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LIFE CYCLE ASSESSMENT OF BIOMASS HARVESTING FOR ON-FARM BIOFUEL PRODUCTION

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LIFE CYCLE ASSESSMENT OF BIOMASS HARVESTING *FOR ON-FARM BIOFUEL PRODUCTION*

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Biosystems and Agricultural Engineering
in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

Director: Dr. M. D. Montross,

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Lexington, Kentucky

2015

ABSTRACT OF THESIS

LIFE CYCLE ASSESSMENT OF BIOMASS HARVESTING
FOR ON-FARM BIOFUEL PRODUCTION

Understanding the energy input and emissions resulting from the development of biofuels is important to quantify the overall benefit of the biofuel. As part of the *On-Farm Biomass Processing* project, a life cycle assessment (LCA) was conducted on the process to harvest and transport agricultural crop residues ready for processing into biofuel. A Microsoft Excel model was developed that inventories the entire life cycle of the process, including incorporation of stochastic analysis within the model. The LCA results of the agricultural equipment manufacture are presented, along with the results of each step of the process, including fertilizer addition, single pass harvest, double pass harvest, and transport from the field to processing facility. Various methods of analyzing co-products are also presented for the single pass harvesting step, in which comparisons between market based, mass based and process-purpose based allocation methods are reviewed. The process-purpose based method of fuel consumption difference between combine operation in conventional harvest versus single pass harvest is determined to be the most realistic of the process. A detailed comparison of the energy and emission differences between single pass and double pass harvesting is given, along with the total LCA results of harvesting and transporting the biomass.

KEYWORDS: life cycle assessment, LCA, cellulosic biofuels, stochastic analysis, Greenhouse Gas, GHG

Michael Hagan

May 1, 2015

LIFE CYCLE ASSESSMENT OF BIOMASS HARVESTING
FOR ON-FARM BIOFUEL PRODUCTION

By

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Director of Thesis

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May 1, 2015

To my children, who remind me each day of the real joys of life

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CHAPTER 1 : INTRODUCTION

1.1 Introduction

Petroleum accounts for 93% of the energy used for transportation fuels in the United States, which corresponds to 71% of all petroleum usage (U.S. Energy Information Administration, 2011). With higher petroleum prices and concern over foreign imports, this has led to the various "energy crises" experienced by the United States over the years. These "energy crises" can be more specifically expressed as liquid transportation fuel crises, affecting our economy's mobility (Dale, 2008). Coupled with the environmental burdens of greenhouse gas emissions and other harmful pollutants, and the fact that our petroleum resources are finite, this has prompted Congress to pass the 2007 Energy Independence and Security Act (EISA) (Energy Indepenence and Security Act of 2007, 2007). At a high level, EISA has specifications for increased renewable fuel usage, new Corporate Average Fuel Economy (CAFE) standards, and life cycle greenhouse gas (GHG) emissions reductions from corn based ethanol (Scheffran, 2010).

To address our economy's mobile vulnerability to petroleum fuels and to satisfy the requirements of the EISA, many alternatives to petroleum are being developed. One potential alternative transportation fuel to petroleum is biofuel, consisting primarily of ethanol and biodiesel from conventional feedstocks, and cellulosic biofuels. What makes biofuels an especially attractive alternative to petroleum is that they are, "by and large, 'drop in' replacements for either diesel or gasoline." (Dale, 2008) Biofuels also present many other benefits than just diversity at the pump, such as environmental, economic, and renewable energy benefits (Scheffran, 2010).

Assessing the feasibility of biofuels and other petroleum alternatives has become an increasingly important task as it directs resource allocation and energy policy. Life cycle assessment (LCA) has become a typical approach to do this, being that the LCA takes a "cradle to grave" approach to determining the inputs and outputs of a process or product. In other words, two processes can be fairly and objectively compared since the total inputs and outputs over the entire supply chain and life of the product are evaluated.

Typically, energy inputs, greenhouse gasses, and other environmental emissions are the key inputs and outputs evaluated as part of the LCA process. Many times impact categories are assigned to specific outputs in order to gain a better understanding of the environmental implications of the LCA results. In regards to energy flows, a key metric often produced from LCA is net energy and whether the result is positive or negative. Meaning, for a replacement fuel to be viable the fossil energy inputs must be less than the resulting energy the fuel provides, i.e. positive net energy (Farrell et al., 2006). In this way, LCA studies can produce results that are holistic yet simple and straightforward.

Caution should be used when blindly reviewing LCA results, however, since the goal and scope of an LCA have tremendous influence on the end result, and in some cases the functional units and metrics themselves are causes for debate. Dr. Bruce Dale argues this about the net energy metric, explaining that the metric itself is flawed due to its underlying assumption that all forms of energy are created equal (Dale, 2007). In other words, a MJ of coal equals a MJ of petroleum. This is obviously not the case, since the different qualities of the energy sources must also be taken into account. Society values the characteristics of petroleum because it makes a good transportation fuel, while coal or natural gas characteristics do not lend themselves as well for transportation fuels.

Nonetheless, it is crucial for the LCA author to establish clear goals and scope when performing LCA, since every study will use different data sources and make different assumptions. When using similar boundary conditions and comparing appropriate fuels (gasoline and/or diesel to biofuels), the net energy metric provides comparative insight into the energy and emission differences of the fuels. So long as the upfront goal and scope of the LCA study is clear, the ability for LCA to account for all the energy inputs and outputs of the process make it an ideal tool for evaluating alternatives to petroleum.

When looking at biofuels as replacements to petroleum, commercial industries currently exist for ethanol and biodiesel, however cellulosic biofuels are still in the experimental phase. For purposes of clarification, cellulosic biofuels are renewable fuels derived from cellulose, hemicellulose, and lignin (Schnepf & Yacobucci, 2013) and encompass both cellulosic ethanol and bio-butanol products. Feedstocks can include agricultural residues (corn stover and wheat straw), dedicated energy crops (switchgrass), and wood based products (sawdust, waste paper, etc.). Two primary obstacles exist for cellulosic biofuels: the logistics of harvesting, supplying, and storing the feedstock necessary for conversion (Richard, 2010) and the chemical conversion process from feedstock to fuel.

1.2 Project Background

This project strived to address harvesting biomass feedstocks necessary for cellulosic biofuels production. As a small part of the USDA-BRDI *On-Farm Biomass Processing: Towards an Integrated High Solids Transporting/Storing/Processing System* project, the ultimate goal is to reduce transportation and storage costs by keeping harvested biomass on the farm and preprocessing it into a liquid mixture of valuable chemicals on-farm (University of Kentucky, 2011). A high level diagram of the process is shown in Figure 1.1.

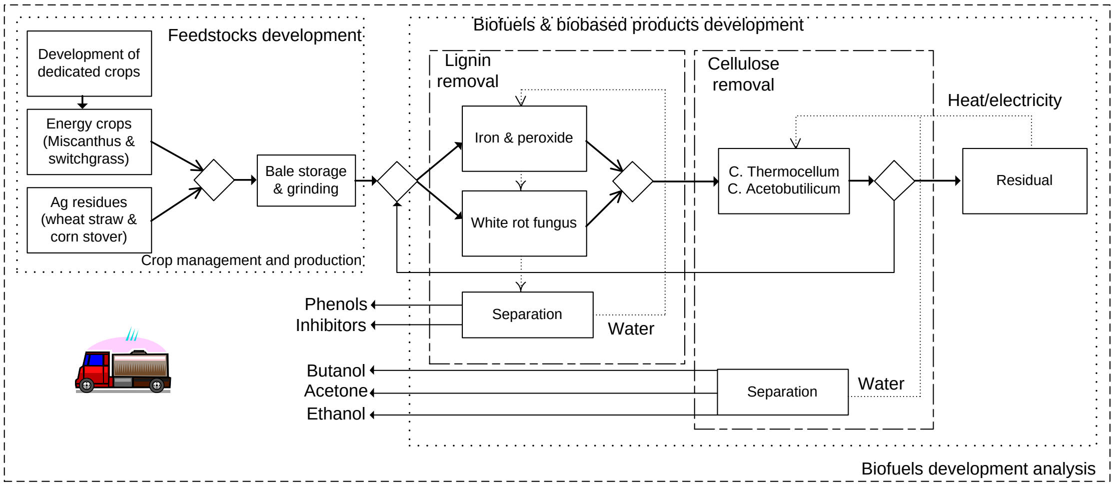


Figure 1.1 *On-Farm Biomass Processing*: Towards an Integrated High Solids Transporting/Storing/Processing System Process Overview

As is illustrated in Figure 1.1, the *On-Farm Biomass Processing* project is divided into two main categories: Feedstocks development and Biofuels & Biobased products development. At a high level, "Feedstocks Development" consists of the development of energy crop and agricultural residue supply chains, including crop growth, crop and residue harvesting, transportation, storage and particle size reduction. The "Biofuels and biobased products development" phase takes the feedstocks as input into the chemical processing and breakdown of the cellulosic material into butanol, acetone, and ethanol products, that will be hauled off the farm as a mixture. What makes this process different than other cellulosic biofuel conversion processes is that it occurs on farm, which reduces transportation costs by approximately 25% and allows for ample storage space for the biomass versus at the processing facility.

During the “Feedstocks Development” researchers specifically evaluated several different feedstocks, including energy crops (miscanthus and switchgrass) and agricultural crop residues (wheat straw and corn stover). The primary focus of this project is the analysis of the agricultural residues wheat straw and corn stover as direct inputs into the *On-Farm Biomass Processing* process as a whole. A full explanation of the goal and scope, as well as system boundaries and assumptions are explained further in the text.

1.3 Project Objectives

Focusing on the development of the agricultural crop residues wheat straw and corn stover in the Feedstock Development phase of the *On-Farm Biomass Processing* project, this project specifically strived to address the following objectives:

1.3.1 *Objective 1: Develop a Comprehensive LCA Model of the Agricultural Residue Collection Process*

The LCA model evaluates the whole lifecycle energy inputs and emissions of the process for the steps that differ from normal wheat or corn production since it is assumed wheat and corn production is the primary product of the crop growing process. In other words, harvesting straw and stover as inputs into the biofuel process is considered secondary to the primary process of growing wheat and corn for grain. Therefore, the LCA model only considers those steps required for biofuel production that are above and beyond normal grain production. The high level lifecycle steps considered are: additional fertilizer required for crop production, harvesting methods (single and double pass), and transportation of baled biomass to the storage facility, along with all the equipment necessary in each process. Specific system boundaries are illustrated further in this chapter.

Since this LCA is a small part of the *On-Farm Biomass Processing* project, the LCA provided results and conclusions that stand alone but that are also easily integrated into the larger scale project study. This enables environmental and process efficiency conclusions to be made on the feedstock development side of the project, and also feed into the final energy and emissions impacts of the on-farm biomass production process.

1.3.2 *Objective 2: Utilize Stochastic Simulation to Improve Model Robustness*

Traditionally LCA has used average or point values in estimating the inputs and outputs of a process or product (Mullins, Griffin, & Matthews, 2011). Since real world conditions often vary significantly, it is useful to incorporate this variability into the analysis. This is especially critical when evaluating biofuels for the replacement of petroleum since varying weather, farming practices, and locations have tremendous effects on agriculture. Utilizing stochastic simulation improves the robustness of the LCA model results, and therefore reduces the sensitivities that the assumptions and individual inputs have on the overall results.

Furthermore, where continuous field data is available, utilizing distribution fitting functions and stochastic simulation enables direct input of the raw data into the model. This allows for clear and easy traceability of the data used in the model, improves the quality of model data (especially for high impact inputs), and provides higher confidence in model results.

1.3.3 *Objective 3: Evaluate the Specific Energy Input and Environmental Emission Differences between Single Pass and Double Pass Harvesting*

New equipment and modifications to existing equipment have been developed that have made it possible to harvest wheat straw and corn stover simultaneously during grain harvest. This method of harvest is called single pass, in which the combine pulls a baler, as compared to more traditional harvesting methods that require a second pass (double pass method) with a tractor and baler after the combine has harvested the grain.

Each method requires different equipment setups and in field processes, and will therefore have different energy inputs and emissions outputs. Single pass versus double pass harvesting is not a new concept, and multiple studies have been performed comparing the differences and efficiencies of the two (Shinners et al., 2009) ((S&T)2 Consultants Inc., 2009). While these studies were similar to this project; the system boundaries, functional units and project scopes are different, and thus it is necessary to evaluate and compare the two methods under the guidelines of this project.

Additionally, single pass and double pass harvesting present major process differences in the agricultural residue supply chain evaluated in this project. This correspondingly can yield significant differences in the LCA results, thus it was important to compare the two processes and how they affected the *On-Farm Biomass Processing* project.

1.4 Project Justification

In order to quantify the success of the *On-Farm Biomass Processing* project, specifically in regards to the mandates specified in the Renewable Fuel Standard (RFS) part of the EISA, an evaluation of life cycle GHG emissions must be performed. The 2007 EISA specifies cellulosic biofuels must reduce lifecycle GHG emissions by at least 60% as compared to the 2005 baseline for gasoline or diesel fuel (Schnepf & Yacobucci, 2013).

While this project is a small part of the *On-Farm Biomass Processing* project, it represents key steps of the feedstock development process in which energy inputs and emissions must be counted. Therefore, the justification for this LCA is to understand the energy inputs and emissions that result from the whole life cycle of agricultural residue harvest and transportation to the on-farm processing facility. This will provide quantitative results of the benefits of alternative cellulosic feedstock harvesting strategies considering the benefits of harvesting, storing and preprocessing the feedstocks on farm.

