatering, Algae Transport, and Algae New Harvest Units. Table 6.1 shows the effects of primary energy type on the electricity impacts of producing algae. Coal electricity emits the largest amount of emissions, followed by US average grid and natural gas, with renewable electricity emitting the least.

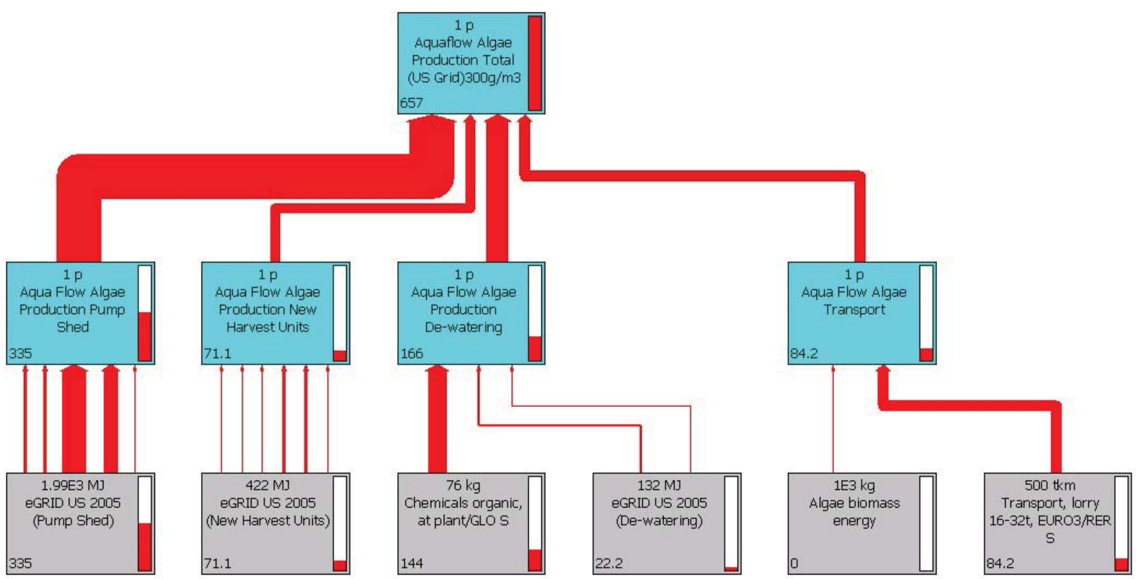

Figure 6.1 Greenhouse gas emissions per dry metric ton algae biomass (657 kg CO_2 eq. / metric ton algae) assuming average US grid electricity.

Table 6.1

Effect of Electricity Type (Primary Energy) on GHG Emissions of Algae

Algae Production Electricity Type	**GHG Emissions (kg CO_2 eq. / dry mt algae)**
Coal	1030
US Grid Average	657
Natural Gas	656
Geothermal	286
Biomass	258
Nuclear	236
Wind	235
Hydro	231

6.1.2 Microalgae IH^2 Biofuel Production and Use

The inputs listed in Table 3.2 were entered into a project in SimaPro in order to determine the greenhouse gas emissions per MJ of IH^2 biofuels produced and used in vehicles. Figure 6.2 shows the total GHG emissions of .0619 kg CO_2 eq./MJ IH^2 biofuels, or 61.9 g CO_2 eq./MJ. To place these emissions into perspective, petroleum gasoline has life cycle GHG emissions of 91.2 g CO_2 eq./MJ. This IH^2 biofuel result was obtained assuming US average grid electricity used for algae feedstock production and also for electricity use during IH^2 biofuel production (IH^2 processes in Figure 6.2). The largest contributor to emissions is algae feedstock production and transport to the IH^2 facility, followed by IH^2 processes for producing biofuels. Natural gas combusted for drying algae from 80% to 20% is the largest single cause of GHG emissions and electricity use for algae harvesting and dewatering is also a major cause for emissions. The emission credits from co-products ammonia and ammonium sulfate total about 20% of the net GHG emissions. The GHG results in Figure 6.2 include effects of biofuels combustion, but do not include transport of IH^2 biofuels to blending locations for mixing into petroleum fuel stocks, nor from the blending location to filling stations. The latter step is considered negligible based on prior experience with biofuel life cycles, and therefore is omitted from this study.

Electricity type has a large impact on GHG emissions as shown in Table 6.1, and similarly has a large effect on IH^2 biofuel emissions as shown in Table 6.2. When coal electricity is used, emissions are highest at 82.8 g CO_2 eq./MJ and are least when a renewable power source is used such as hydroelectric power; 37.9 g CO_2 eq./MJ. There is a very strong influence of electricity type on these GHG results. When mode of transportation from IH^2 facility gate to blending location assuming 100 km distance is explored, there is very little difference between the transport modes.

Table 6.2

Effect of Electricity Type on IH^2 Biofuel GHG Emissions

Algae IH^2 Biofuel Life Cycle: Effect of Electricity Type (No IH^2 Biofuel Transport to Blending)	**GHG Emissions (g CO_2 eq. / MJ)**
Coal	82.8
US Average Grid	61.9
Hydro	37.9

Table 6.3

Effect of Transport Mode to Blending Location on IH^2 Biofuel GHG Emissions. Electricity Type is US Average Grid Power.

Algae IH^2 Biofuel Life Cycle: Effect of IH^2 Biofuel Transport Mode	**GHG Emissions (g CO_2 eq. / MJ)**
Road	62.2
Rail	61.9
Pipeline	61.9

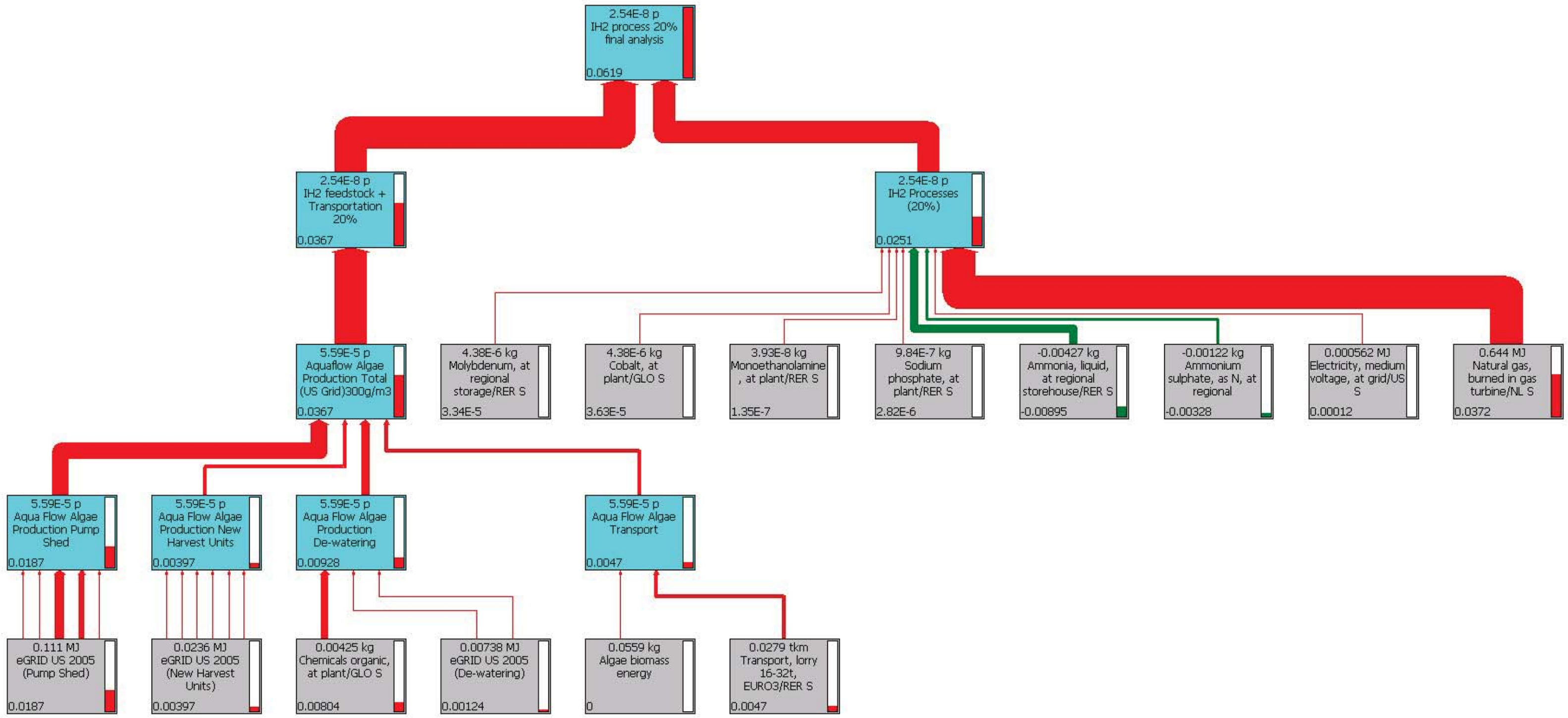

Figure 6.2 Network diagram for microalgae IH^2 biofuels emission of GHGs (kg CO_2 eq./MJ IH^2 biofuels). Red lines show relative magnitude of greenhouse gas impacts while green lines show credits due to co-products of production. Line width corresponds to magnitude of impact or credit.

6.1.3 Comparison of different scenarios for the transportation of IH^2 fuel to blending stations.

The different scenarios considered for the IH^2 fuel transportation from gate to a blending station and other changes based on the different scenarios which will be discussed in this report are as follows:

1. Transportation of IH^2 biofuel to a blending station using different modes of transport.
2. Transportation of IH^2 biofuel to a blending station using road transport over different distances.

6.1.4 Transportation Mode Scenario:

Transportation of the IH^2 biofuel to one selected blending station using different modes of transport. Tables 6.4 are the results obtained from the different transportation modes considering 20% feedstock moisture content. The different modes of transport were: a) Rail b) Road c) Pipeline

Assumption: The IH^2 biofuel transportation distance from facility to filling station is 100 km.

Discussion:

It is assumed that the IH^2 biofuel fuel shares similar properties as their respective fossil fuels used. The transportation of the IH^2 biofuel using the pipeline mode has the least GHG emissions at 61.9g CO_2 eq./ MJ of fuel. The emission from the rail transport was moderate at 8.99E-5g CO_2 eq. / MJ of fuel. The highest emission was from road transport, at 1.25g CO_2 eq./ MJ of fuel, with a cumulative total emission of 62.2g CO_2 eq./ MJ of IH^2 fuel. These transport numbers and total IH^2 biofuel GHG emissions can be seen in Table 6.4 below. The IH^2 fuel transport step adds negligible amount of GHG emissions to the total GHG emissions, regardless of transport mode assuming 100 km distance.

Table 6.4

GHG emissions for the IH^2 process with 20% moisture Micro algae feedstock for different transport modes for IH^2 product.

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**
	Base case (no IH^2 fuel transport)	**Road transport**	**Rail transport**	**Pipeline transport**
IH^2 Feedstock and Transportation	36.7	36.7	36.7	36.7
IH^2 Process	25.1	25.1	25.1	25.1
IH^2 biofuel Transportation	1.25	1.25	8.99E-5	3.57E-5
Total GHG Emissions	**62.2**	**62.2**	**61.9**	**61.9**

6.1.5 Distance of Road Transport to IH^2 Fuel Blending Facility Scenario:

In this scenario an estimation of the effects of different transportation distances on GHG emissions, from the location of the IH^2 biofuel production facility to different blending sites using road transport, will be made. We will use the same distances as in the Johnson Timber IH^2 LCA report for this Micro algae analysis. The transportation distances to the various blending sites are shown in Table 6.5. The results obtained from the different transportation locations of the IH^2 biofuel are shown below in Table 6.5.

Table 6.5

Estimated distances for different blending locations

Different blending locations	**Distances**
Scenario 1	147 miles
Scenario 2	202 miles
Scenario 3	277 miles
Scenario 4	392 miles

6.1.6 Discussion of Micro Algae IH^2 Biofuel LCA Results

From Table 6.6 below, the GHG emissions contribution from the IH^2 biofuel transport section varies with the IH^2 biofuel road transportation distances for Micro algae feedstocks. This also directly affects the total GHG emissions achieved from the analysis. From Figure 6.2 above, it is clear that two major inputs dominate the GHG emissions; electricity for algae harvesting and natural gas for algae drying. The effects of uncertainty in these inputs can affect life cycle GHG emissions. For example, if electricity inputs for harvesting are increased or decreased by 50% to represent uncertainty in this input, IH^2 biofuel GHG emissions increase or decrease to 77.9 and 45.9 g CO_2 eq / MJ, respectively. Similarly for natural gas uncertainty, IH^2 biofuel GHG emissions increase or decrease to 80.5 and 43.3 g CO_2 eq / MJ, respectively.

Savings of GHG emissions of IH^2 biofuel compared to petroleum fuels is shown in Figure 6.3. IH^2 biofuels in this comparison are produced using coal, US grid, and hydro power, and savings of GHG emissions compared to petroleum gasoline are 8%, 32%, and 58%, respectively. It is clear from these results that significant savings of emissions are only possible when renewable power is utilized for algae harvesting and dewatering. However, further reductions in GHG emissions is still possible if a renewable energy source could be found for the natural gas required for drying the algae biomass from 80% - 20%. Possible candidates could be landfill gas, anaerobic digester gas, and solar drying.