1.5 LCA Goal and Scope Definition

As all successful projects require a clear goal and scope, so especially do LCA projects as the project results depend highly on the scope and system boundaries set in the beginning. As was mentioned previously in the text, the primary objective of this LCA was to quantify total energy and emissions that result from on-farm harvesting and transportation of wheat straw and corn stover for cellulosic biofuel. This project is an attributional LCA, whereas the product being considered is wheat straw or corn stover in large square bale form. A large square bale is defined as having the following approximate dimensions: 0.9 meter height, 1.2 meter width and 2.4 meter length (3x4x8 feet, respectively). Approximate bale density is 190 kilograms per meter cubed (11.9 pounds per cubic foot). Two harvesting techniques are explored, single pass versus double pass, to understand the resulting difference in energy and emissions. Figure 1.2 illustrates the process flow diagram for wheat straw and corn stover, along with boundary conditions for this analysis.

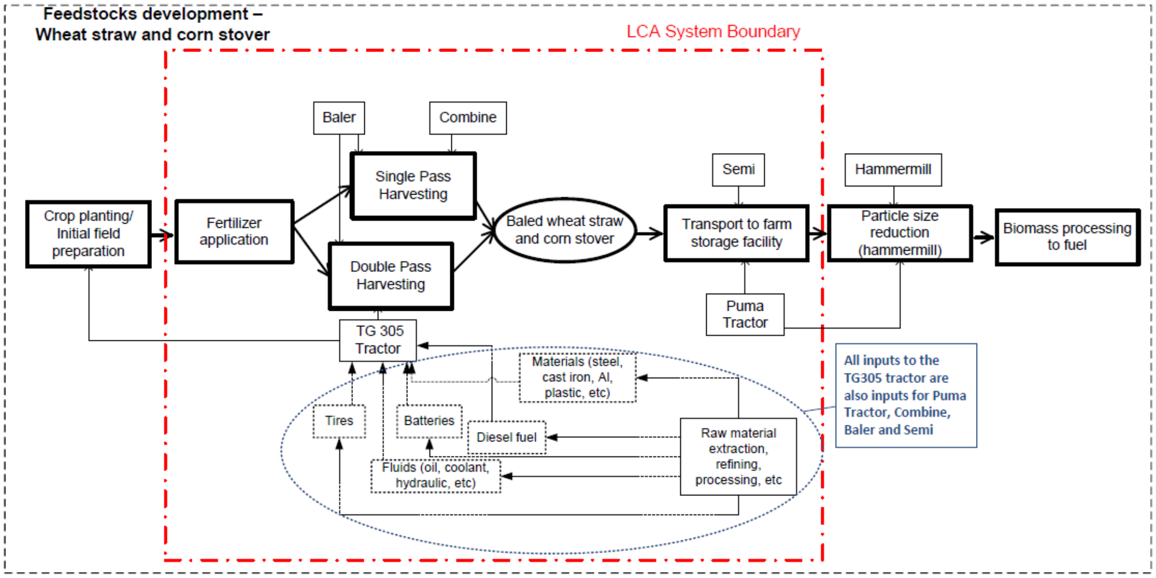


Figure 1.2 Wheat Straw and Corn Stover Harvesting Process Flow Diagram.

1.5.1 *Functional Unit*

The functional unit used in this analysis is MJ per hour (mmBTU/hr) for energy or grams per hour for emissions. This was chosen primarily as a way to normalize the results, since most agricultural equipment is purchased and used for many different reasons other than biomass harvesting. By analyzing the process in units per hour, results can be normalized only for their share during biomass harvest. As an example, the energy consumed during manufacture of a tractor is normalized into MJ per hour over the entire tractor life. Therefore, the tractors energy share for biomass harvesting depends on how many hours it is used during harvest. If 1 hour is assumed, a fair comparison can be made between all equipment used in the process. If desired, the total number of hours used for each piece of equipment can be totaled and multiplied by the units per hour to give the total energy consumed or emissions generated for each ton of biomass produced.

The process takes additional biomass from the field which would normally contribute nutrient value to the subsequent year’s crop, which were included in this study. While the energy and emissions that result from making up the lost nutrients can be quantified, fertilizers which are applied on a season by season basis do not lend themselves to an hourly rate, as was done for the equipment. It was for this reason that MJ per hectare for energy and gram per hectare emissions was also used as a functional unit when looking at this specific aspect of the process.

Additionally, when comparing the single pass harvest with double pass process, different speeds are achieved by the combine in single pass as compared with the tractor in double pass harvest. Thus, the rate or throughput of biomass processing is different in the two methods, and it is helpful to view these results on a “per area” basis instead of a “per time” basis. MJ per hectare and grams per hectare were also used in this circumstance to present the results.

1.5.2 *Cutoff Criteria*

In conducting a LCA, the number of data inputs can become enormous. For this reason, a cutoff criterion is typically used in the LCA to limit inputs that have little impact on the final results. A cutoff criteria was implemented for inputs in this analysis and is discussed in more detail in Section 3.4   While some LCA’s will eliminate those inputs entirely from the analysis, this study kept all the inputs but applied stochastic analysis only to inputs that were above the cutoff criteria.

1.5.3 *Co-Product Handling*

Co-products in this life cycle assessment are handled several ways to assess the variance in results due to co-product allocation. Since LCA results are normalized per hour of operation, this eliminates the need for the majority of co-product issues that arise in an agricultural setting. However, one primary co-product of the single pass harvesting process still remains: the combine harvesting step in which the combine is used to collect the wheat or corn grain and wheat straw or corn stover for baling. In this step, the two co-products are compared based on the allocation methods of mass and market based allocation (Wang et al., 2011), as well as a comparison for rate of fuel increase of the combine over traditional harvesting.

1.5.4 *Impact Categories*

Discussed in great detail in Chapter 3, the LCA model used the same structured format as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transport (GREET) model (Argonne National Laboratory, 2014). This yielded Life Cycle Inventory (LCI) results for Total Energy and the subsets of Fossil Fuels, Coal, Natural Gas and Petroleum for the energy expended as part of the process. For emissions of the process: VOC, CO, NO_x, PM10, PM2.5, SO_x, CH_4, N_2O, CO_2, and Greenhouse Gas emissions were considered. Since this is a fairly large list of LCI categories, it was decided to focus primarily on Total Energy and Greenhouse Gas emissions as the primary impact categories for energy consumption and emissions, respectively. While perhaps not true impact categories such as climate change or acidification as given in ISO 14044 (ISO, 2006b), these two categories successfully meet the objectives of this study in quantifying the difference in life cycle energy and emissions that result from single pass versus double pass harvesting of biomass. These categories also lend themselves to being easily transferred to future LCA studies on the subsequent steps of the process.

1.5.5 *Data Sources and Quality*

Data quality is an important consideration in LCA for two primary reasons: the LCA results may be referenced in scenarios in which the data does not apply; and data quality and sources may add significant variation to the LCA results. This is why it is important to discuss the data quality and source requirements in the beginning stages of the project.

Data sources for this project, reviewed in great detail in Chapter 3, were primarily gathered from open literature, field data and the GREET model. The GREET model provided much of the equipment manufacturing data and raw material procurement data. Early stages of the model showed that the field operations (fuel use, crop yields, etc.) composed the largest share of energy and emissions of the process; therefore field data was gathered where possible to obtain the most accurate data for these high impact inputs. Open literature was used where field data was not available and when outside the scope of the GREET model. Additional information on the GREET model is reviewed in Chapter 2, and specific model structure and data sources are covered in Chapter 3.

Where continuous data were available, especially in the field data collected, statistical distributions were fitted to the data and run as inputs into the model during the stochastic analysis. Where only point values or minimum, maximum and mean data were available, these inputs were also modeled as a triangle distributions or uniform distributions. Where applicable, the cutoff criteria reviewed above was used and only the point values were used in the analysis.

Field data in this study were focused geographically in western Kentucky on a large farm (Logan County); however the results should not be limited to farm size or the geographical region. Data from the GREET model was generally based on United States averages and field data collected is assumed to be similar across corn and wheat producing states. Field data was collected during the 2011 and 2012 wheat and corn crop harvests with the help of Miles Stratton (Miles Enterprises). This two year span helps to give more confidence in the field data since agricultural yields and field work are highly variable year to year. Data gaps do exist however, where data was unavailable for specific operations due to equipment malfunction, etc. in one year or another. These are covered in Chapter 3.

The temporal boundary generally spans from 2010 through 2015. The GREET model data is based on a 2010 target year and as was previously mentioned, all field data was collected during the 2011 and 2012 crop years. Open literature referenced is also typically used during this time. Unless significant improvements to the inputs change or new equipment is developed that changes the process, the results of this LCA study are anticipated to be viable for many more years. Off road emissions standards continue to tighten for agricultural equipment, so this is one area that may see an improvement in upcoming years.

1.5.6 *Critical Review*

ISO standard 14044 states that a critical review should be conducted on an LCA where the “results are intended to be used to support a comparative assertion intended to be disclosed to the public” (ISO, 2006b). Since this LCA project is intended to meet the requirements of a graduate degree and is a part of the *On-Farm Biomass Processing* Project, the critical review will come from the graduate committee and principal investigators of the *On-Farm Biomass Processing* Project.

1.6 Organization of Thesis

Chapter 1 introduces the thesis, project background, specific project objectives and justification of the project. Following the standard guidelines for an LCA study, this chapter also defines the goal and scope of the LCA. Chapter 2 presents a literature review of LCA materials and models reviewed for this analysis, as well as references utilized for incorporating uncertainty and co-products in LCA studies. Chapter 3 presents the materials and methods used for this project, specifically the life cycle inventory data and the Microsoft Excel model structure that was developed for the project. The field data collection process is reviewed as well as the methods of incorporating uncertainty or stochastic analysis into the model. Chapter 4 presents the result of the LCA model and discusses the impacts as part of the LCA impact assessment while Chapter 5 summarizes the results and conclusions of the project. Chapter 6 discusses future work. The appendix supplements the main text by adding additional information and LCA model details.

CHAPTER 2 : LITERATURE REVIEW

Perform a search for "life cycle assessment" and one would be inundated with a breadth of resources. Since life cycle assessment has become the premier analysis tool for accounting of energy flows and environmental impacts, LCA studies have been performed for a myriad of different products and processes. In this literature review, the goal is to sift through the breadth of resources and report on which specific resources were utilized or at least considered and referenced for this analysis. A detailed look into the models, software packages and databases is given, in addition to explanation as to why certain models and resources were used.

2.1 ISO Life Cycle Assessment Standards

ISO 14040:2006 Life Cycle Assessment Principals and Practices Framework and ISO 14044:2006 Life Cycle Assessment Requirements and Guidelines are international standards that provide the general framework for conducting Life Cycle Assessments. While broad in scope, the standards are meant to leave the specific process or method of conducting the LCA up to the conductor, but do provide high level guidelines that ensure a consistent LCA process. Four primary phases are in an LCA study:

1. The goal and scope definition
2. The inventory analysis phase (LCI)
3. The impact assessment phase (LCIA)
4. The interpretation phase

As can be ascertained, the goal and scope definition clearly states the intended outcome, system boundaries, functional units, etc. of the project. The goal and scope definition of this project has been reviewed in Chapter 1. The inventory analysis phase involves all the data collection and calculations of the inputs and outputs of the system, while the impact assessment aims to evaluate the significance of the LCI results into specific environmental impact categories. In many cases, LCI studies are conducted without the impact assessment phase. Lastly, the interpretation phase presents conclusions based on the LCI and LCIA phase results. These remaining phases are covered further in the standards (ISO, 2006a), (ISO, 2006b).

2.2 Environmental Protection Agency (EPA) Resources

The National Risk Management Research Laboratory (NRMRL) is part of the EPA that is charged with investigating methods and technology to mitigate environmental problems in order to safeguard human and environment health (National Risk Management Research Laboratory, 2014). As such, the NRMRL promotes the use of the LCA methodology through their website by listing many LCA resources and by publishing a basic guide to LCA (Scientific Applications International Corporation (SAIC), 2006). This guide, produced by the Scientific Applications International Corporation (SAIC) and titled "Life Cycle Assessment: Principals and Practice," closely follows the ISO standards for the four primary phases of an LCA. As such, it was referenced heavily along with the ISO standards to develop the primary building blocks of this LCA. NRMRL also provides many links to LCA resources that were referenced for this project, including journal articles, conference proceedings, software and databases on the website (National Risk Management Research Laboratory, 2014).

2.3 Attributional and Consequential Modeling

Traditionally LCA studies have been attributional studies, being defined as the process to quantify how energy and emissions are flowing within a system at a certain time (Scientific Applications International Corporation (SAIC), 2006). Attributional studies typically involve evaluating only one product or process at a time and the results produced have known levels of accuracy. A relatively new approach to LCA is consequential studies, meaning the process to determine what consequences, both internal and external to a certain product lifecycle, may result from changing the outputs of that product. As one may imagine, the results of consequential LCA studies are highly dependent upon future models, which present a far greater uncertainty in the results. The results of this type of LCA study are more generally useful in a broader sense, such as for policy makers, as it gives insight into what the consequences of certain policy decisions might be (Brander et al., 2008).

Deciding to perform an attributional or consequential study is an important decision to make in the goal and scope phase of a project. The data collected will then match the respective study to fulfill the goal in the project timeframe. The goal and scope of this project was presented in Chapter 1, with the specific mention of this being an attributional study considering wheat straw and corn stover as the products. This was chosen to specifically evaluate the products in the current timeframe and to have known levels of accuracy on the data being used.

2.4 LCA Models and Databases

In the beginning phases of the project, many existing LCA models and software were reviewed for either direct use as the LCA model for this project or as a data source for model input. Several of the main models and software are reviewed below, along with a brief explanation of their relevance and utilization in this project.

2.4.1 *Argonne National Laboratory GREET Model*

The Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, more popularly known as GREET, was heavily referenced in this LCA project. The GREET model was developed by the UChicago Argonne, LLC as Operator of Argonne National Laboratory under contract with the Department of Energy (Argonne National Laboratory, 2014). The GREET 1 model was first developed in 1996, and has undergone multiple revisions to the Version 2012 which was used for this project. The GREET 1 model is primarily a fuel cycle model, in which various fuels from gasoline to diesel, natural gas and ethanol, to name a few, are analyzed from cradle to grave to determine the total energy consumption and total emissions generated from fuel production and use.

The GREET 2 model is a vehicle cycle model which takes the GREET 1 data as input and adds vehicle manufacturing, use and end of life recycling for three different types of vehicles to create the overall LCA picture for transportation vehicles. GREET version 2.7 released in 2012 was the version referenced for this LCA project. Like the GREET 1 model, GREET 2 presents total energy consumption and total emissions generated from the vehicle process (UChicago Argonne, LLC, 2012). Figure 2.1 illustrates the scope of the GREET 1 and GREET 2 models.

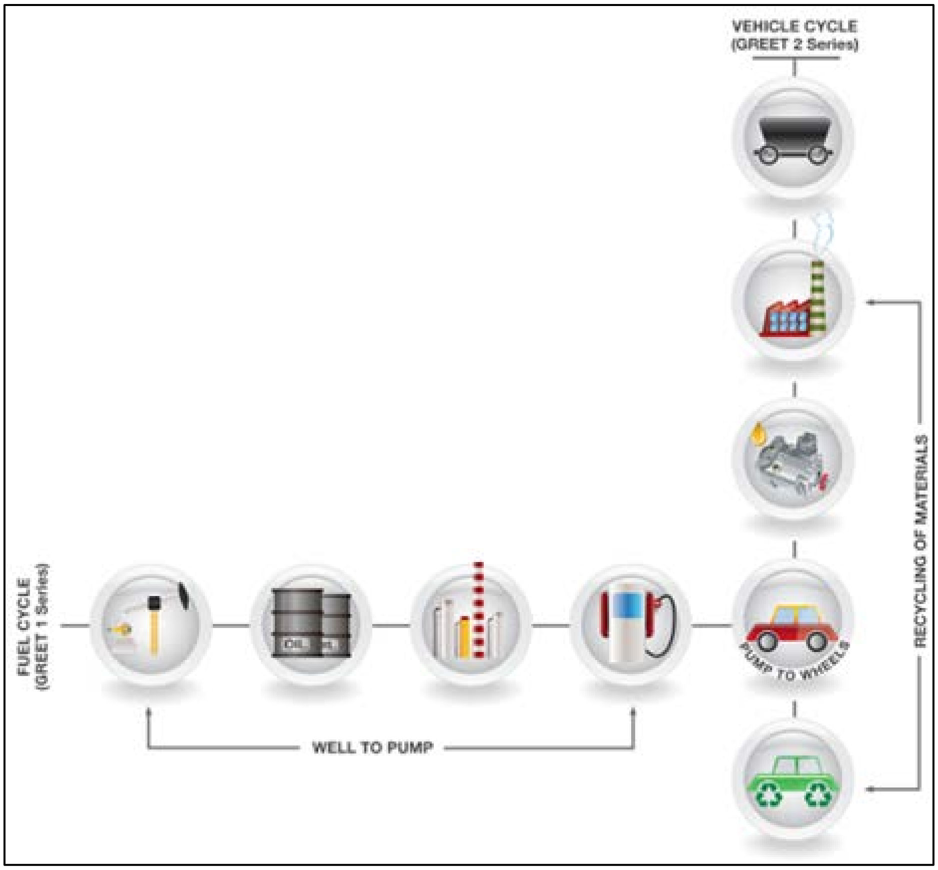


Figure 2.1 Pictorial Representation of the Boundary Conditions of the GREET 1 Fuel Cycle and GREET 2 Vehicle Cycle LCA models. https://greet.es.anl.gov/main

Since the GREET 1 and 2 models were developed in Microsoft Excel, data transfer and incorporation into this project's Microsoft Excel model was very easy. Many of the other LCI databases available today present only the final energy and emissions numbers from a product or process without showing the specific data and calculations used to get the final results. Many of the data sources used in the GREET model are from open literature, but other data sources such as process models and companies are also referenced as well. The ability to review the calculations and data presented in the model and the fact that the data itself align with the specific data needs of this project made use of the GREET model an easy decision.

In fact, the raw material, battery manufacture, vehicle fluids, and fuel feedstock energy consumption and emission results from GREET were copied and pasted into this LCA model as direct inputs. In addition, much of the model structure for the equipment inventory worksheets for the tractors, combine, baler and semi used in this project also used very similar structure and calculations as the vehicles used the in the GREET models. The model results and summary page, while differing in structure than the GREET models, use the same classification of energy uses and emissions components. Table 2.1 details the energy and emission components that are outputs of the GREET model that were also used in this project. A more detailed breakdown of the specific data and equations borrowed from the GREET model is presented in the next chapter. Since GREET is an open source software, the copyright statement and disclaimer are presented in Appendix A for reference.

Table 2.1 Energy Consumption and Emission Output Categories used in GREET Models.

Energy Consumption components	**Emission Output components**
Total Energy	Volatile Organic Compounds (VOC)
Fossil Fuel Energy (non-renewable energy)	Carbon Monoxide (CO)
Coal	Nitric Oxide and Nitrogen Dioxide ($NO_{x)}$
Natural Gas	Particulate Matter < 10 micron (PM10)
Petroleum	Particulate Matter < 2.5 micron (PM2.5)
	Sulfur Oxides ($SO_{x)}$
	Methane (CH_4)
	Nitrous Oxide (N_2O)
	Carbon dioxide (CO_2)
	CO_2 including carbon from VOC and CO
	CO_2 Equivalent GHGs (CO_2, N_2O, CH_4)

2.4.2 *EBAMM*

The Energy and Resources Group (ERG) Biofuels Analysis Meta-Model, or EBAMM, was developed by students and faculty at UC Berkeley to evaluate six analyses of fuel ethanol (Farrell et al., 2006). The EBAMM model adjusted the six paper studies to have equivalent system boundaries and units, and therefore provided a direct comparison of the results and assumptions in the studies. Key indicators used by the EBAMM model are net energy, primary energy inputs, and greenhouse gas emissions.

The study concluded that corn ethanol has energy and environmental benefits although studies sometimes greatly differ in the handling of co-products. Cellulosic ethanol is shown to have tremendous energy and environmental benefits over both gasoline and current ethanol from corn, however further research is required as the field is emerging and developing rapidly. The data used in the EBAMM model was not directly used as part of this LCA; however the EBAMM framework and results were utilized as a reference in this study. The EBAMM model as well as supporting information is available online (UC Berkeley, 2006).

2.4.3 *U.S. LCI Database (NREL)*

The U.S. Life Cycle Inventory Database was developed by the National Renewable Energy Laboratory and its partners. It is meant to provide consistent and transparent LCI data for specific US systems. The database is freely accessible on the NREL website (U.S. Life Cycle Inventory Database, 2012), and reports the input and output flows of various processes as elementary or product flows with their corresponding unit. The US LCI database was used as a reference in this project when data was not available from the GREET model, field data or other known open sources specific to this project.

2.4.4 *Ecoinvent*

Ecoinvent is an LCI database developed by the Swiss Centre for Life Cycle Inventories, which is composed of a partnership of many organizations and institutes. Its mission is to establish scientific and transparent international life cycle assessment data to industry, research and public institutions. It is one of the world’s leading databases for generic life cycle inventory datasets, and used by many of the LCA specific software packages available in their ecoSpold2 data format. A few of the software packages that were considered for this project, discussed further below, use the Ecoinvent database (Swiss Centre for Life Cycle Inventories, n.d.). The Ecoinvent database was thoroughly researched for inclusion in this project, but the necessary generic data was able to be obtained from the GREET model, while the critical data referenced in the project was obtained through field work.

2.4.5 *GaBi*

GaBi is software developed by PE International to perform life cycle assessments, life cycle costing analysis, and life cycle reporting (PE International, n.d.). The primary

LCI databases used are Ecoinvent, the U.S. LCI database, and its own GaBi Database. PE International offers a free 30 day trial that was utilized to evaluate the software for use in this project. While useful for many LCA studies, it was decided that the specific and detailed nature of the data and processes under investigation in this project lend itself to the more customizable features of a Microsoft Excel based model.

2.4.6 *SimaPro*

Similar to the GaBi software mentioned above, SimaPro is a life cycle assessment software developed by PRe Consultants (PRe Consultants, n.d.). The primary database used is Ecoinvent, with many supporting databases including the US input/output library, European Life Cycle Data, and Swiss Input/Out database to name a few. PRe Consultants also offers a free demo for the software, which was downloaded and investigated. Like GaBi, this software can prove very helpful for many LCA studies, but for the same fully customizable reasons as above, a Microsoft Excel based model was chosen for this project.

2.5 Uncertainty in Life Cycle Assessment

To successfully achieve the second objective of this project of utilizing stochastic simulation to improve model robustness, it is important to understand the sources of variation and uncertainty that can arise in life cycle assessments. Uncertainty in LCA can arise from several different sources: model uncertainty, scenario uncertainty, and data uncertainty (Johnson et al., 2011).

Model uncertainty primarily deals with how the model is set up, which includes the system boundaries, model equations, co-product handling, and time and space representation of the process. This is generally specified in the goal and scope definition of the LCA, although it creates difficulty in comparing results of different studies due to differing process boundaries, co-products, and other key assumptions (Farrell et al., 2006). There is currently no good way of normalizing this uncertainty, since it is primarily a result of budgetary and time constraint decisions at the beginning of the LCA. However, uncertainty resulting from the model equations is generally low, since the process of producing biomass for energy consists of adding energy and emissions from sequential independent process steps (Johnson et al., 2011).

Scenario uncertainty refers to the “discrete possible future states of the world upon which parameters of the model and model results depend” (Johnson et al., 2011). Examples of this uncertainty may include varying distances of transporting biomass, varying crop yields or yield enhancements over time, and energy scenarios, i.e. diesel use for farm machinery versus potential biodiesel use in the future, to name a few. Methods of handling this uncertainty primarily consist of adding varying scenario choices to the potential results of the model. This can quickly add complexity to the model; therefore it is up to the goal and scope definition to filter out scenarios outside of the project constraints, and/or running stochastic simulations to evaluate a wide variety of possible outcomes. This type of uncertainty is characteristic of consequential LCA models and not typically present in attributional modeling. Since this LCA is an attributional study, scenario uncertainty is not considered in this project.

Data uncertainty is precisely that, uncertainty arising from the variation and sources of data used in the LCA model. Typically, this can be resolved by research and experimentation to find more precise data. However, depending on the scope and time constraints of the LCA, and the modeling for processes in which the fundamental behaviors are not fully understood, finding more precise data is often difficult. Therefore, there are two primary methods for dealing with data uncertainty: boundary analysis and stochastic analysis (Johnson et al., 2011). Boundary analysis takes the minimum, maximum and most likely values into consideration for determining inputs and outputs of the model. Stochastic simulation requires knowledge of the probability distribution of the input, which is then typically analyzed using Monte Carlo techniques to determine the resulting statistical output.

It is important to note that boundary analysis and stochastic simulation in combination with Monte Carlo techniques can be applied to all forms of uncertainty mentioned above. The benefits of using these techniques for data uncertainty are clear; however, many discrete scenarios can be modeled quickly by running thousands of separate analyses, and therefore can also have powerful implications for scenario and model uncertainties as well. Efforts have been made in recent years to incorporate these methods of uncertainty into LCA’s, which has resulted in more robust life cycle assessments.

To address the uncertainty arising in this project, this method of combining boundary analysis and stochastic simulation with Monte Carlo techniques was used with the help of @Risk software, developed by Palisade Corporation (Palisade Corporation, 2014). The software fully integrates with Microsoft Excel, and has the ability to input many different distributions depending on the available data. In boundary analysis cases, triangle distributions can be used. For stochastic data, a distribution fitting function can help determine the best distribution to use as an input. The software then takes each distribution input and runs thousands of iterations to form the distribution output. This gives LCA model results as a distribution of the outputs, which is more representative of real world conditions than simply using point values. Further discussion on the specific use of @Risk in the model is covered in Chapter 3.

2.6 Co-Product Handling within LCA

Co-product handling, or in other words, the method of assigning shares of inputs and outputs of processes, is cause for significant variation in LCA's (Wang et al., 2011). The functional units of grams per hour and MJ per hour were chosen for this project since it eliminates most of the co-products except in the single pass harvesting process. However, single pass harvesting and the various ways of handling the co-products of wheat and straw or corn and stover are cause for significant variation in the LCA outcome. For this reason several different ways of handling co-products were investigated.

ISO 14044 lists specific steps that should be taken when applying an allocation of co-products, broadly: to avoid allocation where possible, to separate products by underlying physical relationships or, as a last result, to allocate co-products proportionately based on another relationship between them (i.e. economic value) (ISO, 2006b). The standard also recommends conducting a sensitivity analysis when several methods seem applicable.