Table 6.6

GHG emissions for production and transportation of IH^2 biofuel produced considering a 20% moisture Micro algae feedstock for Aquaflow Bionomic Company to different blending sites

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**
IH^2 Road Transport Distance	147 miles	202 miles	277 miles	392 miles
IH^2 Feedstock and Transportation	36.7	36.7	36.7	36.7
IH^2 Process	25.1	25.1	25.1	25.1
IH^2 biofuel Transportation	0.56	0.774	1.06	1.5
Total GHG Emissions	**62.4**	**62.6**	**62.9**	**63.4**

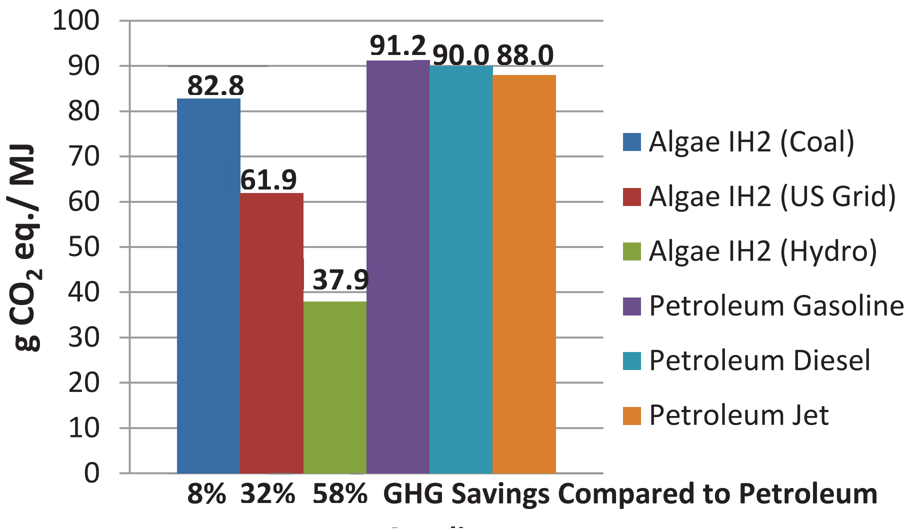

Figure 6.3 Savings of GHG emissions relative to petroleum fuels for algae IH^2 fuels.

6.2 Bagasse Biomass and IH^2 Biofuel Results

6.2.1 Bagasse Biomass Production

The main categories of the bagasse handling which are considered for the LCA analysis were i) bagasse transportation ii) bagasse loading and unloading, and iii) bagasse energy. Figure 6.4 below shows the greenhouse gas emissions per dry metric ton for loading, unloading, and transportation to a IH^2 unit 100 km distance from the sugarcane milling factory. The total GHG emissions are 27.1 kg CO_2 eq. per dry metric ton bagasse. The largest contributor to this total is the transportation process. The bagasse transportation is equivalent to 24.40 kg CO_2 eq. per dry metric ton secondly is the loading and unloading of the bagasse which is very low at 2.65 kg CO_2 eq. per dry metric ton which is about 15% of the total emissions.

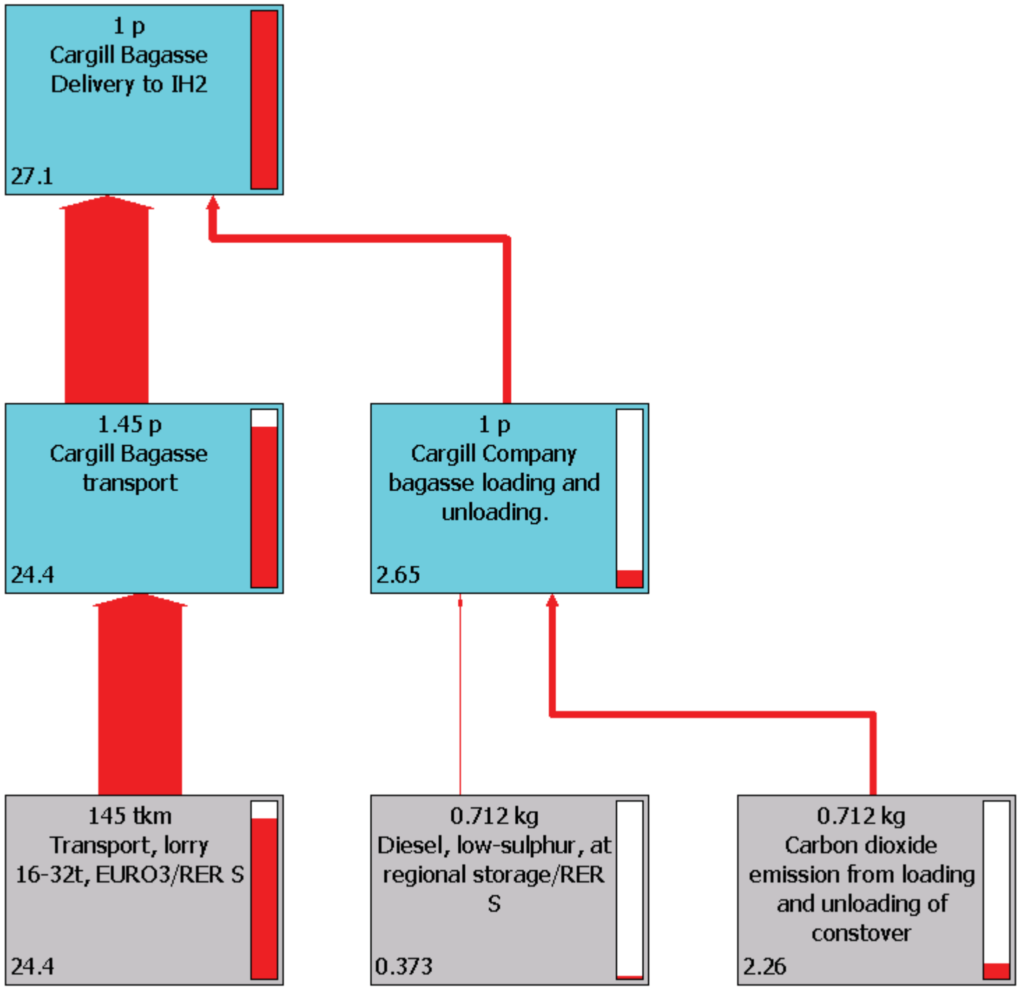

Figure 6.4 Network diagram with magnitudes of GHG emissions from Bagasse handling to the IH^2 process (kg CO_2 eq./dry mt bagasse).

6.2.2 Bagasse IH^2 Biofuel Production and Use

The total GHG emissions for this feedstock where the **char is burned** for steam production, is 2.6 g CO_2 eq /MJ of IH^2 fuel produced, as shown in the Figure 6.5. The IH^2 feedstock handling and transportation accounts for most of the emissions, which is 1.92 g CO_2 eq /MJ of IH^2 fuel produced. The lowest emissions are from the IH^2 process which is a credit of -0.892 g CO_2 eq /MJ of IH^2 fuel produced, due to the emissions credits from ammonia and ammonium sulfate co-products. These emission credits were obtained from ecoprofiles in the ecoinvent database in SimaPro 7.2. The IH^2 feedstock onsite preparation is 1.57 g eq CO_2/MJ of IH^2 fuel produced.

Table 6.7

GHG emissions for the IH^2 process with bagasse feedstock

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**
IH^2 Feedstock Transportation	1.55
IH^2 Feedstock Onsite Preparation	1.27
IH^2 Process	-0.72
Total GHG Emissions	**2.1**

The total GHG emissions for bagasse feedstock for **char as a product scenario** is 2.1 g CO_2 eq /MJ of IH^2 fuel produced, as shown in the Table 6.7. These results are very similar to the char burned case except slightly lower because of the lower EA factor (.724).

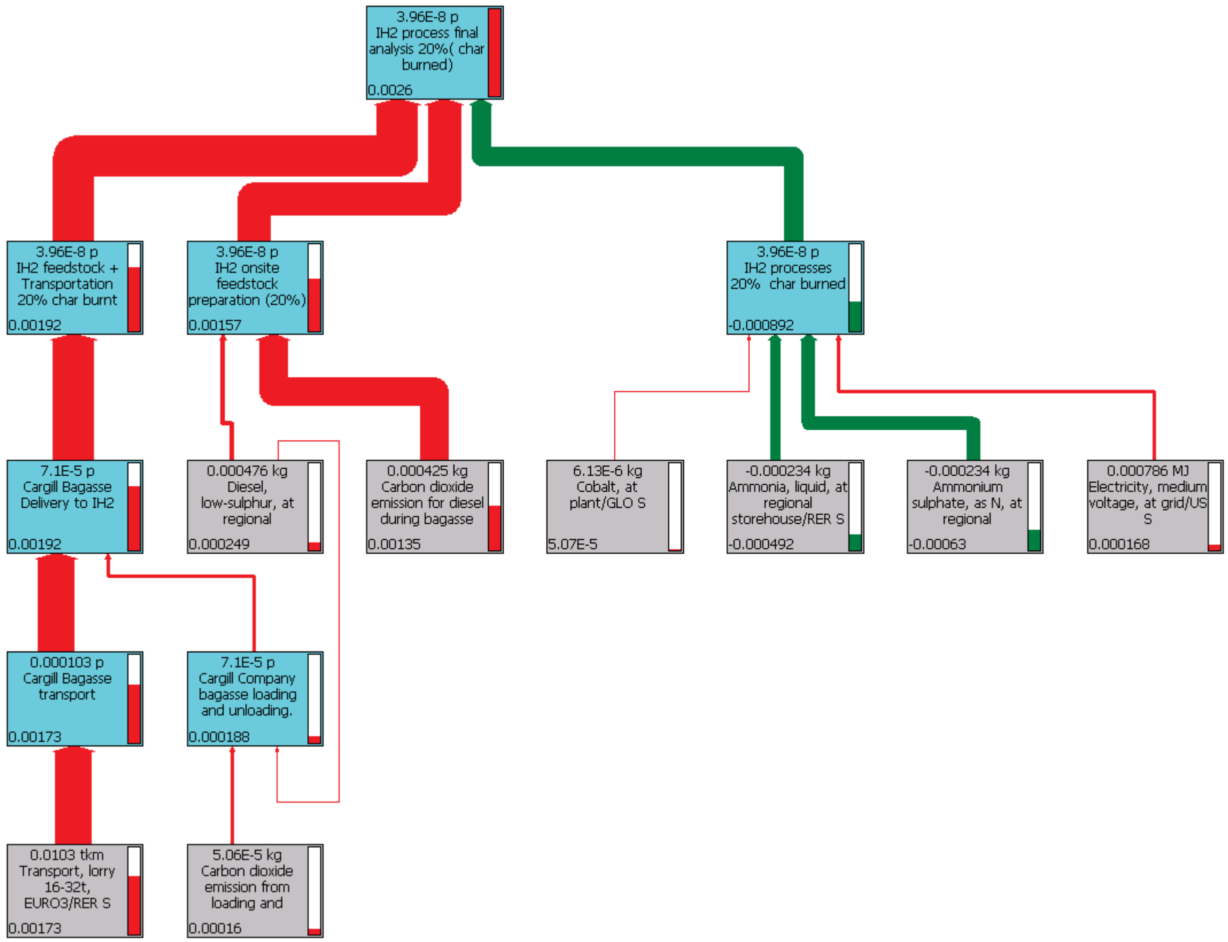

Figure 6.5 Network diagram for bagasse IH^2 biofuels emission of GHGs (kg CO_2 eq./MJ IH^2 biofuels). Red lines show relative magnitude of greenhouse gas impacts while green lines show credits due to co-products of production. Line width corresponds to magnitude of impact or credit.

Table 6.8

GHG emissions for the IH^2 process bagasse showing effects of 100 km transport of IH^2 fuel to blending stations by different transport modes

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**
	Base case (char product)	**Base case (char burned)**	**Road transport**	**Rail transport**	**Pipeline transport**
IH^2 Feedstock and Transportation	1.55	1.92	1.92	1.92	1.92
IH^2 Feedstock Onsite Preparation	1.27	1.57	1.57	1.57	1.57
IH^2 Process	-0.72	-0.89	-0.89	-0.89	-0.89
IH^2 biofuel Transportation	-	-	0.17	.044	.018
Total GHG Emissions	**2.1**	**2.6**	**2.77**	**2.65**	**2.62**

In Table 6.8 are results obtained from the different IH^2 biofuel transportation modes for the char burned base case. The different modes of transport were: a) Rail b) Road c) Pipeline. The IH^2 biofuel transportation distance from facility to filling station is 100 km. For this short distance, there is little effect of IH^2 biofuel transport to blending stations.

In this scenario an estimation was made of the effects of different transportation distances on GHG emissions from the location of the IH^2 biofuel production facility to different blending sites using **road transport**. We will use the same distances as in the Johnson Timber IH^2 LCA report for this bagasse analysis.

The transportation distances to the various blending sites are shown in Table 6.9. The results obtained from the different transportation locations of the IH^2 biofuel are shown below in Table 6.10.