Wang et al. 2011 expanded on ISO 14044 and described five specific methods to handle biofuel co-products: mass based, energy-content based, market-value based, process-purpose based, and the displacement method (Wang et al., 2011). The study utilized the GREET model to perform a sensitivity analysis of the different co-product methods on several biofuel pathways, concluding that the choice of co-product method significantly influenced the results. Withholding recommendation of one single method to use, the authors suggested that transparency in the method used and the use of multiple co-product methods strengthened results.

Based on the above research, multiple methods of co-product handling were utilized in this project to assess the sensitivity to the results. The mass based method, market-value method, and a variation of the process-purpose based method were used. The mass based method takes into account the mass yields of grain versus the mass yields of biomass while the market-value method compares the market value of the grain versus that of the biomass. Perhaps most applicable for this project, the process-purpose method looks at the ratio of the difference in fuel consumption of the combine in single pass operation versus a combine in conventional harvest operation. This gives the specific amount of additional energy and emissions that result from harvesting the biomass in this step. Chapter 3 further expands upon the specific use of these co-product methods.

CHAPTER 3 : MATERIALS AND METHODS

3.1 Life Cycle Inventory Analysis

Although there are only a few process steps that differ from normal grain production, the inputs into these processes are numerous. From an equipment standpoint, tractors, balers, combines, semis and trailers are necessary for the harvesting and transportation steps. However, each of these pieces of equipment can be further broken down into raw material acquisition and processing, equipment manufacturing, and fuel refining and consumption. Since accounting for 100% of the inputs to the machinery is difficult, key material compositions were determined for each piece of equipment and the associated LCA's of that material was used to estimate the overall energy and emissions associated with that equipment. A large amount of energy and emissions result from the raw material acquisition and manufacture of the agricultural equipment. However, since this equipment is used for many other farming practices, this initial energy and emissions is normalized over the machinery life.

After the machinery is manufactured and assembled, diesel fuel is the primary material input of the biomass harvesting process. To fully account for the diesel fuel energy and emissions, the life cycle assessment of petroleum crude extraction and refining into ultra-low sulfur diesel is included in the LCA of biomass harvesting. Adding the diesel fuel consumption per hour of each piece of equipment yields the total energy use and emissions resulting from diesel fuel use.

In addition to the machinery used in the harvest, additional fertilizer is needed to make up for that lost from biomass removal. The three primary fertilizers: nitrogen, phosphorous and potassium were considered in this analysis. Since very little nitrogen remains in the soil year to year in Kentucky (lost via denitrification or leaching), the additional nitrogen requirement is assumed to be zero (AGR-1, 2012-2013). However, the model can accommodate the addition of nitrogen if necessary.

To capture the energy inputs and emissions outputs from this vast and detailed process, a Microsoft Excel model was developed for each and every input. The Excel model structure was based off of the GREET 2 model structure and is illustrated below in Table 3.1 for the steel input in equipment as example. This common format is used in all process steps (raw material inputs, equipment manufacture, fertilizer addition, double pass harvesting, single pass harvesting, and transportation) for simplicity and so that results can easily be added together or referenced from one worksheet to another. Since the GREET model uses English units (mmBTU/pound and grams/pound), the same units will be repeated here during explanation of the LCA model. SI units will be used when reporting the LCA results.

Table 3.1 Energy Input and Emissions Output Structure used in the Model Based Off of GREET. Steel Shown as Example.

	Virgin Steel	Recycled Steel	Average Steel
Energy Use: mmBtu per lb of material product			
Total energy	0.024	0.010	0.020
Fossil fuels	0.022	0.009	0.019
Coal	0.017	0.005	0.013
Natural gas	0.006	0.004	0.005
Petroleum	0.000	0.000	0.000
Total Emissions: grams per lb of material product			
VOC	2.105	0.161	1.592
CO	14.678	1.738	11.262
NOx	2.510	1.033	2.120
PM10	3.997	1.248	3.271
PM2.5	1.304	0.440	1.076
SOx	8.232	2.239	6.650
CH4	5.189	2.566	4.497
N2O	0.017	0.011	0.016
CO2	2,091	749	1,736
CO2 (VOC, CO, CO2)	2,120	752	1,759
GHGs	2,255	820	1,876

The data sources, equations and assumptions used in the Microsoft Excel model to capture the above process steps in the life cycle inventory analysis are discussed below. The section titles follow the sequence of worksheet titles in the Microsoft Excel model to aid in explanation. Note that the Microsoft Excel model developed for this project has no current plans to be continually supported or updated in the future.

3.2 Microsoft Excel Model Structure

3.2.1 *Goal and Scope Definition*

The Goal and Scope Definition sheet is the first worksheet in the Microsoft Excel model. As the name suggests, it briefly explains the goal of this study and process boundaries that were previously covered in Chapter 1. To avoid redundancy, the reader is directed to Chapter 1.

3.2.2 *Help*

The Help worksheet is the next worksheet in the model and is provided to give an explanation of the color scheme of the data inputs. Since there are many different sources of data referenced in the model, a simple color scheme was used to easily tell the type or quality of data used. Illustrated in Table 3.2, some of the data included in the model are point values and were simply referenced in black wording with standard white background. Where life cycle data could not be found on certain low impact data, red wording with a white background was used to show the data was estimated. Following the GREET models format, yellow colored background cells show that a cell could be changed by the user to adjust the ratios of certain inputs, such as the ratio of recycled to virgin steel in the material inputs.

Integrating @Risk software provided the means of stochastic analysis but also created several different data input/output options. @Risk itself has the ability to color a cell if it has an input or output function associated with it, however, since some users referencing the model would not have the @Risk software, the cell was colored using the standard Microsoft Excel color feature. In this way a user without @Risk software will see that a cell has a statistical input or output distribution and can scroll down to the bottom of the worksheet to see a copy of the distribution that was used. A user with @Risk software will simply click on the cell and the distribution will automatically popup. The cell color codes used for statistical input/output functions are also illustrated in Table 3.2. When reviewing the data in this report, the color scheme explained here will be used in any tables or figures of the model to aid in model clarity.

Table 3.2 Microsoft Excel Cell Color Codes

black	Black wording cells are best point values found in research
red	Red wording cells are point estimates
🟨	Yellow colored cells show point values that user can change to adjust component share
🟩	green colored cells shows a statistical distribution input cell
🟧	orange colored cells show a statistical distribution output cell

3.2.3 *Inputs*

The Inputs worksheet details the raw material inputs and basic component inputs that build up the equipment used in the process. These inputs feed directly into all the equipment worksheets and are taken directly from the GREET 2 model based on the model default parameters. The GREET 2 model uses these inputs to build the energy and emissions from automobiles. Since this LCA is focused on agricultural equipment, it uses the same raw material inputs but builds agricultural machinery. Key inputs are summarized in Table 3.3. A brief explanation of the data in each input category is discussed further below.

Table 3.3 Summary of LCA Data Tables Included in the “Inputs” Worksheet

Share of Virgin and Recycled Materials Used
Global Warming Potentials of Greenhouse Gases: relative to CO_2
Carbon and Sulfur Ratios of Pollutants
Energy Consumption and Emissions of Material Products
Energy Consumption and Emissions Related to Battery Assembly
Energy Consumption and Emissions Related to Fluids Production and Disposal
Energy Consumption and Emissions Related to Vehicle Assembly, Disposal and Recycling
Energy Consumption and Emissions Related to Fuel Feedstock and Fuel Development
Fuel Properties
Emission Factors of Fuel Combustion

Since many materials in use today are a combination of virgin materials and recycled materials, the “Share of Virgin and Recycled Materials Used” table captures the percent assumed of each. Again, this data was taken directly from the GREET 2 default model parameters. The data is illustrated in Table 3.4 and can be changed by the user in the model to adjust percentages as needed.

Table 3.4 Share of Virgin and Recycled Materials used in the LCA Model, from the GREET Model

Material	Virgin Material Product	Recycled Material Product
Steel	73.6%	26.4%
Wrought Aluminum	89.0%	11.0%
Cast Aluminum	15.0%	85.0%
Lead	27.0%	73.0%
Nickel	56.0%	44.0%

Global warming potentials are most often expressed as carbon dioxide equivalent, meaning that other gases that have global warming potential need to be correlated to carbon dioxide. Nitrous oxide and methane are two gases that are critical in contributing to the greenhouse gases impact category of the model. The 100 year global warming potentials of these gases relative to CO_2 were used in this analysis and are shown in Table 3.5. The values used in the model show that nitrous oxide has 298 times more impact on global warming than CO_2, while methane has 25 times more impact. As in the GREET 2 model, it is assumed that VOC's, CO and NO_2 do not contribute to global warming.

Table 3.5 Global Warming Potentials of Greenhouse Gases Relative to Carbon Dioxide

CO2	1
CH_4	25
N_2O	298
VOC	0
CO	0
NO_2	0

The carbon and sulfur ratios of pollutants are the next table in the "Inputs" worksheet and is shown here in Table 3.6. This table simply represents the ratios of carbon in volatile organic compounds, carbon monoxide, methane and carbon dioxide and the sulfur ratio in sulfur dioxide by weight. Identical to the GREET 2 model, this

LCA used these ratios to determine the emissions output of each piece of machinery in the process.

Table 3.6 Carbon and Sulfur Ratios of Pollutants, from GREET Model

Carbon ratio of VOC	0.85
Carbon ratio of CO	0.43
Carbon ratio of CH4	0.75
Carbon ratio of CO2	0.27
Sulfur ratio of SO2	0.50

As an example, clear regulations exist for the sulfur content of diesel fuel. Using the fuel consumption rate of the equipment, density and sulfur content ratio, SO_x emissions can be estimated by the following equation:

$$\left(Fuel\ consumption\ \frac{liters}{hr}\right) \times \left(Fuel\ density\ \frac{grams}{liter}\right) \times Sulfur\ ratio\ by\ weight\ in\ fuel \div Sulfur\ ratio\ in\ SO_2 = SO_X \frac{grams}{hr}\ emissions \quad \text{Equation 3.1}$$

The energy consumption and emissions of material products table comprises the summary of energy and emissions from all raw material inputs used in the LCA. Taken directly from the GREET 2 Material Summary worksheet, the data represents the total energy and emissions generated from the processes (mining, refining, melting, casting, rolling, stamping, etc.) required to have the raw material ready for input into equipment. The twelve different raw material categories utilized in the equipment composition and the six categories used in battery composition are represented in Table 3.7. Specific equipment composition percentages are discussed further in the Equipment section of the model. While not included in the machinery or battery materials categories, the energy consumed and emissions generated from polypropylene is borrowed from the GREET 2 model for input into baler twine.

Table 3.7 Materials Analyzed in Equipment and Battery Composition

Machinery Materials Categories	**Battery Materials Categories**
Steel	Plastic (polypropylene)
Stainless Steel	Lead
Cast Iron	Sulfuric Acid
Wrought Aluminum	Fiberglass
Cast Aluminum	Water
Copper/Brass	Others
Magnesium	
Glass	
Average Plastic	
Rubber	
Platinum	
Others	

Lead acid batteries are common in both automobiles and agricultural equipment, thus the energy and emissions of battery manufacture could be directly taken from the GREET 2 model. Although the battery weight or number may increase on agricultural equipment due to greater required amperage or electrical circuit demand, this is taken into account on the specific equipment worksheets discussed further below. The energy consumption and emissions produced related to battery assembly alone is assumed to be equivalent regardless of battery size. Table 3.8 shows the energy and emissions from battery assembly.

Table 3.8 Summary of Energy Consumption and Emissions of Battery Assembly, from GREET Model

	Battery Assembly: Lead-Acid	
Energy Use: mmBtu	**per ton**	**per lb**
Total Energy	3.688	0.002
Fossil fuels	3.391	0.002
Coal	1.260	0.001
Natural gas	2.078	0.001
Petroleum	0.052	0.000
Total Emissions: grams		
VOC	25.336	0.013
CO	67.475	0.034
NOx	336.357	0.168
PM10	245.839	0.123
PM2.5	77.598	0.039
SOx	538.825	0.269
CH4	1,204	0.602
N2O	4.001	0.002
CO2	252,890	126
CO2 (VOC, CO, CO2)	253,075	127
GHGs	284,378	142

Equipment fluids are another common input of both automobiles and agricultural equipment, allowing the GREET 2 model default inputs to be used. Although agricultural equipment uses much larger quantities of the fluids, this is captured on the equipment specific worksheets. The energy consumption and emissions captures both fluid production and disposal per kilogram of product. In this way, the larger quantities of fluids used in agricultural equipment can be quantified. Table 3.9 lists the fluids considered in this LCA.

Table 3.9 Equipment Fluids Considered in the LCA Model

Engine oil
Power steering
Brake fluid
Trans/Hyd/Drive fluid
Coolant
Windshield wiper fluid
Adhesives
DEF fluid

The GREET 2 model derives the energy consumption and emissions of the petroleum based fluids as similar to that of conventional gasoline: from the feedstocks of crude petroleum and refining into the finished gasoline product. In this way it does not distinguish between petroleum products, but assumes engine oil, power steering fluid, etc. have the same energy consumption and emissions as conventional gasoline itself on a per weight bases. While in reality there are differences in the energy consumption and emissions of these petroleum based vehicle fluids, this assumption was also assumed in this LCA as a starting point in the analysis. Through multiple iterations, it was determined that the equipment fluids were a minor input into the life cycle inventory results and were under the cutoff criteria, and was therefore considered as an acceptable assumption not needing further refinement. The model can automatically update the results if future works to refine the subtle differences merits change.