Table 6.9

Distances to different blending sites being considered

Different blending locations	**Distances**
Scenario 1	147 miles
Scenario 2	202 miles
Scenario 3	277 miles
Scenario 4	392 miles

Table 6.10

GHG emissions for production and transportation of IH^2 biofuel produced assuming a 20% moisture bagasse feedstock to different blending sites

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**
IH^2 Road Transport Distance	147 miles	202 miles	277 miles	392 miles
IH^2 Feedstock and Transportation	1.92	1.92	1.92	1.92
IH^2 Feedstock Onsite Preparation	1.57	1.57	1.57	1.57
IH^2 Process	-0.89	-0.89	-0.89	-0.89
IH^2 biofuel Transportation	0.28	0.39	0.53	0.75
Total GHG Emissions	**2.88**	**2.99**	**3.13**	**3.35**

From Table 6.10 below, the GHG emissions contribution from the IH^2 biofuel transport section varies with the IH^2 biofuel transportation distances for bagasse feedstocks. There is not much effect of distance to blending facility, even for the longest regional distance of 392 miles, on the total GHG emissions for bagasse IH^2 biofuels.

6.2.3 Discussion of Bagasse IH^2 Biofuel LCA Results

A comparison was conducted between the GHG emissions of IH^2 biofuels from bagasse biomass emissions to the emissions from convectional petroleum gasoline, diesel, and jet fuel shown in Figure 6.6 below. It is clear that two major inputs dominate the GHG emissions; diesel for bagasse IH^2 feedstock transportation and diesel onsite preparation for bagasse. The effects of uncertainty in these inputs can affect life cycle GHG emissions. For example, if transportation inputs for harvesting are increased or decreased by 50% to represent uncertainty in this input, IH^2 biofuel GHG emissions increase or decrease to 3.47 and 1.74 g CO_2 eq / MJ, respectively. Similarly for onsite feedstock preparation uncertainty, IH^2 biofuel GHG emissions increase or decrease to 3.39 and 1.82 g CO_2 eq / MJ, respectively. These emissions from the bagasse IH^2 biofuels are relatively low compared to the data from National Energy Technology Laboratory (NETL 2008). Savings of GHG emissions compared to petroleum fuels is approximately 97%, easily qualifying these biofuels as adavanced biofuels according to the Renewable Fuels Standard (50% reduction required).

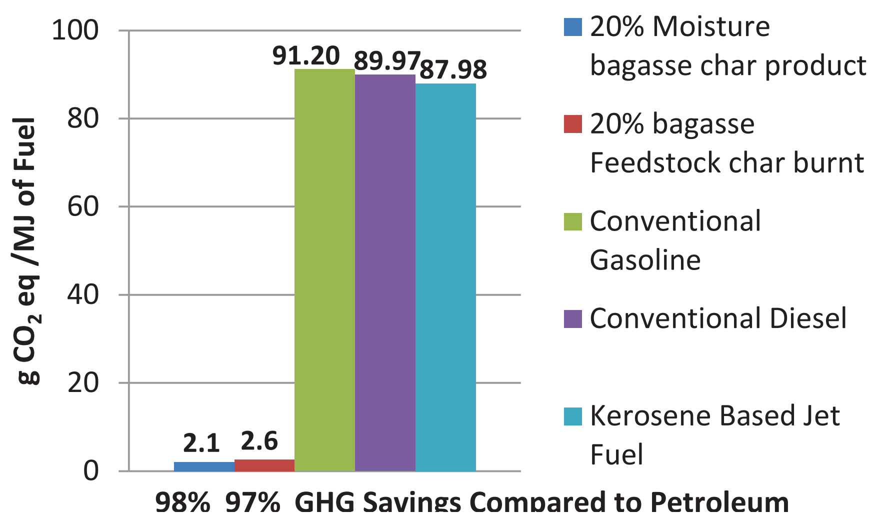

Figure 6.6 Results of IH^2 fuel for bagasse feedstock ghg emisisons results savings compared to petroleum fuels (no transport step to blending was included here-negligible effect).

6.3 Corn Stover Biomass and IH^2 Biofuel Results

6.3.1 Corn Stover Biomass Production

The main categories of the corn stover production system which are considered for the LCA analysis were i. fertilizer replacement, ii. corn stover collection, iii. corn stover transportation, and iv. corn stover loading and loading. Figure 6.7 shows the greenhouse gas emissions per dry metric ton of fertilizer replacement, collection, loading, unloading and transported to a IH^2 unit 48 km (30 mi.) distant from the corn stover fields. The total GHG emissions are 66.8 kg CO_2 eq. per dry metric ton corn stover biomass. The largest contributor to this total is the fertilizer replacement, followed by collection, transport, and loading/unloading.

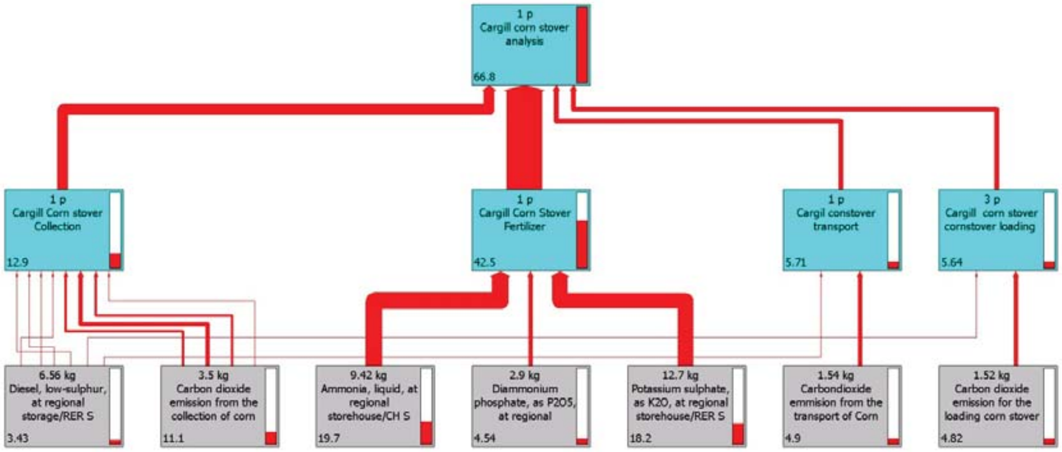

Figure 6.7 Network diagram with GHG emissions from Corn Stover collection, loading, transport, and fertilizer replacement (kg CO_2 eq./dry mt stover).

6.3.2 Corn Stover IH^2 Biofuel Production and Use

The total GHG emissions for corn stover IH^2 biofuel where the **char is burned** for steam production is shown in a network diagram in Figure 6.8. The largest emission is from corn stover production, followed by size reduction, and with a credit for co-products ammonia and ammonium sulfate. Several IH^2 biofuel transportation scenarios were studied assuming 100 km distance to locations of blending into petroleum fuel stocks; a) rail, b) road, and c) pipeline. Table 6.11 shows the results from these scenarios. Road transport adds about 5% to these base case emissions, but rail and pipeline transport contribute negligibly to the total emissions.

In another scenario an estimation was made of the effects of different transportation distances on GHG emissions from the location of the IH^2 biofuel production facility to different blending sites using **road transport**. We will use the same distances as in the Johnson Timber IH^2 LCA report for this bagasse analysis. The transportation distances to the various blending sites are shown in Table 6.12. The results obtained from the different transportation locations of the IH^2 biofuel are shown below in Table 6.12. As in the bagasse case, there is not much effect of distance to blending facility, even for the longest regional distance of 392 miles, on the total GHG emissions for corn stover IH^2 biofuels.

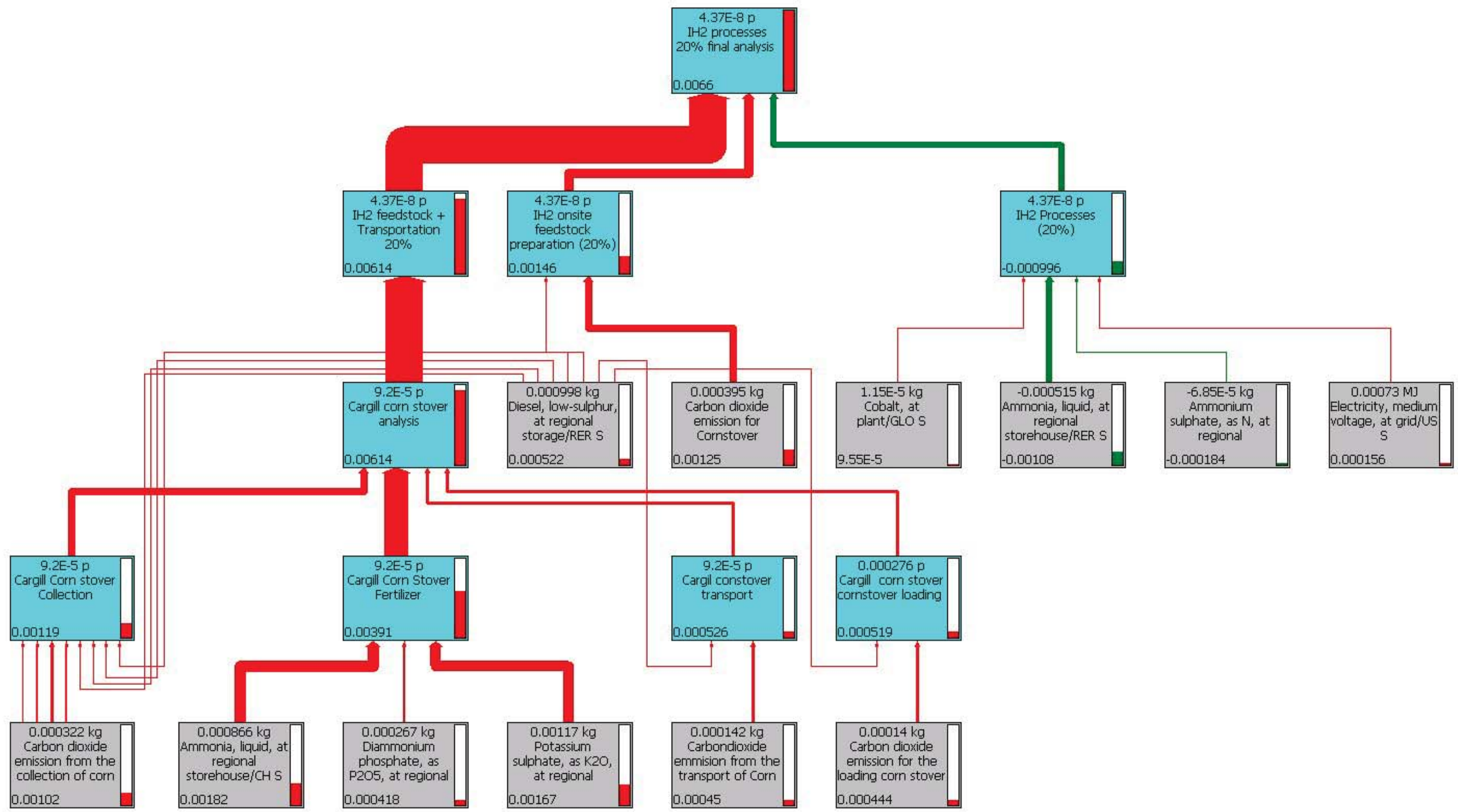

Figure 6.8 Network diagram for corn stover IH^2 biofuels emission of GHGs (kg CO_2 eq./MJ IH^2 biofuels). Red lines show relative magnitude of greenhouse gas impacts while green lines show credits due to co-products of production. Line width corresponds to magnitude of impact or credit

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Table 6.11

GHG emissions for the IH^2 process with 20% moisture feedstock corn stover

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**
	Base case (no IH^2 fuel transport)	**Road transport**	**Rail transport**	**Pipeline transport**
IH^2 Feedstock and Transportation	6.14	6.14	6.14	6.14
IH^2 Feedstock Onsite Preparation	1.46	1.46	1.46	1.46
IH^2 Process	-0.996	-0.996	-0.996	-0.996
IH^2 biofuel Transportation	-	0.38	0.09	0.04
Total GHG Emissions	**6.60**	**6.98**	**6.69**	**6.64**

Table 6.12

GHG emissions for production and transportation of IH^2 biofuel produced considering a 20% moisture corn stover feedstock to different blending sites

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**
IH^2 Road Transport Distance	147 miles	202 miles	277 miles	392 miles
IH^2 Feedstock and Transportation	6.14	6.14	6.14	6.14
IH^2 Feedstock Onsite Preparation	1.46	1.46	1.46	1.46
IH^2 Process	-0.996	-0.996	-0.996	-0.996
IH^2 biofuel Transportation	0.56	0.77	1.06	1.50
Total GHG Emissions	**7.16**	**7.37**	**7.66**	**8.10**

6.3.3 Discussion of Corn Stover IH^2 Biofuel LCA Results

A comparison was conducted between the GHG emissions of IH^2 biofuels from corn stover biomass emissions to the emissions from convectional petroleum gasoline, diesel, and jet fuel shown in Figure 6.10. It is clear that two major inputs dominate the GHG emissions; diesel for cornstover IH^2 feedstock collection and Fertilizer for replenishing the lost nutrients for the next crop to be grown. The effects of uncertainty in these inputs can affect life cycle GHG emissions. For example, if onsite preparation inputs are increased or decreased by 50% to represent uncertainty in this input, IH^2 biofuel GHG emissions increase or decrease to 7.33 and 5.87 g CO_2 eq / MJ, respectively. Similarly for fertilizer replenishment increasing or decreasing by 50%, IH^2 biofuel GHG emissions increase or decrease to 9.67 and 3.53g CO_2 eq / MJ, respectively. These emissions from the corn stover IH^2 biofuels are relatively low compared to the data from National Energy Technology Laboratory (NETL 2008). Savings of GHG emissions compared to petroleum fuels is approximately 93%, easily qualifying these biofuels as adavanced biofuels according to the Renewable Fuels Standard (50% reduction required).

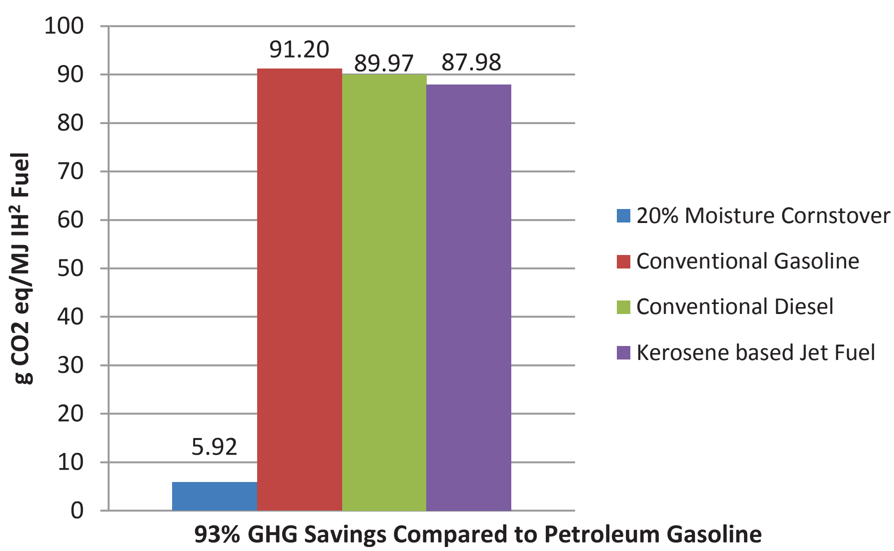

Figure 6.10 Results of IH^2 fuel for corn stover feedstock GHG emisisons results savings compared to petroleum fuels (no transport step to blending was included here-negligible effect).

6.4 Forest Resources Biomass and IH^2 Biofuel Results

6.4.1 Forest Resources Biomass Production

The results obtained from this analysis are grouped into three main sections: collection, transportation and yard preprocessing. Figure 6.11 shows a network diagram of the GHG impacts of these three sections on the basis of 1 dry metric ton assuming a 1,000 dry metric ton / day facility. The largest source if GHG emission is electricity consumed for size reduction of the biomass. Diesel fuel for biomass collection is the next largest, followed by diesel fuel for transportation.

Two sets of results were obtained, one for the 500 and 1,000 dry metric ton/day plants assuming diesel fuel costs of \$3/gallon, and another assuming \$6/gallon. These results are shown in Tables 6.13 and 6.14. The general trends are that emissions increase for the larger feedstock supply and for lower fuel prices. The reasons for these trends are that larger distances are needed for transport for the larger supply need, and for higher fuel prices, this favors collection of higher cost resources closer to the facility. These economic tradeoffs are possible with the forest procurement model provided by Mr. Gephardt, and the environmental tradeoffs are provided by the LCA.

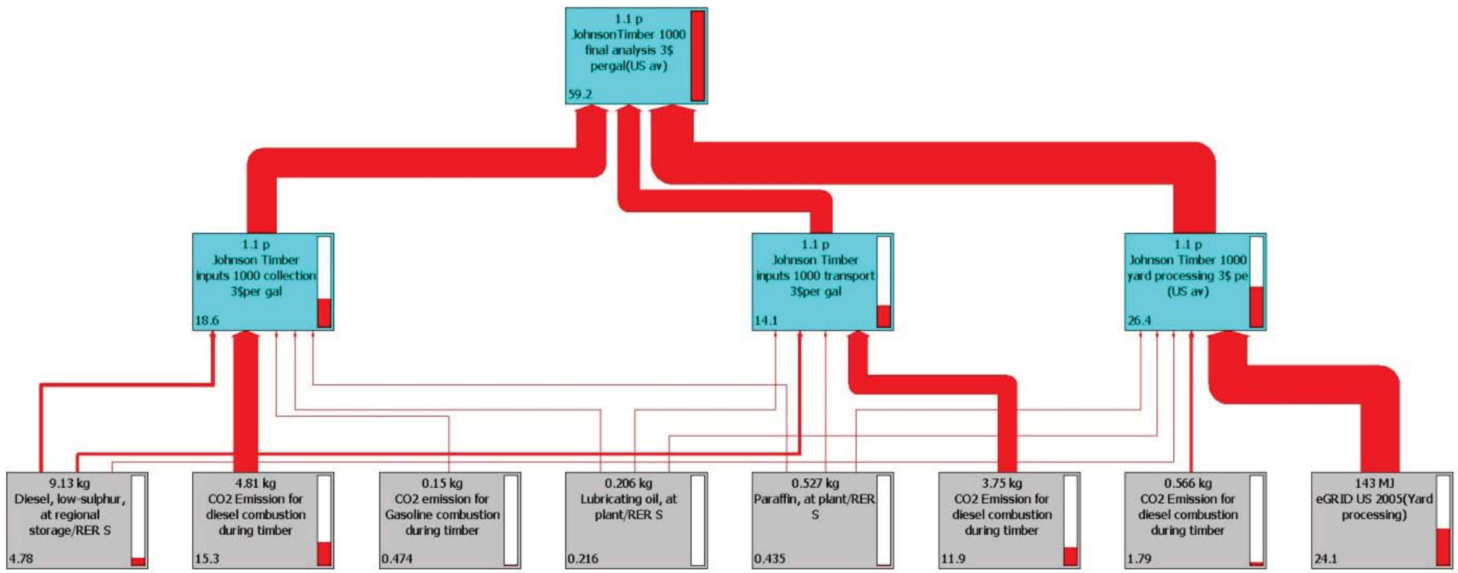

Figure 6.11 Network diagram with GHG emissions from Forest Feedstock collection, transport, and preprocessing (kg CO_2 eq./dry mt forest resources) assuming a 1,000 dry metric ton/day and \$3/gallon diesel fuel.

Table 6.13

Greenhouse Gas Emissions per dry metric ton/day of wood and forest residues collected, transported, and processed on-site. Impacts of all greenhouse gases were converted to CO_2 equivalents using Global Warming Potentials (GWP). Plant sizes of 500 and 1000 dry metric ton/day input feedstock considering electrical energy from US average grid as the yard processing energy source and assumption of $3 per gallon of diesel fuel used.

	GHG Emissions (kg CO_2 eq./dry metric ton) for 500 dry metric ton per day plant	**GHG Emissions (kg CO_2 eq./dry metric ton) for 1000 dry metric ton per day plant**
Diesel low sulfur at regional storage	3.8	4.78
Gasoline production (unleaded)	0.09	0.11
Lubricating Oil	0.18	0.22
Grease (Paraffin)	0.37	0.44
Hydraulic Oil (White spirit)	0.15	0.18
eGRID US 2005 (yard processing)	24.1	24.1
CO_2 emission for diesel combustion (during timber transportation)	9.4	15.3
CO_2 emission for diesel combustion (during timber collection)	17.7	13.90
CO_2 emission for gasoline combustion(during timber Transportation)	0.37	0.47
Total	**52.1**	**59.2**

Table 6.14

Greenhouse Gas Emissions per dry metric ton/day of wood and forest residues collected, transported, and processed on-site. Impacts of all greenhouse gases were converted to CO_2 equivalents using Global Warming Potentials (GWP). Plant size of 500 and 1000 dry metric ton/day input feedstock considering electrical energy from US average grid as the yard processing energy source and assumption of $6 per gallon of diesel fuel used.

	GHG Emissions (kg CO_2 eq./dry metric ton) for 500 dry metric ton per day plant	GHG Emissions (kg CO_2 eq./dry metric ton) for 1000 dry metric ton per day plant
Diesel low sulfur at regional storage	3.42	4.21
Gasoline production (unleaded)	0.08	0.11
Lubricating Oil	0.17	0.21
Grease(Paraffin)	0.37	0.44
Hydraulic (White spirit)	0.15	0.18
eGRID US 2005 (yard processing)	24.1	24.1
CO_2 emission for diesel combustion (during timber transportation)	9.0	10.3
CO_2 emission for diesel combustion (during timber collection)	11.7	13.4
CO_2 emission for gasoline combustion(during timber Transportation)	0.36	0.47
Total	**49.4**	**55.2**

6.4.2 Forest Resources IH^2 Biofuel Production and Use

A network diagram showing contributions to GHG emissions of IH^2 biofuels produced from 30% moisture content forest biomass is displayed in Figure 6.12. The largest emissions are from feedstock collection, transportation and size reduction (4.14 g CO_2

eq/MJ). Impacts from IH^2 conversion process are very small, and an environmental credit is realized from co-products produced. Net GHG emissions are 3.25 g CO_2 eq/MJ.

When 50% moisture content forest feedstocks are input to the IH^2 facility, GHG emissions are slightly higher as shown in Table 6.15. Slightly larger emissions are a result of a higher EAF applied in this case because a smaller amount of co-product steam is produced compared to the 30% moisture content case.

Table 6.15

GHG emissions for the IH^2 process with 50% moisture feedstock content.

Life Cycle Stages	**GHG Emissions (g CO2 eq./MJ of IH^2 fuel)**
IH^2 Feedstock Transportation	4.61
IH^2 Process	-0.99
Total GHG Emissions	**3.62**

Transportation scenarios to deliver IH^2 biofuel to a blending station located 100 km away using different modes of transport was studied. Table 6.16 contains these results. Road transportation has the highest impact, rail intermediate, and pipeline is the lowest. The effect of biofuel transport to blending locations is minimal.

More transport scenarios were studied by varying distance to blending locations assuming road transport. These distances were obtained by considering several blending facility locations in the Upper Midwest in the region surrounding Park Falls, WI, as shown in Table 6.17. GHG emissions for these transport scenarios are presented in Table 6.18. Even for the longest distance, additional emissions are only slightly larger than 1 g CO_2 eq/MJ.

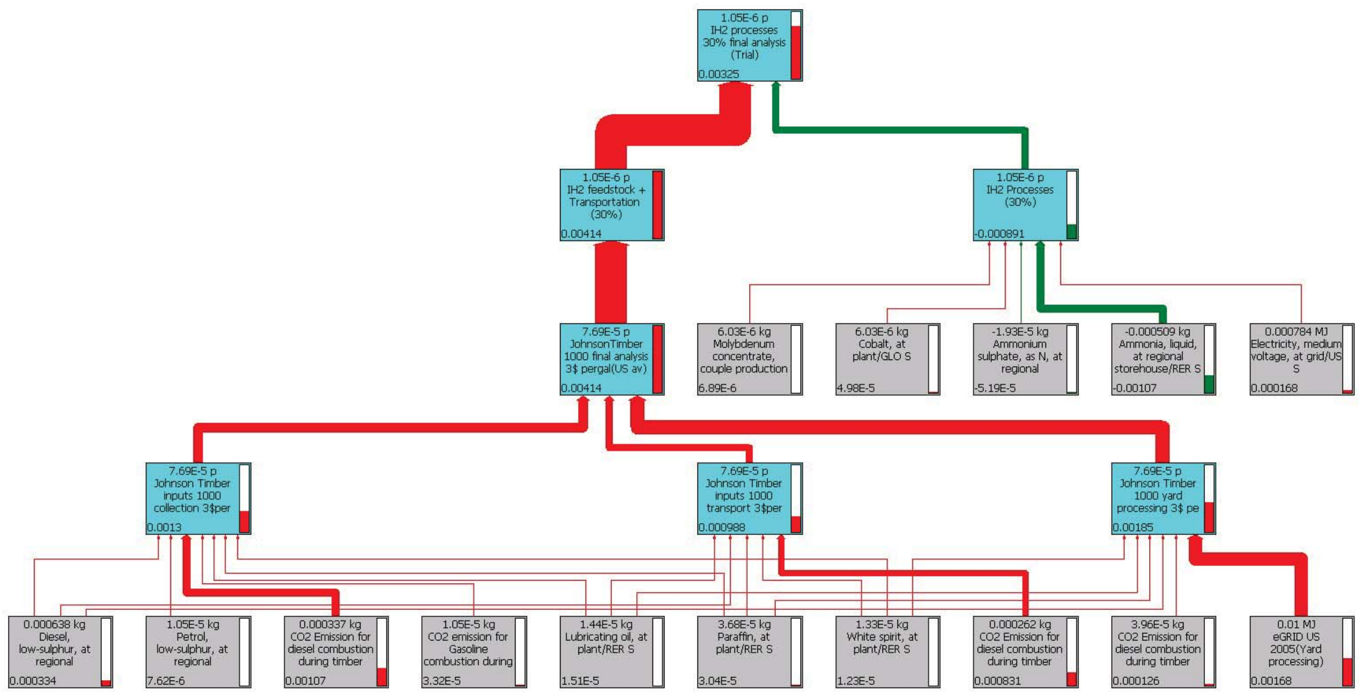

Figure 6.12 Network diagram for forest resources IH^2 biofuels emission of GHGs (kg CO_2 eq./MJ IH^2 biofuels). Red lines show relative magnitude of greenhouse gas impacts while green lines show credits due to co-products of production. Line width corresponds to magnitude of impact or credit.