The next table borrowed from the GREET 2 model included in the inputs worksheet is the energy consumption and emissions related to vehicle assembly, disposal and recycling. One area of weakness in the model is specific data related to tractor and agricultural equipment manufacturing and assembly. Since no public data could be found, it was decided to use the GREET 2 data for SUV’s and scale up the energy and emissions based on weight as a starting point in the analysis. Since the agricultural equipment manufacture was determined to have a small impact on the results as compared to the operations inputs, this assumption was deemed acceptable. Table 3.10 lists the energy consumption and emissions of vehicle paint production, painting, assembly and recycling that was taken from the GREET 2 model.

Table 3.10 Energy Consumption and Emissions of SUV Assembly, Disposal and Recycling, from GREET Model

	Paint Production	Vehicle Painting	Vehicle Assembly	Vehicle Disposal	Total ADR
Energy Use: mmBtu per vehicle					
Total Energy	0.697	3.640	7.832	4.756	16.925
Fossil fuels	0.599	3.483	7.193	4.091	15.366
Coal	0.413	0.664	2.707	2.820	6.603
Natural gas	0.171	2.786	4.375	1.168	8.499
Petroleum	0.015	0.034	0.112	0.104	0.265
Total Emissions: grams per vehicle					
VOC	4.827	1,625	53.812	32.966	1,716
CO	10.618	96.095	142.927	72.512	322.153
NOx	72.416	329.215	715.822	494.520	1,612
PM10	78.806	195.199	527.633	538.162	1,340
PM2.5	23.714	76.528	166.346	161.940	428.528
Sox	171.288	301.099	1,156	1,170	2,798
CH4	136.872	1,489	2,542	934.688	5,103
N2O	0.754	3.956	8.496	5.146	18.351
CO2	52,707	233,177	537,893	359,934	1,183,712
CO2 (VOC, CO, CO2)	52,739	238,392	538,286	360,151	1,189,568
GHGs	56,385	276,803	604,370	385,052	1,322,610

The energy consumption and emissions related to fuel feedstock and fuel development is shown in Table 3.11 and taken from the GREET 1 Fuel Cycle model. The default GREET 1 parameters were used as they represented a good average of US processes. The feedstock development numbers represent the total energy and emissions from the recovery of the crude, assuming a 90% conventional crude, 10% oil sands crude ratio. It also represents the transportation to US refineries and storage. Three primary fuels are used in this model: conventional gasoline, conventional diesel, and low sulfur diesel. The energy and emissions numbers represent the refining, transportation, distribution and storage of each respective fuel. A loss factor is included in the GREET model to account for inefficiencies throughout the fuel refining process, however it factored out very closely to one. As is also shown in Table 3.11, the crude and low sulfur diesel cells are colored green to show that a statistical distribution is applied to those inputs.

Table 3.11 Energy Consumption and Emissions of Fuel Feedstock and Fuel Development, from GREET Model

	Feedstocks	**Fuels**		
	Crude for Use in U.S. Refineries	**Conv. Gasoline**	**Conv. Diesel**	**LS Diesel**
Loss factor		1.00	1.00	1.00
Energy Use: Btu per mmBtu of fuel				
Total energy	62,701	138,192	137,419	137,446
Fossil fuels	61,182	136,453	135,681	135,707
Coal	6,938	7,422	7,422	7,423
Natural gas	40,189	70,740	70,710	70,715
Petroleum	14,055	58,292	57,548	57,569
Emissions: Grams per mmBtu of Fuel Throughput at Each Stage				
VOC	3.62	23.163	4.49	4.49
CO	5.81	5.968	5.99	5.99
NOx	27.84	18.466	18.28	18.30
PM10	2.73	4.133	4.10	4.10
PM2.5	1.68	2.175	2.15	2.15
SOx	12.22	13.536	13.26	13.27
CH4	104.07	38.306	38.30	38.30
N2O	0.07	0.147	0.15	0.15
CO2	5,318	10,940	10,940	10,942
CO2 (w/ C in VOC & CO)	5,338	11,022	10,963	10,965
GHGs	7,961	12,024	11,965	11,967

The next table of inputs in the Inputs worksheet is the fuel properties. This table is also from the GREET 1 Fuel Cycle model. Included are the heating values, density, carbon ratio, sulfur ratio by ppm, and sulfur ratio by weight for various fuels. The values are standard but are required for conversion of energy consumption and emissions from in field consumption data of the agricultural equipment. The model gives the option to use either lower heating value or higher heating value (LHV or HHV in the table), however lower heating value was used in this analysis since the latent heat of vaporization of water is not recovered in the combustion process. Table 3.12 lists the values for the various fuels used in this analysis.

Table 3.12 Fuel Properties, from GREET Model

	Heating Value			**Density**	**C ratio**	**S ratio**	**S ratio**
	Calculation: LHV	**LHV**	**HHV**		**Percent by weight**	**ppm by weight**	**Actual ratio by weight**
Use LHV or HHV in calculations?	**1**	1 -- LHV; 2 -- HHV					
Liquid Fuels:	**Btu/gal**	**Btu/gal**	**Btu/gal**	**grams/gal**			
Crude oil	129,670	129,670	138,350	3,205	85.3%	16,000	0.016000
Conventional gasoline	116,090	116,090	124,340	2,819	86.3%	26	0.000026
U.S. conventional diesel	128,450	128,450	137,380	3,167	86.5%	200	0.000200
Diesel for non-road engines	128,450	128,450	137,380	3,167	86.5%	163	0.000163
Low-sulfur diesel	129,488	129,488	138,490	3,206	87.1%	11	0.000011

The last table in the Inputs worksheet is the emission factors for fuel combustion. Illustrated in Table 3.13, it gives the exhaust emissions from fuel combustion in grams per mmBTU of fuel burned. The data is based on the GREET 1 Fuel cycle model for a 2015 Class 8 Heavy Duty Engine, which although was simulated in 2002, the data correlated closely with current emissions standards for NO_x and PM (Environmental Protection Agency, 2014).

Table 3.13 Emissions Factors of Fuel Combustion, from GREET Model

	2015 Class 8 Heavy duty truck (g/mmBTU fuel)
Exhaust VOC	6.228
CO	14.831
NOx	43.869
Exhaust PM10	2.063
Exhaust PM2.5	1.440
CH4	1.557
N2O	2.001

3.2.4 *Equipment*

There are five separate worksheets within the Microsoft Excel model that capture the equipment used in the process: Tractor-Puma, Tractor-TG305, Combine, Baler, and Semi. The Semi worksheet includes both the semi-truck itself and a flatbed trailer. Each piece of machinery is used in one or multiple process steps. Specific models of machinery were selected for this project since they were available for use during the field research and they met the functional needs of the process. The equipment models and where they are used in the process are summarized below in Table 3.14 and represented pictorially in Figure 3.1 - Figure 3.4. While these specific models were used to develop the LCA, it is estimated that equipment of similar size and power rating will have similar LCA results. Each of the equipment worksheets consist of near identical format and structure, so only the Tractor-Puma worksheet will be detailed with a summary of the other equipment parameters further in the text.

Table 3.14 Equipment Models and Where Used in the LCA

Equipment type	**Model**	**Process Step Used**
Midsize Row Crop Tractor	2011 CaseIH Puma 160	Transport
Large Row Crop Tractor	2011 New Holland TG 305	Double Pass Harvesting
Combine	2011 CaseIH 9120 Axial Flow	Single Pass Harvesting
Large Square Baler	2011 CaseIH LB433 Baler	Single and Double Pass
Day Cab Semi and Trailer	Volvo VN Series	Transport

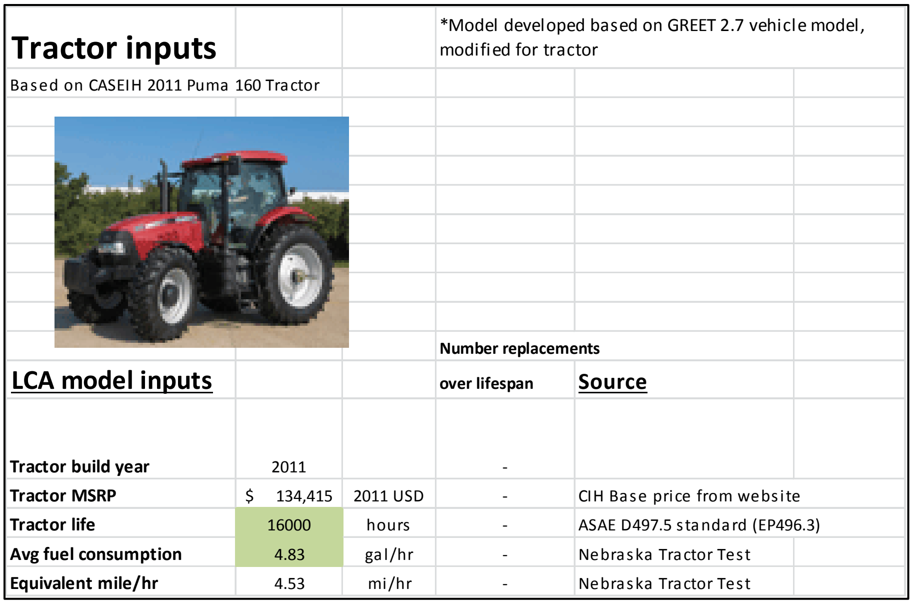
Figure 3.1 Case IH Puma 160 Tractor

Figure 3.2 New Holland TG 305 Tractor and Baler

Figure 3.3 Case IH 9120 Combine and LB433 Baler

Figure 3.4 Volvo VN Series Day Cab Semi and Flat Bed Trailer

Each equipment worksheet starts out with the general characteristics of the machinery, as shown in Figure 3.5. As is illustrated in the figure, a picture of the equipment is included for clarity. Basic information such as model year, Manufacturer's Suggested Retail Price (MSRP), estimated life, fuel consumption, and equivalent speed are presented with the respective units and source of data for traceability. The "Number replacements over lifespan" column is to account for wearable items such as oil changes that are captured further in the spreadsheet.



Tractor inputs

*Model developed based on GREET 2.7 vehicle model, modified for tractor

Based on CASEIH 2011 Puma 160 Tractor

LCA model inputs			Number replacements over lifespan	Source
Tractor build year	2011		-	
Tractor MSRP	$ 134,415	2011 USD	-	CIH Base price from website
Tractor life	16000	hours	-	ASAE D497.5 standard (EP496.3)
Avg fuel consumption	4.83	gal/hr	-	Nebraska Tractor Test
Equivalent mile/hr	4.53	mi/hr	-	Nebraska Tractor Test

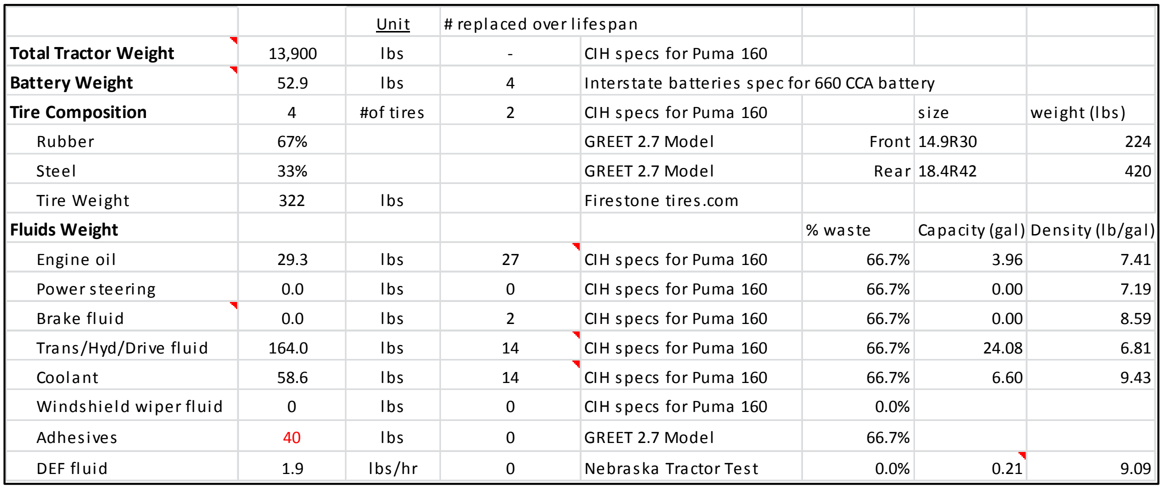
Figure 3.5 Tractor LCA Inputs Sheet

Equipment life, and in this case tractor life, is based on the ASABE standard of 16,000 hours (ASAE D497.4, 2003). Since this is a major input into the LCA, the cell is colored green to indicate a statistical distribution accompanies the input. The actual distributions used for each input and each piece of machinery are reviewed in section 3.4 Stochastic Analysis. Average fuel consumption is also a statistical input function based on the Nebraska Tractor Tests data (University of Nebraska - Lincoln, 2007) or field data where available.

The Baler data inventory sheet is the only equipment worksheet that differs from the above. Since the baler itself does not burn fuel, the only consumable during operation is baling twine. ASAE standard S315.4 stipulates that agricultural baler twine is composed of polypropylene or similar materials, therefore the energy consumption and emissions generated from polypropylene material per kilogram are used (Argonne National Laboratory, 2014). This multiplied by the linear density and usage rate yields the energy consumption and emissions generated per hour of use.