Table 6.16

GHG emissions for the IH^2 process with 30% moisture forest resources assuming 100 km transport of IH^2 biofuel by different modes

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH^2 fuel)**
	Base case (no IH^2 fuel transport)	**Road transport**	**Rail transport**	**Pipeline transport**
IH^2 Feedstock and Transportation	4.14	4.14	4.14	4.14
IH^2 Process	-0.89	-0.89	-0.89	-0.89
IH^2 biofuel Transportation	-	0.35	0.11	0.03
Total GHG Emissions	**3.25**	**3.60**	**3.36**	**3.28**

Table 6.17

Estimated distances for different blending locations

Different blending locations	**Distances**
Minneapolis, MN	147 miles
Green Bay, WI	202 miles
Milwaukee, WI	277 miles
Chicago, IL	392 miles

Table 6.18

GHG emissions for production and transportation of IH² biofuel produced considering a 30% moisture forest residue feedstock for Johnson Timber Incorporated to different blending sites

Life Cycle Stages	**GHG Emissions (g CO_2 eq./MJ of IH² fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH² fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH² fuel)**	**GHG Emissions (g CO_2 eq./MJ of IH² fuel)**
IH² Road Transport Distance	147 miles	202 miles	277 miles	392 miles
IH² Feedstock and Transportation	4.14	4.14	4.14	4.14
IH² Process	-0.89	-0.89	-0.89	-0.89
IH² Biofuel Transportation	0.51	0.70	0.96	1.36
Total GHG Emissions	**3.76**	**3.95**	**4.21**	**4.61**

6.4.3 Discussion of Forest Resources IH² Biofuel LCA Results

A comparison was conducted between the GHG emissions of IH² biofuels from forest biomass emissions to the emissions from convectional petroleum gasoline, diesel, and jet fuel shown in Figure 6.13. It is clear that two major inputs dominate the GHG emissions; diesel for Collection and transportation of IH² feedstock and electricity used for yard processing. The effects of uncertainty in these inputs can affect life cycle GHG emissions. For example, if the sum of the collection and transporation inputs are increased or decreased by 50% to represent uncertainty in this input, IH² biofuel GHG emissions increase or decrease to 3.9 and 2.6 g CO_2 eq / MJ, respectively. Similarly for increase or decrease of electricity used for yard processing by 50%, IH² biofuel GHG emissions increase or decrease to 4.18 and 2.33 g CO_2 eq / MJ, respectively. These emissions from the forest resource IH² biofuels are relatively low compared to the data from National Energy Technology Laboratory (NETL 2008). Savings of GHG emissions compared to petroleum fuels are approximately 96% for both the 30% and 50% moisture content biomass-based fuels, easily qualifying these biofuels as adavanced biofuels according to the Renewable Fuels Standard (50% reduction required).

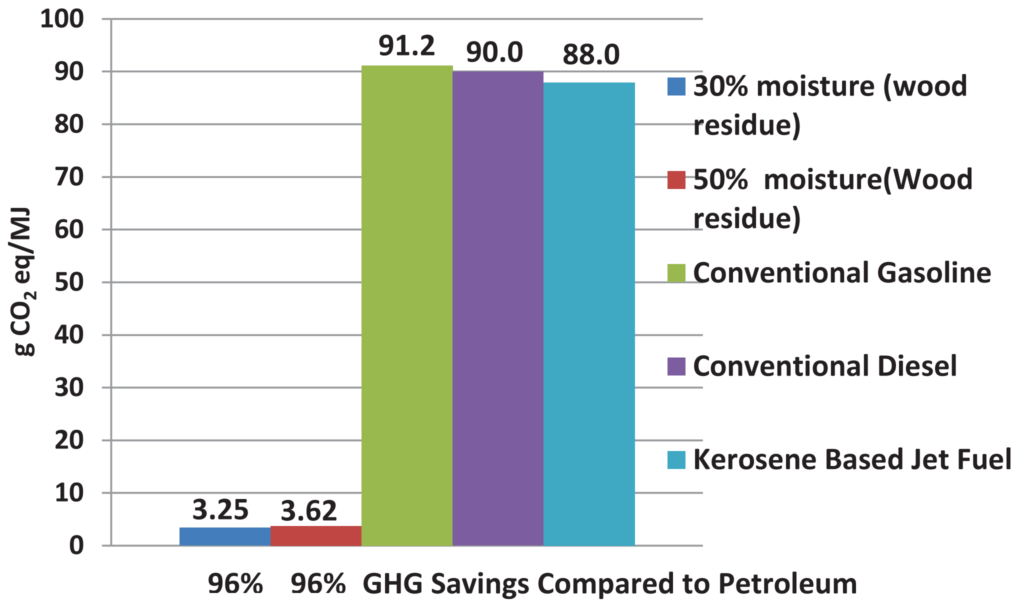

Figure 6.13 Results of IH^2 fuel for forest feedstock GHG emisisons savings compared to petroleum fuels (no transport step to blending was included here- negligible effect).

7. Conclusions and Recommendations

The uncertainty analysis was carried out by analyzing the highest impact inputs from LCA analysis results for each feedstock separately. The uncertainty results show a significant effect on the algae feedstock by making the greenhouse gas (GHG) emissions not to meet the 50% required potential greenhouse gas (GHG) savings required. Where's the uncertainty results for the other feedstocks does not make the feedstock not to meet the required standards.

The purpose of this report was to evaluate the cradle-to-grave life cycle assessment (LCA) of the Gas Technology Institute (GTI) Integrated Hydropyrolysis and Hydroconversion (IH^2) production chain, including the production of input feedstocks and use of output IH^2 biofuels. This report contains a preliminary LCA based on input data for the production and delivery of biomass feedstocks to a future IH^2 biofuel facility, and also based on inputs for the IH^2 process provided by GTI. Alternative bio-based transportation fuels, such as the IH^2 biofuels, have the potential to decrease climate change emissions from vehicular transportation. The goal is to compare environmental impacts of IH^2 biofuels to equivalent fossil fuels in order to determine savings of greenhouse gas (GHG) emissions, but along this path, intermediate results for each biomass feedstock were generated and compared to each other. The functional unit for biomass feedstocks and IH^2 biofuels was 1 dry metric and 1 MJ of energy, respectively.

The main conclusion from this study is that GHG emissions for production and use of IH^2 biofuels from a variety of feedstocks (microalgae, cane bagasse, corn stover, forest resources) are very small compared to comparable petroleum fuels, with the possible exception of fuels derived from microalgae. Savings of GHG emissions per MJ of transportation fuels between 93-98% are typical of IH^2 biofuels produced from most of the studied biomass species (cane bagasse, corn stover, and forest resources). Explorations of IH^2 biofuel transport modes (truck, rail, pipeline) and transport distances had very little effect on overall system GHG emissions. Microalgae produced using renewable electricity for collection and dewatering helped lower GHG emissions and increase savings above 50% compared to petroleum fuels, but the large energy burden of drying the high moisture microalgae feedstock (80% moisture) continues to be a challenge to approach the savings for bagasse, stover, and forest resources IH^2 biofuels.

In addition to these differences in GHG emissions for IH^2 biofuels from several biomass feedstocks, there are also differences in biofuel production yields. Table ES2 shows yields of IH^2 Biofuels from microalgae, cane bagasse, corn stover, and forest feedstocks. Microalgae IH^2 biofuels exhibit the highest yields, nearly double the productivity of the other biomass feedstocks. Composition of biomass is likely the reason for these large differences in yields. For example, many species of microalgae contain significant oil, which contains fewer oxygen atoms and more hydrogen atoms per molecule. In such cases, a higher percentage of the starting biomass is expected to exit the process as biofuel as opposed to CO_2, H_2O and other minor co-products. The yields in Table 7.1 also impact area productivity, that is, the quantity of biofuel produced per unit area of surface of land or water per year. Area productivity is also affected by biomass productivity per unit surface area per year. Combining both of these productivities will result in a key indicator of overall biofuel production efficiency.

The results in this study represent a limited life cycle assessment that touched on one indicator of sustainability, greenhouse gas emissions and savings of those emissions compared to petroleum fuels. It is highly recommended to revisit this LCA when IH^2 conversion data is obtained on pilot or commercial scales. One topic of future interest might be LCAs of mixtures of these feedstocks for IH^2 biofuel production; for example mixtures of microalgae and forest residue resources. Results from such future studies can help refine IH^2 biofuel system impacts leading to more efficient production of this promising biofuel. It is also recommended to carry out scenario analysis considering the corn stover and bagasse as co-products not waste products. These future studies should also include other sustainability indicators for which little is known from this new transportation production system, including land use change emissions, water quantity and quality, emissions of other air pollutants, worker safety, community impacts from biomass transport, and employment. These expanded studies are particularly important when attempting to understand impacts of large-scale dissemination and implementation of this new renewable transportation fuels technology.

Table 7.1

Yield of IH^2 Biofuels from 2,000 Moisture and Ash Free (MAF) Metric Tons (mt) of Biomass.

IH^2 Biofuel from Different Biomass Types	**Yield of IH^2 Gasoline (mt)**	**Yield of IH^2 Diesel (mt)**	**Total IH^2 Biofuel Yield (mt)**
Microalgae	448	448	996
Cane Bagasse	432	140	572
Corn Stover	320	200	520
Forest Resources	320	200	520

7.1.1 Discussion of comparison results of IH^2 base cases to the biofuel values for EPA 2010 regulation of fuels and fuel additives.

Table 7.2 below shows a comparison between results for IH^2 base cases biofuel values obtained from the energy allocation method to the EPA 2010 regulation of fuels and fuel additive values obtained using the displacement allocation method. This comparison is relevant because both the IH^2 biofuels and the RFS2 biofuels listed are intended to displace petroleum gasoline and diesel in the market. With the exception of algae IH^2 biofuels, the results from IH^2 process were much lower than the EPA 2010 results. The EPA values obtained using the displacement allocation method which generally gives more favorable emission results as compared to the energy allocation method that was used for the IH^2 biofuels. The main reasons for the more favorable result for the IH^2 biofuels is because the feedstocks for sugar cane ethanol, corn ethanol, and soya bean biodiesel incur emissions from land use change, which is not the case for the IH^2 feedstocks, as explained previously in this thesis. A second reason for the more favorable result for IH^2 biofuels is due to the processing differences. IH^2 processing employed process integration where hydropyrolysis and hydroconversion are integrated, allowing for more efficient use of energy.

Table 7.2

Comparison of results of IH^2 base cases with the reference to the biofuel values for EPA 2010 regulation of fuels and fuel additives.

Feedstock Types	Base results for IH^2 Case (g CO_2 eq./MJ of Biofuel)	EPA 2010 results (g CO_2 eq./MJ Biofuel)
Bagasse(char burnt) IH^2 fuel	2.6	
Sugar Cane Ethanol		36
Cornstover IH^2 fuel	6.6	
Corn ethanol		75
Microalgae(Hydro) IH^2 fuel	37.9	
Forest feedstock IH^2 fuel	3.25	
Soya bean Biodiesel		40
Cellulosic Diesel		27