The next part of the equipment life cycle inventory is the weight, battery, tire and fluids specifications section. Illustrated in Figure 3.6, it lists the capacities of each respective component per weight since the GREET model supplied input data from the *Inputs* worksheet lists energy and emissions per weight. Factoring in the "Number Used over Lifespan" accounts for the additional uses of product. For the Fluids section, a Percent Waste column also captures the ratio of waste to product that is used to calculate the energy and emissions generated from disposal. In most cases, a two thirds ratio is assumed for oil based products, which is based on GREET model defaults. Also from the GREET model, it is assumed the disposal process is incineration.

Diesel Exhaust Fluid (DEF) is a recent technology that helps lower NO_x and PM emissions from diesel engines. Composed of a 32.5% urea, 67.5% deionized water solution; it is injected into the exhaust stream to react with NO_x in a selective catalytic reduction (SCR) system to create water and nitrogen (ISO 22241, 2009). This allows engines to run leaner, thereby also creating less PM emissions. To meet the stringent Tier 4 interim and final EPA emissions standards for agricultural equipment, DEF fluid is used and therefore must be accounted for in the equipment inventory. It is included at the bottom of the fluids section with units of mass per hour versus simply mass for the other fluid components.



		Unit	# replaced over lifespan				
Total Tractor Weight	13,900	lbs	-	CIH specs for Puma 160			
Battery Weight	52.9	lbs	4	Interstate batteries spec for 660 CCA battery			
Tire Composition	4	#of tires	2	CIH specs for Puma 160		size	weight (lbs)
Rubber	67%			GREET 2.7 Model	Front	14.9R30	224
Steel	33%			GREET 2.7 Model	Rear	18.4R42	420
Tire Weight	322	lbs		Firestone tires.com			
Fluids Weight					% waste	Capacity (gal)	Density (lb/gal)
Engine oil	29.3	lbs	27	CIH specs for Puma 160	66.7%	3.96	7.41
Power steering	0.0	lbs	0	CIH specs for Puma 160	66.7%	0.00	7.19
Brake fluid	0.0	lbs	2	CIH specs for Puma 160	66.7%	0.00	8.59
Trans/Hyd/Drive fluid	164.0	lbs	14	CIH specs for Puma 160	66.7%	24.08	6.81
Coolant	58.6	lbs	14	CIH specs for Puma 160	66.7%	6.60	9.43
Windshield wiper fluid	0	lbs	0	CIH specs for Puma 160	0.0%		
Adhesives	40	lbs	0	GREET 2.7 Model	66.7%		
DEF fluid	1.9	lbs/hr	0	Nebraska Tractor Test	0.0%	0.21	9.09

Figure 3.6 Overall Weight, Battery, Tire and Fluids Specifications

Tractor Composition is the next section of the equipment inventory worksheet. This determines the percentage by weight of the major components of the machinery and is broken down into four categories: Powertrain System, Transmission system, Chassis, and Body. No available public sources were found that supplied this data or the actual material compositions of agriculture equipment. Therefore, a letter was sent to several equipment manufactures to inquire if the data could be provided. Due to the proprietary nature of the data, it was decided to be withheld.

A simple scaling factor on the GREET model numbers for a pickup truck was determined to be the best method to properly account for the larger powertrain, transmission, and chassis components of agricultural equipment versus the pickup truck. While this is an estimation, it does account for the lower percentage of body weight on agricultural machinery as compared to the powertrain, transmission, and chassis. Additionally, a sensitivity analysis showed the equipment material composition changes generally yielded less than one percent change on the final equipment LCA result. The GREET default parameters for a pickup truck are shown in Table 3.15.

Table 3.15 GREET 2 Default Parameters for Pickup Truck

Composition (% by weight)	
Powertrain System	29.7%
Transmission System	6.7%
Chassis (w/o battery)	28.5%
Body: including BIW, interior, exterior, and glass	35.1%

The equations to calculate the scaling factor for the Case IH Puma Tractor and redistribute the percentages across the other components are detailed below. Basically, the scaling factor is calculated by dividing the tractor weight by the pickup weight. Next, the tractor body composition is determined by dividing the pickup body percentage by the scaling factor. The difference in this calculated tractor body percentage and the original pickup body percentage is spread equally to the powertrain, transmission and chassis. Therefore the powertrain, transmission and chassis are scaled up equally to account for the heavier machinery as compared to the pickup truck. Table 3.16 summarizes the scaling factors used and the percentage compositions for all the equipment used in the process.

$$Scaling\ Factor = {}^{Tractor\ Weight}/_{Pickup\ Weight} = 3.3 \qquad \text{Equation 3.2}$$

$$Pickup\ body\ \% = 35.1\%\ \therefore \frac{35.1\%}{3.3}$$ Equation 3.3

$$= 10.6\%\ Tractor\ Body\ Composition$$

$$Remaining\ \%\ to\ be\ distributed = 35.1\% - 10.6\% = 24.5\%$$ Equation 3.4

$$Power\ Train = 29.7\% + \frac{24.5\%}{3} = 37.9\%$$ Equation 3.5

$$Transmission = 6.7\% + \frac{24.5}{3} = 14.9\%$$ Equation 3.6

$$Chassis = 28.5\% + \frac{24.5}{3} = 36.7\%$$ Equation 3.7

Table 3.16 Summary of Scale Factors and Percent Composition by Weight for Agricultural Equipment

Composition (% by weight)	**Puma Tractor**	**TG305 Tractor**	**9120 Combine**	**LB433 Baler**	**Semi-Truck & Trailer**
Scale Factor	3.3	4.9	10.7	4.1	5.07
Powertrain System	37.9%	39.0%	40.3%	38.5%	39.1%
Transmission System	14.9%	16.0%	17.3%	15.5%	16.1%
Chassis (w/o battery)	36.7%	37.8%	39.1%	37.3%	37.9%
Body: including BIW, interior, exterior, and glass	10.6%	7.2%	3.3%	8.7%	6.9%

The Material Composition by Component follows the Tractor Composition section. This specifies the material makeup of the powertrain, transmission, chassis, body, and battery of the machine on a percent weight basis using the materials identified in the Inputs section. In this way the material composition of the equipment can be totaled by multiplying the percent material by the percent of component. As example, the powertrain system is composed of 42.5% steel by weight. Since the powertrain accounts for 37.9% weight of the Puma tractor, multiplying the two yields 16.1% steel from the powertrain alone. Adding this to the percent steel component from the transmission, chassis and body aggregates the amount of steel in the machine, or 60.7% in the case of the Puma tractor.

It is important to note that the agricultural equipment inventories primarily used the GREET 2 default values for each percentage of material composition since no public data could be found. However, for the semi-truck and trailer, a previous LCA was performed and summarized in the conference paper “Life-Cycle Analysis for Heavy Vehicles” (Gaines et al., 1998). This listed a summary of the material compositions of a semi-truck and trailer combination with gross vehicle weight greater than 26,000 pounds. Therefore, the individual material percentages were adjusted so that the final semi-truck and trailer composition matched that found by Gaines et al. (1998). Table 3.17 summarizes the percent material composition for each piece of equipment.

Table 3.17 Summary of Machinery Material Compositions by Weight

Machinery material composition (% weight)					
Machinery Required	**Puma Tractor**	**TG 305 Tractor**	**9120 Combine**	**Baler**	**Semi and trailer**
Steel	60.7%	60.2%	59.7%	58.1%	51.3%
Stainless Steel	0%	0%	0%	0%	0%
Cast Iron	19%	19.9%	20.8%	20.6%	13.0%
Wrought Aluminum	1.5%	1.6%	1.7%	1.6%	12.2%
Cast Aluminum	6.3%	6.5%	6.7%	7.1%	2.2%
Copper/Brass	1.4%	1.4%	1.4%	1.5%	1.0%
Magnesium	0%	0%	0%	0%	0%
Glass	0.8%	0.5%	0.2%	0%	0.4%
Average Plastic	6.4%	6.0%	5.6%	6.3%	3.0%
Rubber	3.2%	3.3%	3.4%	3.5%	9.0%
Others	0.6%	0.5%	0.4%	1.2%	7.9%

The final piece of the equipment life cycle inventory worksheet is the summary table. This table tallies all the components together to give the total energy and emissions for each piece of equipment. Shown in Table 3.18, the energy and emissions are broken down into the subcomponents of “Material Components”, “Battery”, “Fluids”, and “Assembly”; then totaled for the total machinery result per lifetime in the “Total” column. To get to the functional unit of per hour equipment use, the “Total” column is divided by the equipment life and captured in the “Per Hour of Tractor Life” column. Finally, the “Machine Use” column captures the consumable energy and emissions per hour of machine operation.

The “Material Components”, “Battery” and “Fluids” energy consumption and emissions are calculated by simply multiplying their respective weight by the energy or emissions per weight data in the Inputs worksheet. Additional energy and emissions from components such as oil or batteries that are replaced over the equipment life are factored in, as well as that generated from product waste. The “Assembly” column also takes data from the Inputs worksheet and simply multiplies it by the equipment weight scaling factor since the Inputs data is based on an automobile. The “Machine Use” column includes the energy and emissions from fuel development, the fuel itself once burned, and DEF fluid use if applicable (in the case of the baler, only twine use is considered).

Table 3.18 Summary of Total Energy Consumption and Emissions for Equipment Manufacture and Use, Case IH Puma Tractor Illustrated.

Weight by Materials: kgs, per-vehicle lifetime	Material Components	Battery	Fluids	Assembly	Total	Per hour of tractor life	Machine use
Steel	4216.3						
Stainless steel	0.0						
Cast iron	1199.0						
Wrought Aluminum	97.0						
Cast Aluminum	398.1						
Copper/Brass	88.3						
Magnesium	0.2						
Glass	50.4						
Average Plastic	402.1						
Rubber	982.0						
Platinum	0.0						
Others	40.1						
Plastic (polypropylene)		1.5					
Lead		16.6					
Sulfuric Acid		1.9					
Fiberglass		0.5					
Water		3.4					
Others		0.2					
Energy use: MJ per vehicle lifetime						MJ/hr	MJ/hr
Total energy	363,576	2,491	87,310	59,569	512,944	32.1	799.7
Fossil fuels	340,877	2,399	86,990	54,082	484,349	30.3	797.4
Coal	185,597	1,281	1,400	23,241	211,519	13.2	9.9
Natural gas	121,128	904.3	12,218	29,914	164,164	10.3	79.5
Petroleum	34,152	213.7	73,372	931.0	108,669	6.8	708.0
Total Emissions: grams per vehicle lifetime						grams/hr	grams/hr
VOC	24,219	66.7	5,553	5,722	35,561	2.22	9.78
CO	109,543	121.2	1,700	1,074	112,438	7.03	17.44
NOx	32,492	222.4	9,218	5,373	47,306	2.96	56.97
PM10	44,464	376.2	3,272	4,466	52,578	3.29	5.69
PM2.5	15,205	140.2	2,051	1,428	18,825	1.18	3.37
SOx	97,831	1,764	11,513	9,328	120,436	7.53	16.68
CH4	88,403	836.6	12,212	17,010	118,461	7.40	93.10
N2O	316.3	1.6	38.0	61.2	417.1	0.03	1.39
CO2	24,532,411	114,347	5,294,514	3,945,705	33,886,978	2,118	59,799
CO2 (VOC, CO, CO2	24,780,034	114,746	5,314,492	3,965,225	34,174,497	2,136	70,054
GHGs	27,084,363	136,134	5,631,113	4,408,700	37,260,310	2,329	72,796

It is important to note that the GREET 1 Fuel Cycle model has a worksheet for agricultural inputs that includes farming machinery. It was decided to take the GREET 2 vehicle model structure and modify it for agricultural machinery for several reasons: the GREET 1 model only considers steel production in the raw material input; it uses the same vehicle manufacture and assembly numbers as GREET 2 but does not scale up the factors; the equipment listed is generic whereas this LCA data is specific; and the GREET 1 model uses the average farm size to have energy or emissions per acre. Structuring the equipment life cycle inventories of the model in this way allows for much finer resolution of the energy and emissions generated from each piece of machinery, and allows for future data refinement and quality improvements when available.

3.2.5 *Fertilizers*

Removing wheat straw and corn stover from the field results in nutrients being removed which has to be made up with fertilizer for the subsequent crop. The Fertilizers worksheet was developed to account for this additional fertilizer. To determine the amount of energy and emissions resulting from the additional fertilizer, first the mass of straw and stover removed from the field was determined by field measurements. GREET 1 model data was then referenced for the energy and emissions from nitrogen, phosphorous, and potassium fertilizers development per pound. This data is shown in Table 3.19.