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Appendix

7.2.1 Energy, mass balance and EAF calculations

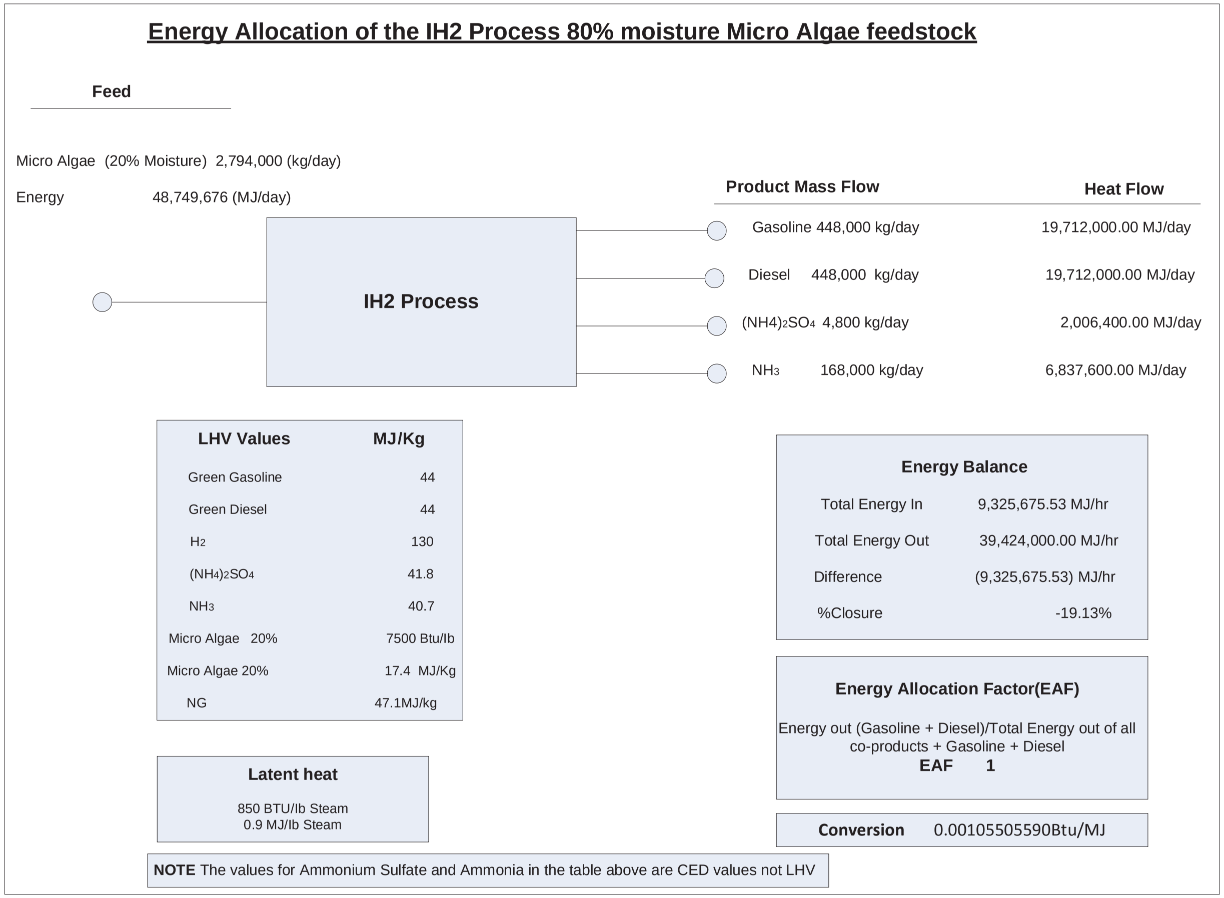

Figure 7.1 Micro algae energy, mass balance and EAF calculation

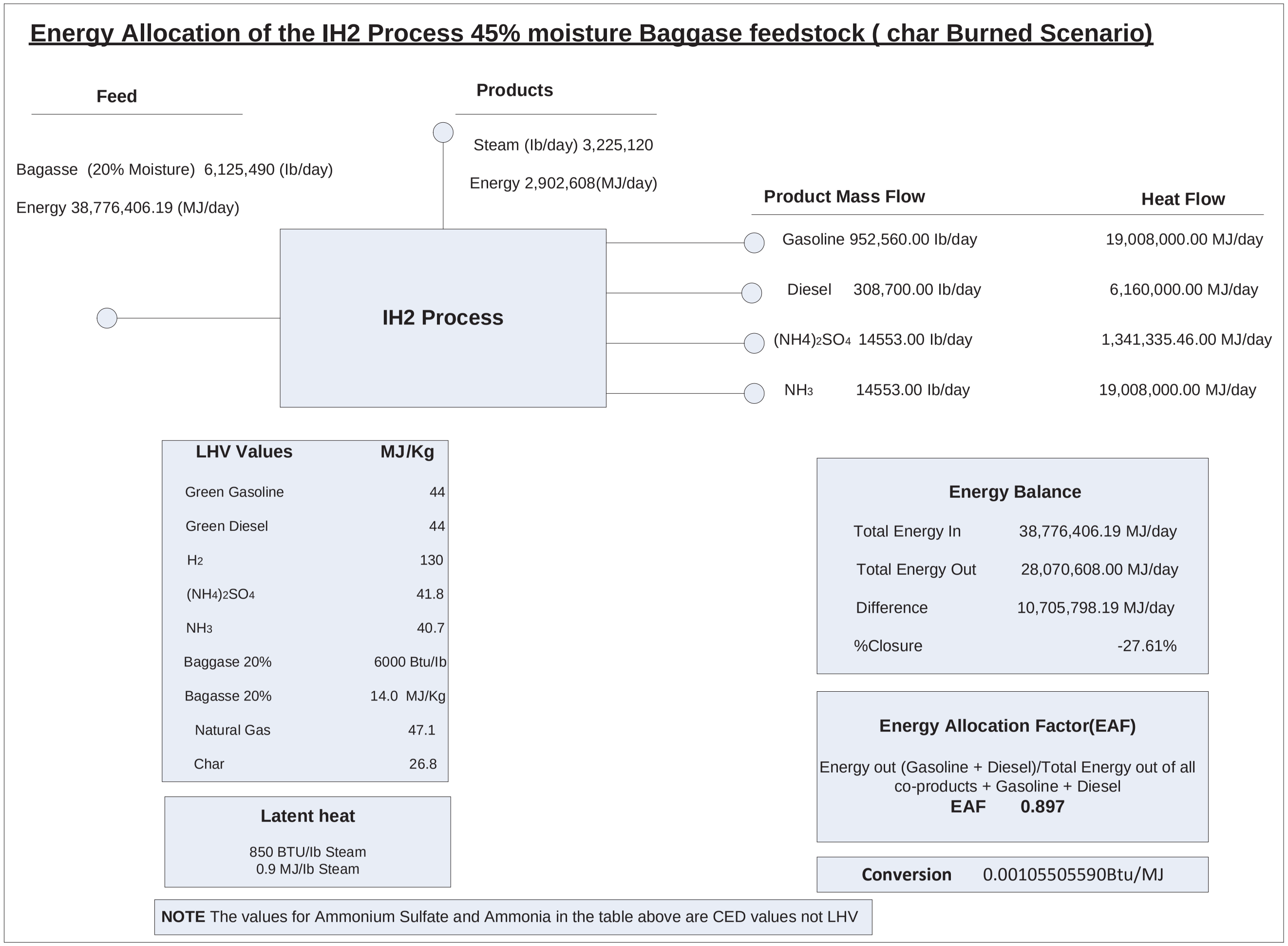

Figure 7.2 Bagasse with char burnt energy, mass balance and EAF calculation

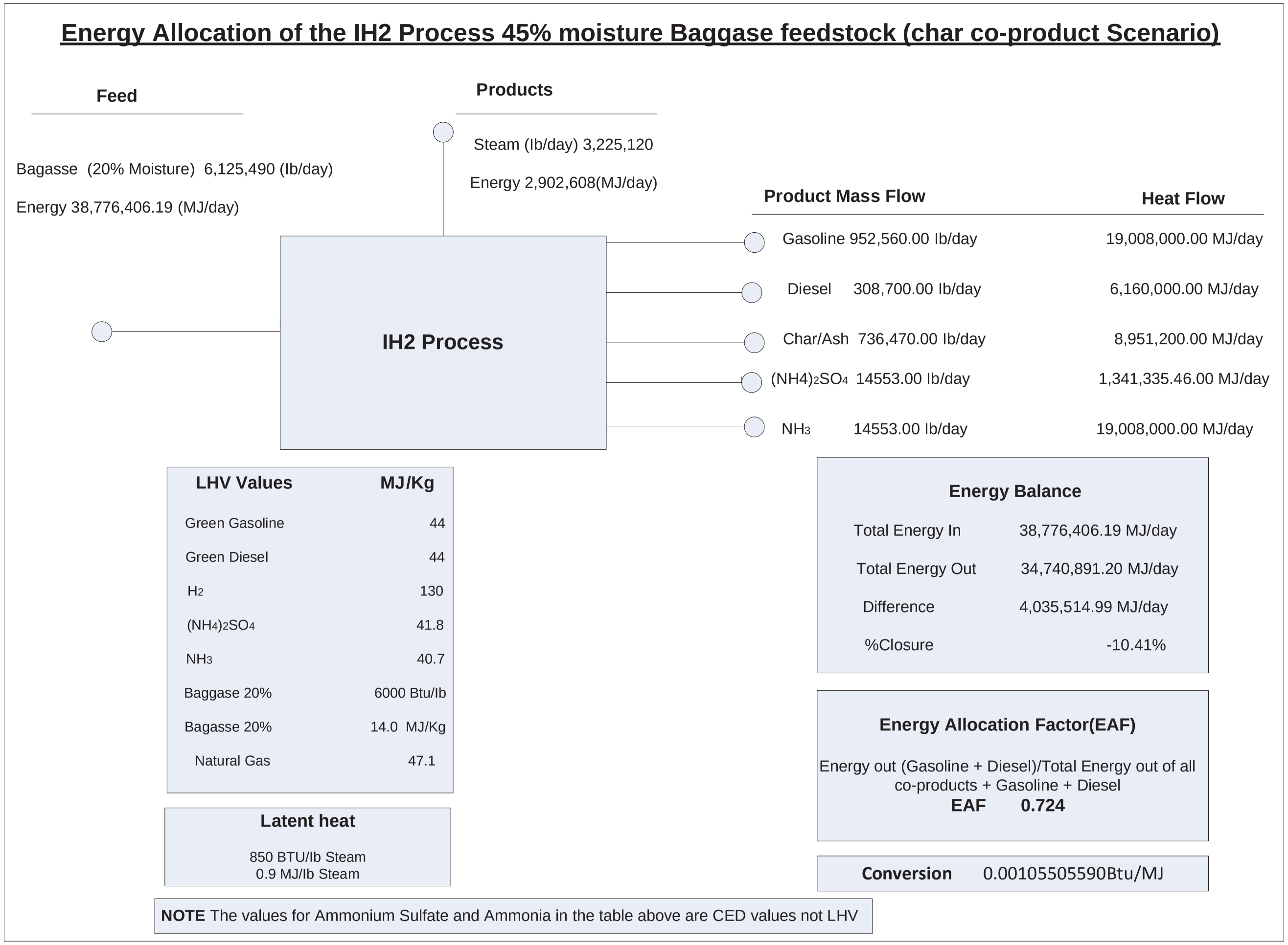

Figure 7.3 Bagasse with char as a product energy, mass balance and EAF calculation