Table 3.19 GREET 1 Model Energy and Emissions from Fertilizer Development

Fertilizer Produced in U.S. (per lb of nutrient)				
	Nitrogen	**P2O5**	**K2O**	**CaCO3**
Loss factor	1.000	1.000	1.000	1.000
Energy Use: Btu per lb				
Total energy	27,388	11,143	3,937	78
Fossil fuels	27,088	10,750	3,653	78
Coal	1,271	1,665	1,201	3
Natural gas	23,208	6,543	1,184	7
Petroleum	2,608	2,541	1,269	67
Total Emissions: grams per lb				
VOC	2.8570	0.7088	0.0627	0.0028
CO	3.1691	1.1833	0.2018	0.0106
NOx	4.2178	3.5007	0.9028	0.0322
PM10	0.7006	0.7109	0.1142	0.0033
PM2.5	0.5682	0.5537	0.0871	0.0018
SOx	9.2438	36.8225	0.5199	0.0023
CH4	5.3511	1.8365	0.5186	0.0078
N2O	1.8235	0.0167	0.0051	0.0001
CO2	1,434	763	294	6.1802

University of Kentucky publication AGR-1 lists crop nutrient removal values for various crops including wheat straw and corn stover (AGR-1, 2012-2013). This gave the mass of fertilizer removed per mass of straw or stover. Combining this data by the following equation yields the total energy and emissions per acre of fertilizer addition. A summary of the results are shown in Table 3.20.

$$\frac{BTU\ energy\ or\ grams\ emissions}{lb\ fertilizer} \times \frac{lb\ fertilizer}{ton\ biomass\ removed} \times \frac{ton\ biomass\ removed}{acre} \qquad \text{Equation 3.8}$$

Table 3.20 Total Energy and Emissions Resulting from Fertilizer Addition

	Wheat straw			Corn stalks		
	N	P2O5	K2O	N	P2O5	K2O
Energy Use: mmBtu per acre						
Total energy	0.443598	0.060160	0.106273	0.395592	0.080475	0.117788
Fossil fuels	0.438734	0.058036	0.098613	0.391254	0.077633	0.109298
Coal	0.020592	0.008992	0.032412	0.018363	0.012028	0.035924
Natural gas	0.375898	0.035324	0.031950	0.335218	0.047251	0.035412
Petroleum	0.042245	0.013721	0.034251	0.037673	0.018354	0.037962
Total Emissions: grams per acre						
VOC	0.000046	0.000004	0.000002	0.000041	0.000005	0.000002
CO	0.000051	0.000006	0.000005	0.000046	0.000009	0.000006
NOx	0.000068	0.000019	0.000024	0.000061	0.000025	0.000027
PM10	0.000011	0.000004	0.000003	0.000010	0.000005	0.000003
PM2.5	0.000009	0.000003	0.000002	0.000008	0.000004	0.000003
SOx	0.000150	0.000199	0.000014	0.000134	0.000266	0.000016
CH4	0.000087	0.000010	0.000014	0.000077	0.000013	0.000016
N2O	0.000030	0.000000	0.000000	0.000026	0.000000	0.000000
CO2	0.023220	0.004118	0.007932	0.020707	0.005508	0.008791

3.2.6 *Co-Products*

As discussed in the LCA Goal and Scope Definition of the project, it was decided that several methods of co-product handling were evaluated. To calculate the different share of energy or emissions between wheat and straw and corn and stover between the various methods, the Co-Products worksheet was developed. Wang et al. 2011 presented several methods of co-product handling, including market based, mass based, and process-purpose based methods which were used in this analysis. The process-purposed based method used the difference in fuel consumption of the combine in single pass operation versus double pass harvesting as means of allocating the energy and emissions resulting from the process. Utilizing these three methods, in conjunction with a 100% allocation designation, produced the following table:

Table 3.21 Co-Product Allocation between Wheat and Straw, Corn and Stover for the various Allocation Methods

	Co-product allocation	Wheat	Straw	Corn	Stover
1	100% allocation	0%	100%	0%	100%
2	Market based	88.7%	11.3%	95.4%	4.6%
3	Mass based	68.5%	31.5%	84.6%	15.4%
4	Fuel consumption based	84.6%	15.4%	84.5%	15.5%

While seemingly simple, extensive data analysis and statistical distribution fitting went in to the table's development. The orange colored cells represent a statistical distribution output cell within the model, so while the most likely or average point values are shown, each cell carries a full statistical distribution with it. Data used to generate each cell is as follows:

Market based:	Pennyrile region cash wheat and corn prices
	Wheat and corn yields
	Straw and stover yields
	Straw and stover market price
Mass based:	Wheat and corn yields
	Straw and stover yields
Fuel Consumption:	Combine fuel consumption in single pass versus double pass harvesting

Reviewing Table 3.21 closely shows that the cells for the Fuel Consumption data are not highlighted orange, however as stated previously, measured combine fuel consumption data was used to generate the results. This is due to the fact that statistical data was used to generate the results but the cell itself does not represent a statistical distribution. To illustrate the process behind the numbers, both distributions for single pass and conventional harvest fuel consumption data for corn were graphed, as shown in Figure 3.7. The red curve shows the data for single pass harvesting, or where the combine is pulling the baler and shows that there is in increase in combine fuel consumption as compared with conventional harvest (blue data, representing combine without baler). The distributions are not normal and many factors could have influenced the data to cause the longer tail to the left of the distributions. Note that combine speeds were nearly identical between single pass and conventional harvest, therefore the increase in fuel consumption was directly caused by heavier engine loading to pull the baler.

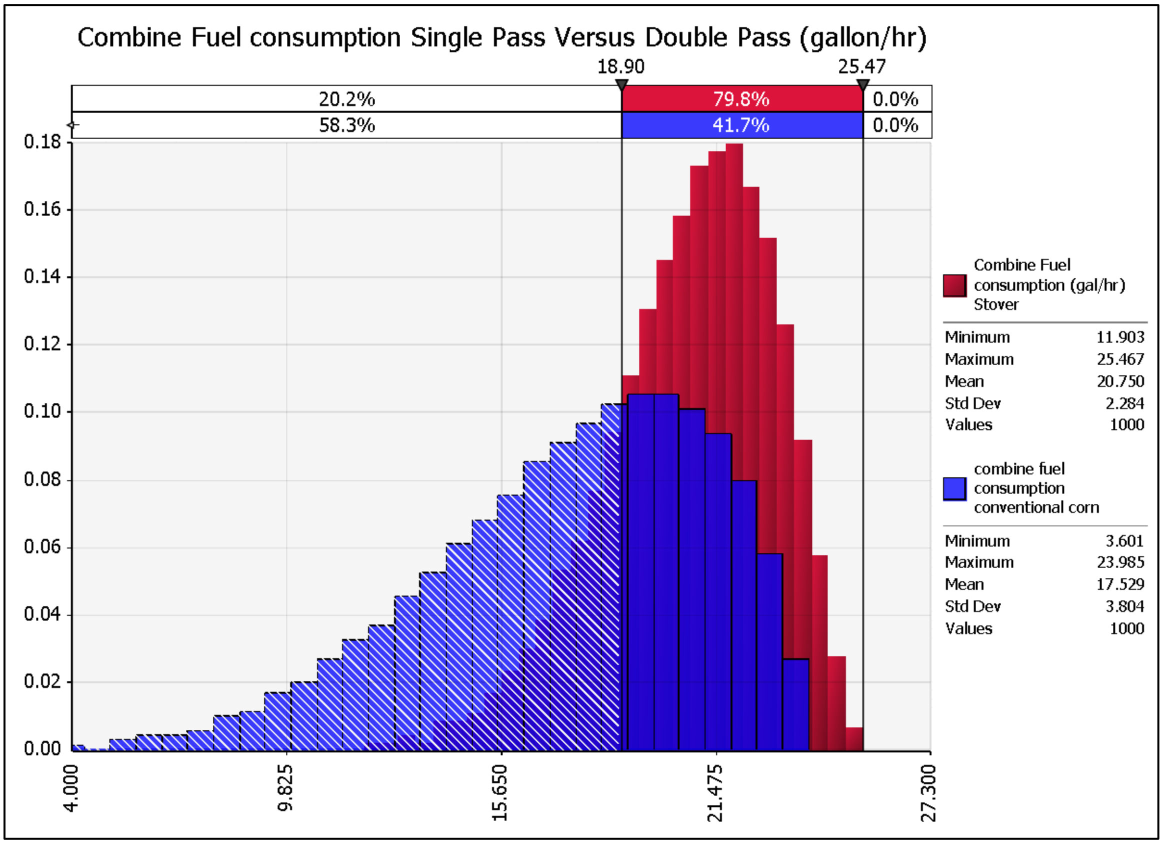


Figure 3.7 Combine Fuel Consumption Data for Single Pass versus Conventional Corn Harvest

Multiple ways to split the data were considered in an attempt to separate the fuel consumption attributed to the baler from the single pass harvest curve. Initially, the two distributions were simply subtracted from one another, but this produced negative values and values greater than 100% due to the Monte Carlo analysis and having overlapping data. Since both curves are probability density curves, the difference in areas under the curve were also considered, but after applying the co-product method, the energy and emissions of the combine alone using co-products did not match well to the combine data in conventional harvest. For this reason a simple difference in the means was determined to be the most representative way to handle the data, since it produced results that mimicked the actual combine data.

Therefore, the mean of the red curve (single pass) of 20.75 gallons per hour subtracted by the mean of the blue curve (conventional) 17.53 gallons per hour yields 3.22 gallons per hour increase. Dividing 3.22 gallons per hour by the initial 20.75 gallons per hour gives the percentage, or 15.5%. This is the percentage of fuel consumption attributed to the baler and taking 100% minus 15.5% gives the percentage fuel consumption attributed to the combine, or 84.5%. These percentages are then used in the Co-Product allocation table to account for the appropriate fuel consumption if the Fuel Consumption Based method is selected. This process was also followed for fuel consumption difference in wheat.

To help illustrate the function of Table 3.21 within the model, Table 3.22 depicts one of the summary tables from the Wheat Straw summary worksheet, which will be covered in more detail below. The yellow colored cells represent the co-product handling method used and designate a changeable cell by the user. The user enters in the corresponding number of co-product method: 1 = 100% allocation, 2 = Market based and so on. The summary table automatically updates the energy consumption and emissions results based on the co-product method employed for each individual process. In this way, individual equipment processes can use different co-product methods, as is the case in Table 3.22 where the Combine uses the Fuel Consumption based method while the Baler uses the 100% allocation method.

Table 3.22 Single Pass Harvesting Summary Table for Illustration

	Machine assembly		Machine use		Total
Co-product handling	4	1	4	1	
	Combine	Baler	Combine	Baler	
Energy use: mmBtu per hour - normalized					
Total energy	0.07	0.15	0.50	1.00	1.71
Fossil fuels	0.06	0.14	0.50	0.98	1.67
Coal	0.03	0.07	0.01	0.09	0.20
Natural gas	0.02	0.05	0.05	0.65	0.77
Petroleum	0.01	0.01	0.44	0.24	0.70
Total Emissions: grams per hour					
VOC	4.78	10.04	6.05	14.04	34.90
CO	17.53	39.80	11.12	95.27	163.71
NOx	6.13	13.74	37.28	45.93	103.08
PM10	8.07	18.58	3.69	19.47	49.80
PM2.5	2.76	6.33	2.19	6.26	17.53
SOx	17.40	40.64	10.81	328.79	397.65
CH4	16.64	37.43	59.92	538.74	652.74
N2O	0.06	0.14	0.92	0.44	1.55
CO2	4,584	10,260	39,389	24,719	78,952
CO2 (VOC, CO, CO2)	4,627	10,354	46,159	24,913	86,052
GHGs	5,061	11,331	47,930	38,512	102,834

3.2.7 *Wheat Straw and Corn Stover Summary Worksheets*

The Wheat Straw and Corn Stover Summary worksheets put together the whole picture of the life cycle inventory by taking the individual worksheets and combining them for the process, with the applicable co-product method applied. While the Wheat Straw and Corn Stover worksheets are separate in the model, they are nearly identical in function, with only the differences being in the fertilizers or co-product calculations. Only the wheat straw summary sheet will be illustrated here.

Each process step illustrated in Figure 1.2 is represented:

- Additional Fertilizer
- Harvest
  - Double Pass
  - Single Pass
  - Convention Combine harvest only for reference
- Transport to Processing Facility

The standard table format with energy and emissions results is used, as is depicted in Table 3.22 above. A summary table is included for final comparison of the LCA results and is shown in Table 3.23.

Table 3.23 Wheat Straw Process Summary Table

	Double Pass	Single Pass	Transport	Total Double Pass	Total Single Pass	Conventional Harvest
Energy use: MJ per hour						
Total energy	2,293	1,805	1,645	**3,938**	**3,450**	**3,266**
Fossil fuels	2,255	1,767	1,635	**3,891**	**3,402**	**3,233**
Coal	202.2	210.9	49.6	**251.8**	**260.5**	**223.0**
Natural gas	857.4	814.5	177.9	**1,035**	**992.4**	**400.4**
Petroleum	1,196	741.2	1,408	**2,603**	**2,149**	**2,609**
Total Emissions: grams per hour						
VOC	39.5	34.9	23.9	**63.4**	**58.8**	**59.6**
CO	167.5	163.7	48.7	**216.2**	**212.4**	**157.7**
NOx	137.7	103.1	118.6	**256.3**	**221.7**	**239.0**
PM10	50.2	49.8	19.2	**19.2**	**69.0**	**64.7**
PM2.5	18.7	17.5	9.5	**9.5**	**27.1**	**27.2**
SOx	401.9	397.6	49.2	**451.1**	**446.8**	**155.3**
CH4	706.5	652.7	198.8	**905.2**	**851.5**	**421.5**
N2O	2.4	1.6	2.8	**5.2**	**4.4**	**5.4**
CO2	115,509	78,952	122,605	**238,114**	**201,558**	**242,058**
CO2 (VOC, CO, CO2)	129,103	86,052	142,848	**271,951**	**228,901**	**279,559**
GHGs	147,484	102,834	148,652	**296,136**	**251,486**	**291,698**

3.3 Field Data Collection

Field data was obtained on items in the LCA model that were highly variable in nature, high impact to the model results, or not readily available in the literature. A summary of the field data gathered and where used in the model is presented in Table 3.24. Several means of data collection were used, including Case IH Advanced Farming System (AFS) mounted on equipment, CyCAN data loggers, and in field direct measurements.