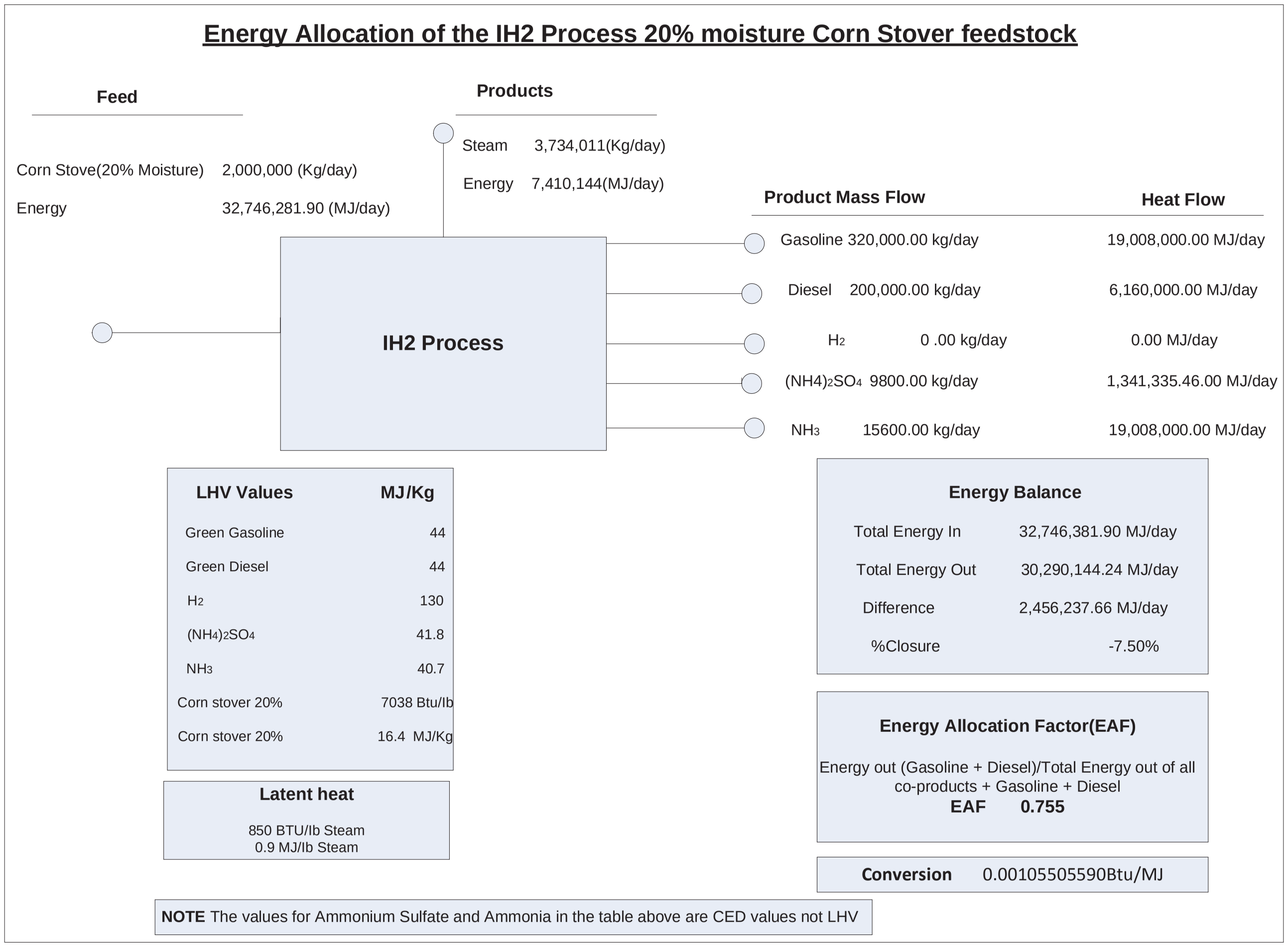

Figure 7.4 Corn stover energy, mass balance and EAF calculation

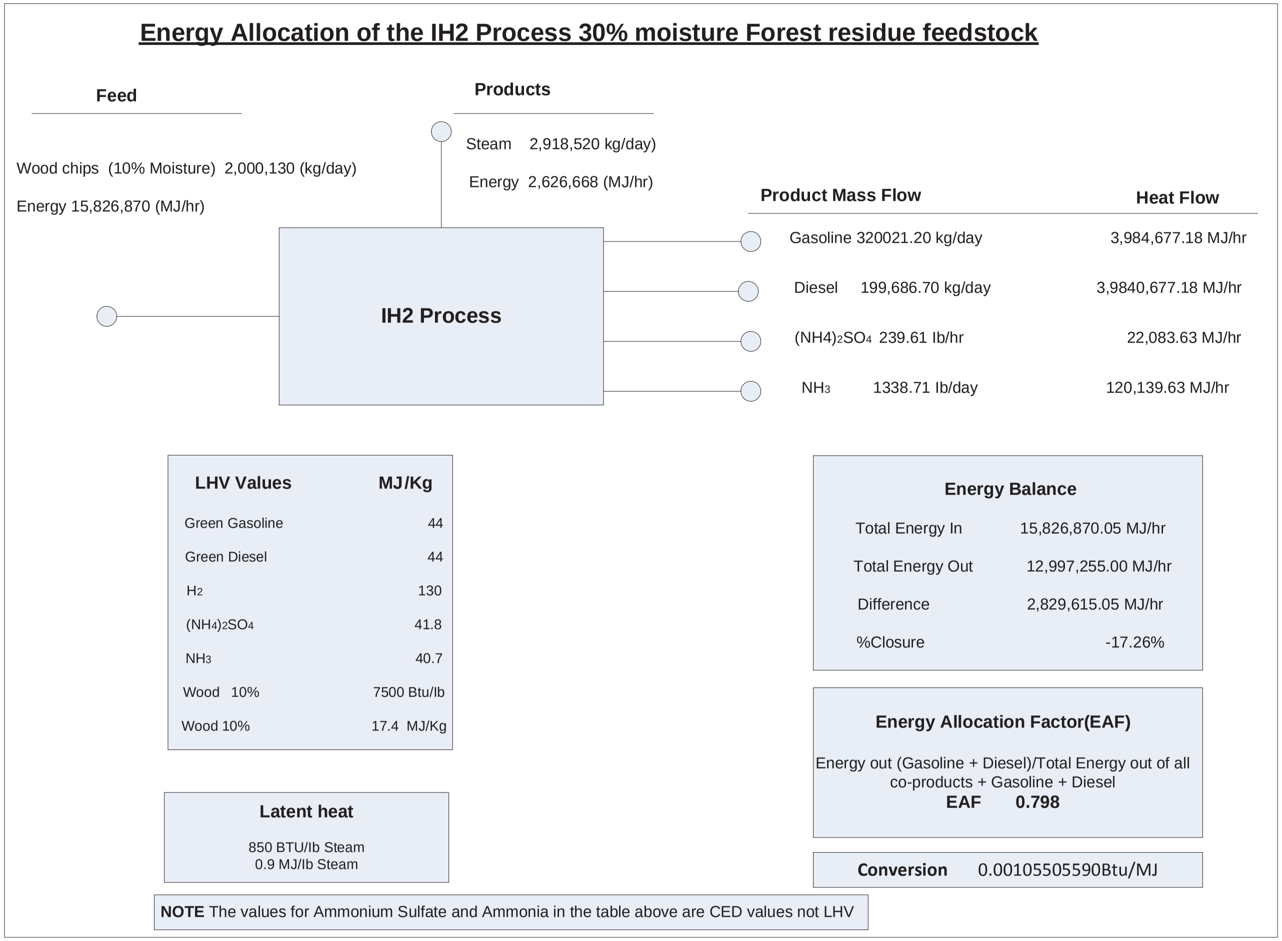

Figure 7.5 Forest Residue 30% moisture feedstock energy, mass balance and EAF calculation

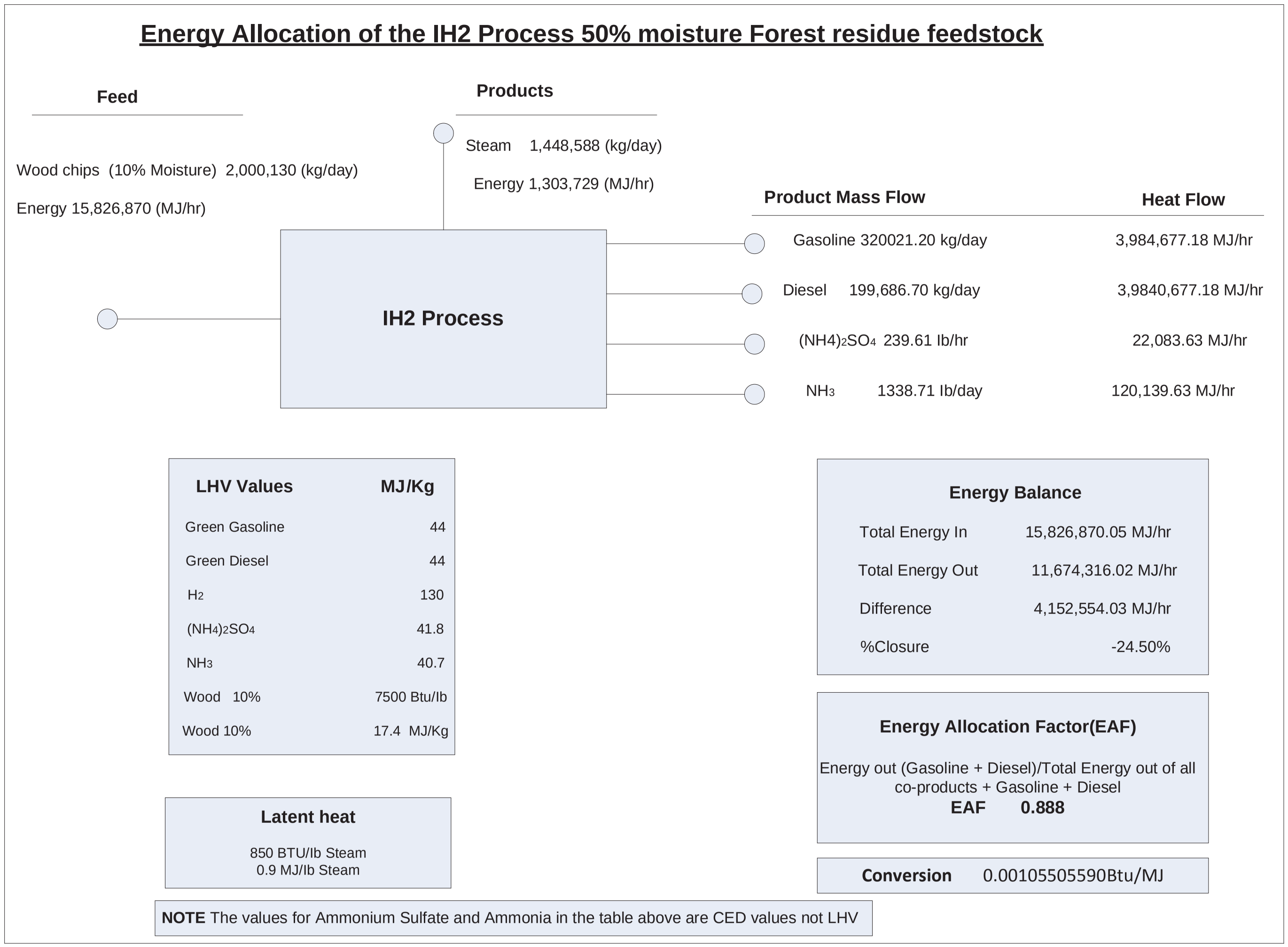

Figure 7.6 Forest Residue 50% moisture feedstock energy, mass balance and EAF calculation

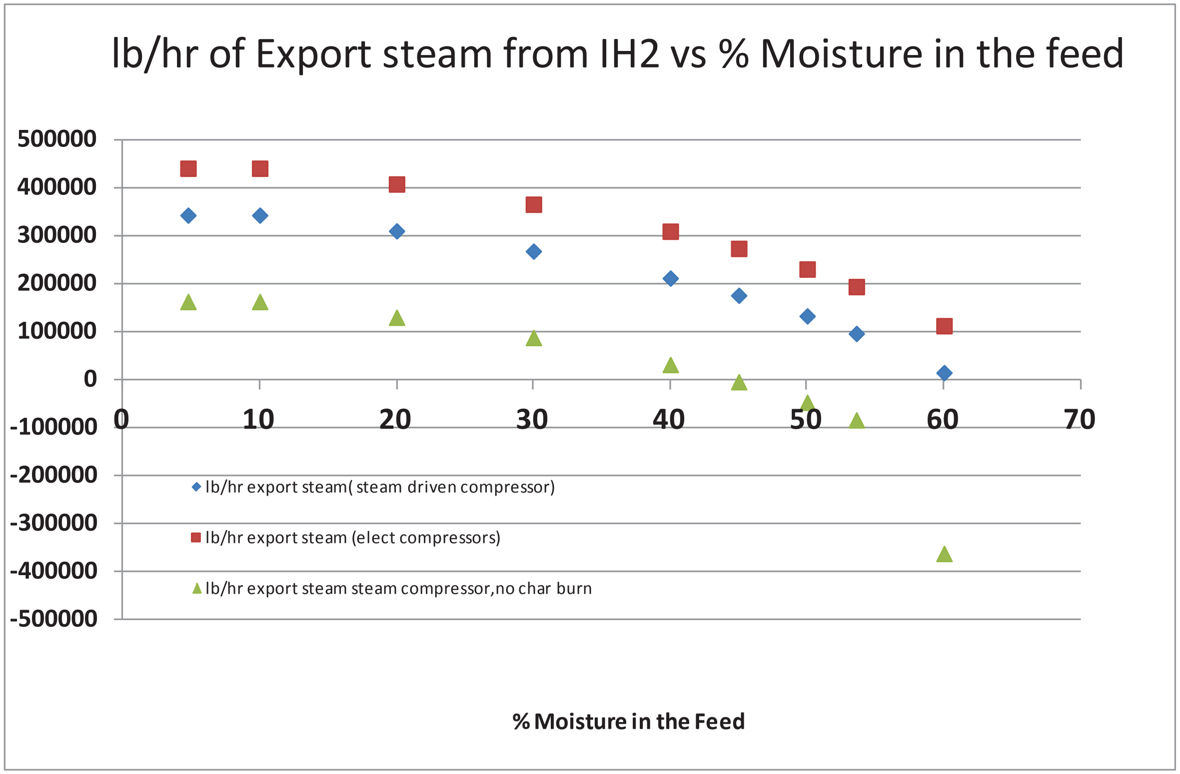

Figure 7.7 Input Plot for Johnson Timber for the exported steam from IH^2 process verses the percentage moisture in feed

7.2.2 Original input data used for Life Cycle Analysis

Table 7.3

Original Johnson Timber feedstock Input table 2000 dry metric ton plant size

Original input data	IH2 UTILITIES										
MT/Day dry feed	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
lb/hr feed	183667	183667	183667	183667	183667	183667	183667	183667	183667	183667	183667
Feed mosture	4.76%	10%	20%	30%	40%	45%	50%	53.59%	60%	70%	90%
water in feed at 10%	9179	20407	20407	20407	20407	20407	20407	20407	20407	20407	9179
total feed lb/hr	192846	204074	229583	262381	306111	333939	367333	395774	459167	612222	1836667
water in feed lb/hr	9179	20407	45917	78714	122444	150273	183667	212107	275500	428556	1653000
export steam lb/hr (accounting for Steam Driven Compressor)	57,000	57,000	57,000	57,000	57,000	57,000	57,000	57,000	57,000	57,000	57,000
export steam from burning char lb/hr	180,000	180,000	180,000	180,000	180,000	180,000	180,000	180,000	180,000	180,000	180,000
export steam from burning PSA2 gas lb/hr	106,000	106,000	106,000	106,000	106,000	106,000	106,000	106,000	106,000	106,000	106,000
total exportsteam possible lb/hr	343,000	343,000	343,000	343,000	343,000	343,000	343,000	343,000	343,000	343,000	343,000
total export energy possible BTU/hr	426,692,000	426,692,000	426,692,000	426,692,000	426,692,000	426,692,000	426,692,000	426,692,000	426,692,000	426,692,000	426,692,000
energy in HP steam-BTU/lb	1244	1244	1244	1244	1244	1244	1244	1244	1244	1244	1244
enrgy for drier- btu/lb of water removed	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600
water removed in drier lb/hr	0	0	25509	58307	102037	129865	163259	191700	255093	408148	1643821
drier energy requiredBTU/hr	0	0	40814815	93291005	163259259	207784512	261214815	306719283	408148148	653037037	2630112838
total energy from steam left	426,692,000	426,692,000	385,877,185	333,400,995	263,432,741	218,907,488	165,477,185	119,972,717	18,543,852	-226,345,037	-2,203,420,838
total lb/hr steam for export w steam driven compresors	343000	343000	310191	268007	211763	175971	133020	96441	14907	-181949	-1771239
steam to compressors lb/hr	97,700	97,700	97,700	97,700	97,700	97,700	97,700	97,700	97,700	97,700	97,700
lb/hr steam for export w motor driven compresors	440,700	440,700	407,891	365,707	309,463	273,671	230,720	194,141	112,607	-84,249	-1,673,539
lb/hr steam for export w steam comp, burn char only	237,000	237,000	204,191	162,007	105,763	69,971	27,020	-9,559	-91,093	-287,949	-1,877,239
lb/hr steam export no char burned-steam driven compressors	163,000	163,000	130,191	88,007	31,763	-4,029	-46,980	-83,559	-165,093	-361,949	-1,951,239

Table 7.4

Original Johnson Timber IH[2] Input tables table B: – Overall YE 2011-3Yields

Product Yields MAF			
Overall	**Wt % Maf**	**Ton/day**	**MM gal/yr**
gasoline	16	320	37.2
diesel	10	200	21.2
char +ash	13	260	
water	8.5	170	14.8
ammonium sulfate	0.19	3.8	
ammonia	0.14	2.8	
CO2+H2 exhaust	58.85*	1177	
total	106.7	2137.6	

Table 7.5

Original Johnson Timber IH^2 Input tables Feedstock Properties Typical Wood Yield 2011-3

Feedstock Properties	
Component	**Amounts**
Feed Type	32% softwood+ 68%hardwood
Flow Rate, t/d (MAF)	2000 T/d
Flow Rate t/d (actual)	
%C (MF)	49.66
%H (MF)	5.96
%O (MF)	42.97
%N (MF)	0.22
%S (MF)	0.07
% ash (MF)	1.12
% moisture	10.0
% Cellulose	39
% hemicelluloses	21
% lignin	24

7.2.3 Detailed General flow diagram of GTI IH^2 process

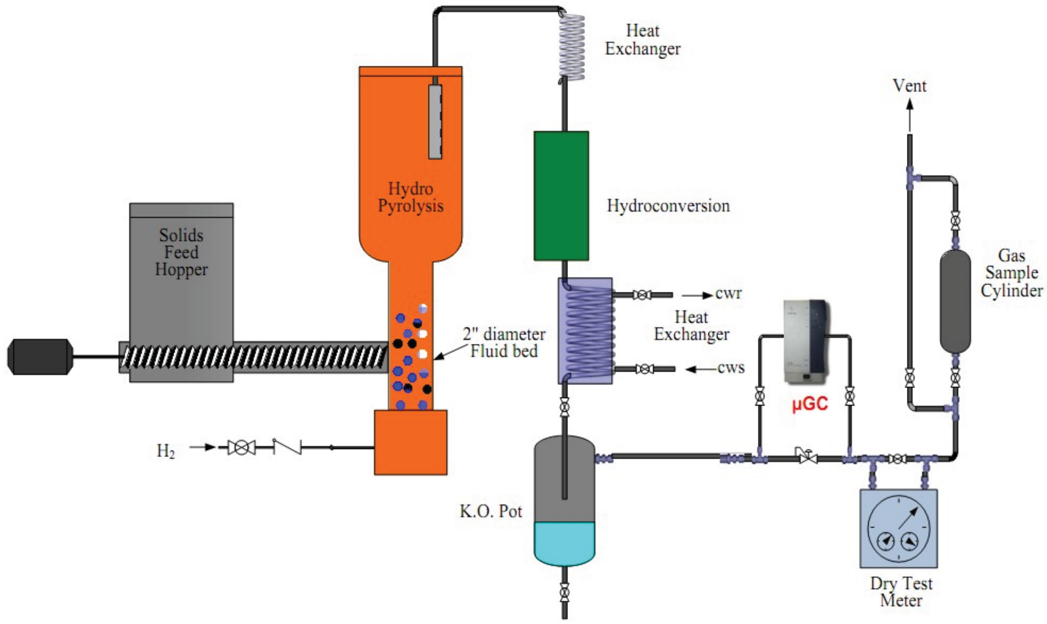

Figure 7.8 More detailed Simplified flow diagram of GTI IH^2 process. (Diagram reference from extended abstract 2009 AIChE by Terry Marker, Larry Felix and Martin Linck from GTI)

7.2.4 IH^2 process diagram for algae conversion to biofuel

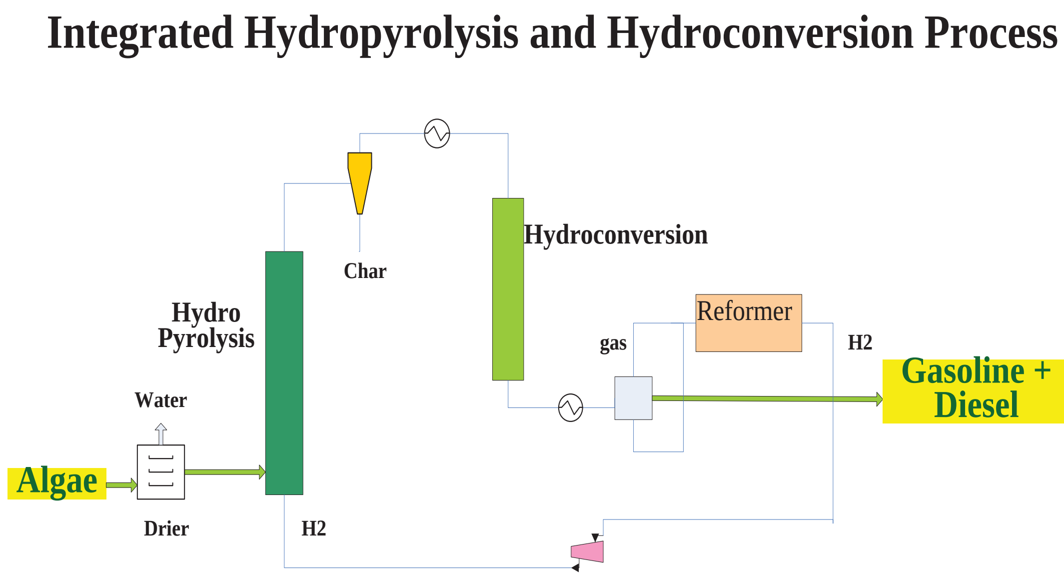

Figure 7.9 Simplified flow diagram of GTI IH^2 process. (Diagram reference from extended abstract 2009 AIChE by Terry Marker, Larry Felix and Martin Linck from GTI)

7.2.5 IH^2 Process Flow diagram for Micro Algae feedstock production

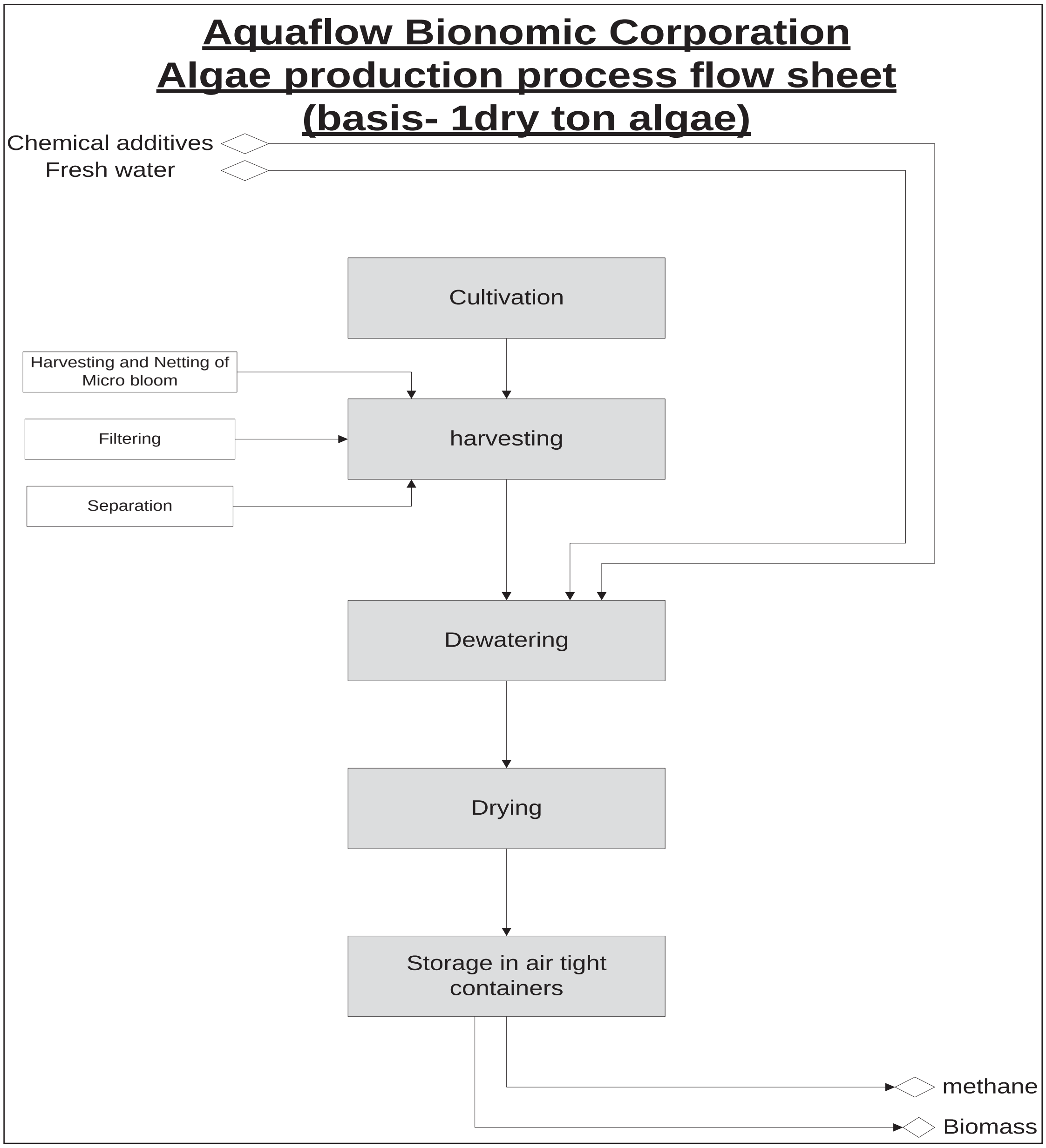

Figure 7.10 The process flow diagram for micro algae production from Aquaflow Bionomic Corporation. The shaded boxes represent the main stages of production.

Table 7.6

Algae IH^2 Input tables Overall Yields from 20% Moisture Algae Table D: YE 2011-7

Product Yields				
Overall	**Wt % Maf**	**Wt% Actual**	**Ton/day**	**MM gal/yr**
gasoline	22.4	16.0	224	26.1
diesel	22.4	16.0	224	23.7
Char/ash	2.0	9.8	137	
water	-5.3	16.2	226	19.7
ammonium sulfate	2.45	1.8	24	
ammonia	8.40	6.0	84	
CO_2+H_2 exhaust	51.52*	36.9*	515*	
Total	103.89		1434	

* This CO_2 contains some Oxygen from air which is added when part of the reformer feed gas is burned in the reformer furnace.

Note: An additional 4189 t/d of moisture would be removed during drying from 80% water to 20% water

Table 7.7

Original Algae IH^2 Input tables Typical Aquaflow Algae Table E: YE 2011-7

Feedstock Property Moisture Ash Free	
Flow rate t/d (MAF)	1000
Flow rate t/d (actual after drying to 20%)	1397
Flow rate t/d (actual before drying-80% moisture)	5586
%C (MAF)	56.71
%H(MAF)	8.01
%O(MAF)	25.84
%N(MAF)	8.54
%S(MAF	0.90
%ash(MF)-after drying	10.5
% Moisture after drying	20.0
% Moisture before drying	80.0

Wastewater Algae Based on Aquaflow Algae mechanically died to 80% moisture; natural gas dried to 20% moisture

7.2.7 Bagasse IH^2 Input tables Overall Yields

Table 7.8

Original Bagasse IH^2 Overall Yields from 20% Moisture Bagasse Table F: YE 2011-8

Overall	Wt % MAF	Wt% Actual	Ton/day	MM gal/yr
gasoline	21.6	15.5	216	25.1
diesel	7.0	5.0	70	7.4
char/ash	5.5	12.0	167	
water	-8.83	13.6	189	16.5
ammonium sulfate	0.33	0.24	3.3	
ammonia	0.33	0.24	3.3	
CO_2+H_2 exhaust	78.52*	56.5*	785*	
total	104.42		1434	

Product Yields

* This CO_2 contains some Oxygen from air which is added when part of the reformer feed gas is burned in the reformer furnace

Note: An additional 631 t/d of moisture would be removed during drying from 45% water to 20% water

Table 7.9

Estimated Overall Utilities starting with 45% moisture bagasse – char product made in table 3.7

Boiler feed water	14,391 lb/h
Export steam 600psi,700F	14,391 lb/h
Electricity required	128 kW

Table 7.10

Estimated Overall Utilities staring with 45% moisture bagasse– char burned in hog boiler in table 3.7

Boiler feed water	67,190 lb/hr
Export steam 600psi,700 F	67,190 lb/hr
Electricity required	128 kW