Table 3.24 Summary of Field Data Gathered and Where Used in the LCA model

Machine	Parameters	Used In
TG 305 Tractor	Fuel consumption Speed	Tractor – TG 305 worksheet
Case IH 9120 Combine (single pass and double pass harvesting)	Fuel consumption Speed Corn yield Wheat yield	Combine, Co-prod&Co-input worksheets
Baler and direct weight measurement	Stover yield Straw yield	Fertilizers, Co-prod&Co-input worksheets

Case IH AFS was used primarily to capture the 9120 Combine performance characteristics. The AFS Pro 600 monitor was used in conjunction with GPS to acquire fuel consumption and speed in both single pass and double pass operations, and corn and wheat yields. A combination of the AFS Farm Management Software and Mapshots AgStudio Software were used to extract and analyze the data (Case IH, 2012) (Mapshots Inc., 2012).

The CyCAN data loggers were utilized for the data acquisition of the TG 305 tractor and baler during double pass harvesting. Acquired from the Agricultural and Biosystems Engineering Department at Iowa State University, the logger connected directly to the ISOBUS diagnostic port of the tractor, allowing all available CAN Bus information to be logged and saved to a compact flash card (Darr, 2012). Figure 3.8 shows the CyCAN logger that was used to capture baler information during double pass harvesting.

Figure 3.8 CyCAN Data Logger Used to Capture TG 305 Tractor and Baler Data During Double Pass Harvesting

Straw and stover yield was closely monitored through baler logged data and direct measurements in both single pass and double pass harvesting operations. A primary initiative of the *On-Farm Biomass Processing* project was to assess the biomass yield potential and losses in storage. Therefore, each bale produced was tagged, weighed and sampled for moisture content following the harvest operation (within 24 hours). In this way a detailed dataset was developed for straw and stover yield per acre for both single pass and double pass harvesting that provided quality data input into the LCA model.

3.4 Stochastic Analysis

Uncertainty analysis was incorporated into the LCA by use of the @Risk software. @Risk is software developed by Palisade Corporation that integrates with Microsoft Excel to perform risk and Monte Carlo analysis (Palisade Corporation, 2014). This software was used in the analysis to address co-product handling, data uncertainty and several scenario uncertainties of biomass harvesting. Where field data was available, stochastic analysis was utilized by first fitting a probability distribution to the data and then modeling that distribution during the simulations. Where only minimum, maximum and most likely data were available, or where only significant input point values were found in the literature, a boundary analysis or a triangle distribution was used. For those significant input point values, a +/- 10% variation was added as uncertainty. Both fitted data and triangle distribution data used in the analysis is shown and discussed more below.

The number of iterations in the Monte Carlo analysis was considered. A sensitivity analysis was performed based on 100, 500, 1000, and 5000 iterations and the results are shown below in Figure 3.9 for the energy use in the Double Pass Harvesting process. Illustrated in the figure, very small differences in energy use result from the changing number of Monte Carlo iterations. Therefore, 1000 iterations was chosen as acceptable for the stochastic simulation in the model.

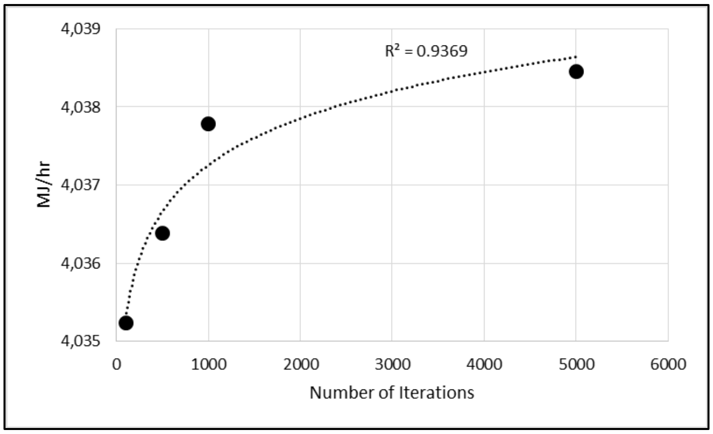


Figure 3.9 Double Pass Harvesting Energy Use versus Number of Monte Carlo Iterations

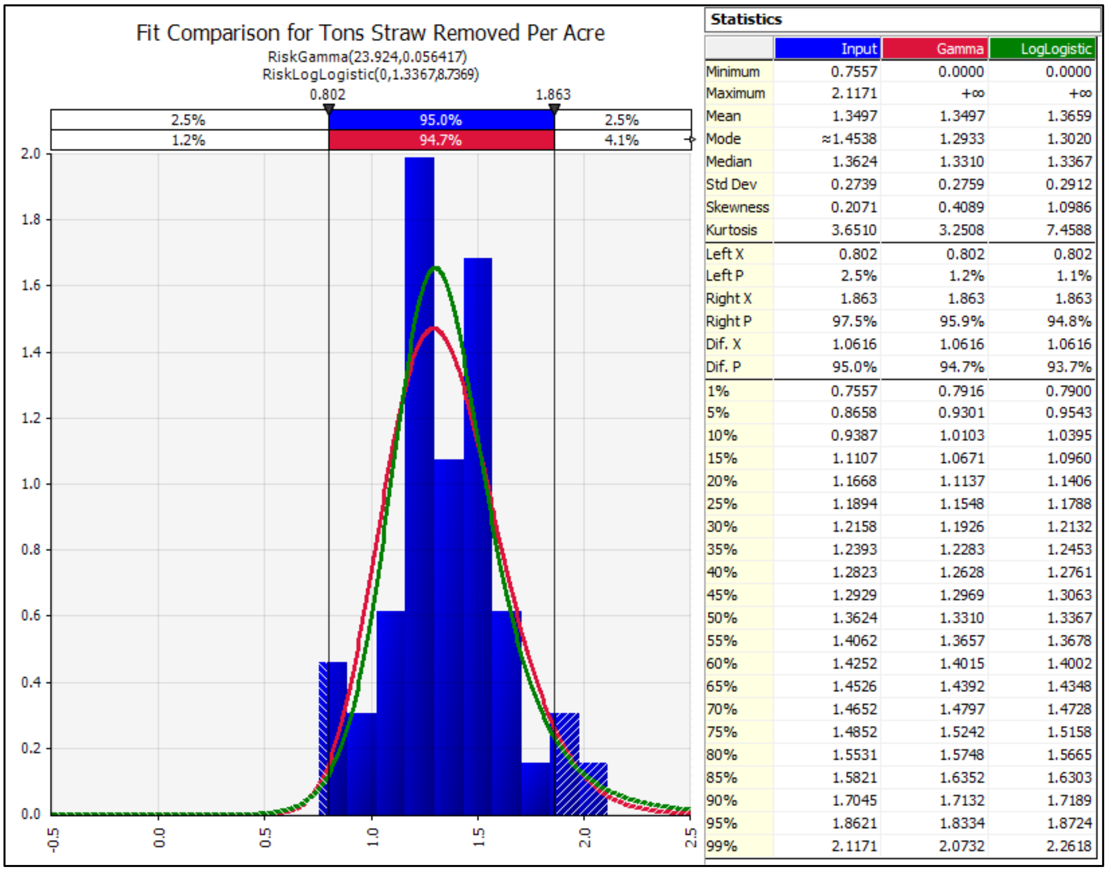
Early iterations of the LCA model showed that in field operations comprised the majority of total energy or GHG emissions produced from the process. In fact, this generally exceeded 90% of the total energy or GHG emissions component as compared to the equipment manufacture. This was primarily a result of the chosen functional unit being normalized per hour of field operation, however there were circumstances when the in field operation total energy or GHG emissions dropped to 80% of the total. One example was the combine which has relatively low life (3000 hours) and is a much larger and heavier piece of equipment, causing the machine manufacture energy and emissions to comprise a larger percentage. It was because of these cases that a cutoff of 80% was used for inputs, meaning that stochastic analysis was primarily applied to field operations inputs and all other inputs were included as point values. While this cutoff limits model accuracy, it greatly reduces the model complexity required to capture the remaining 20% of inputs.

3.4.1 *Fitted Data*

Field data was collected for several key inputs, as was discussed in Section 3.3. To understand the proper statistical distribution the field data represented, a distribution fitting function was used in the @Risk software. Several fit statistics are available in the @Risk software, including the “classical” fit statistics: Chi-Squared, Kolmogorov-Smirnov, and Anderson-Darling, as well as the newer “information criteria” tests: Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The AIC and BIC statistical tests are typically used for model selection, or the “process of picking one particular fitted distribution type over another” (Palisade Corporation, 2014). They are a better test in this regard since they rank distributions relative to each other for both model quality and model complexity; however they do not test for absolute goodness of fit. In other words, the AIC or BIC test can rank which statistical models are better representations of the data using the least complexity, but none of the models may fit the actual data very well.

It is for this reason that the AIC test was chosen as the primary test to evaluate model selection of the field data; however, close review of each distribution was necessary to ensure the model represented the raw data. In some instances there were small data ranges or highly repeated values that produced an AIC fit that was not representative of the actual data. In these cases a uniform distribution or other generic distribution was used. Only statistical distributions that modeled the actual process in nature were considered. In most data sets used in this analysis a lower bound of zero was required for the model since real world values could not be negative (fuel consumption, crop yields, etc.). It is for this reason the simple normal distribution could not be used. The process of fitting wheat straw yield data is illustrated below as example.

Wheat straw yield data was collected as an input to the project. The field collected input data is shown in blue in Figure 3.10 along with a few of the probability distributions that were analyzed for best fit. Basic statistical properties are shown on the right of the chart for both input data and fitted distributions. Comparing the mean and standard deviation values show a good approximate fit between the input and gamma distributions; where the actual data and theoretical data both show means of 1.3497 tons per acre and standard deviations of 0.2739 and 0.2759, respectively.



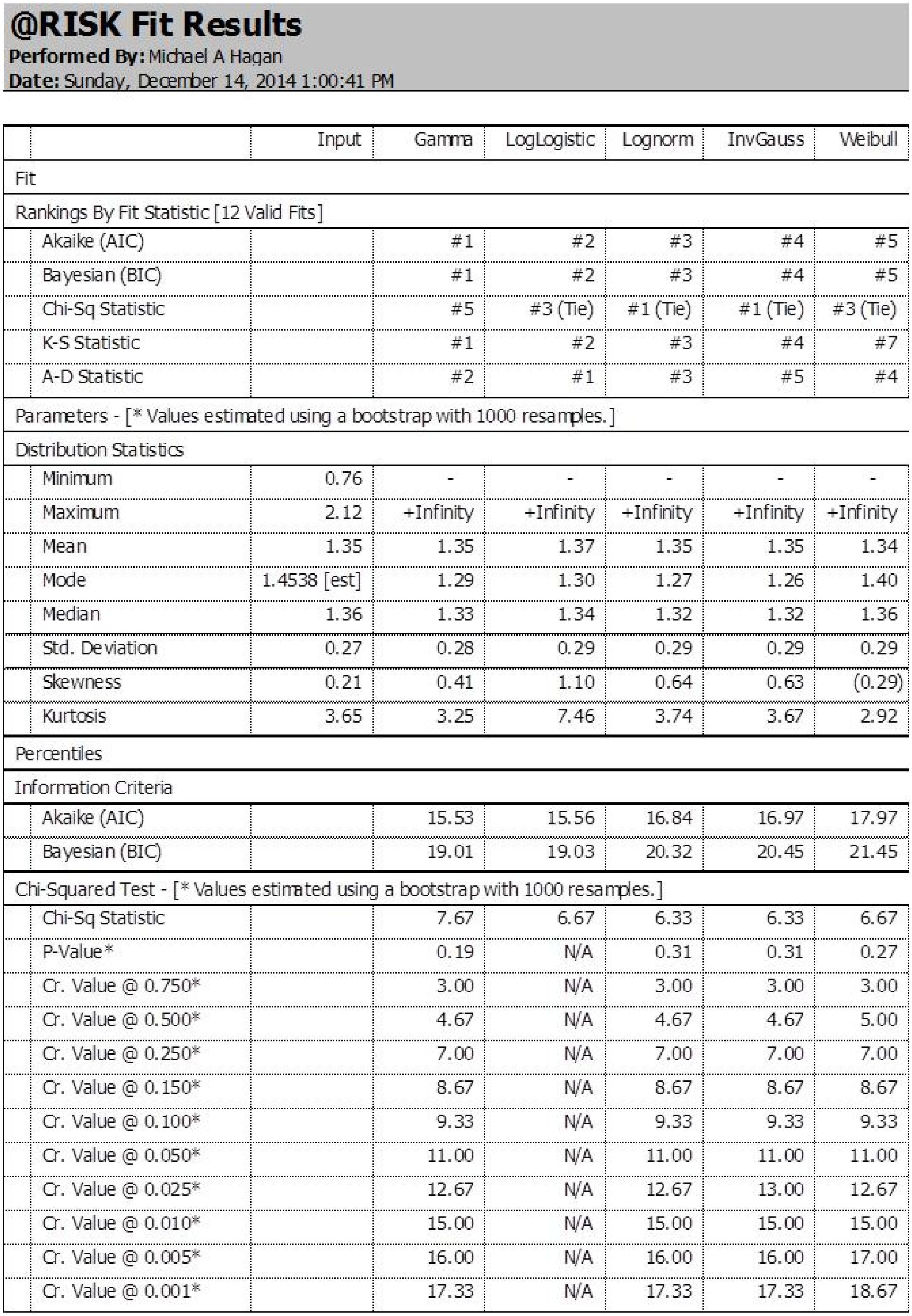
Statistics

	Input	Gamma	LogLogistic
Minimum	0.7557	0.0000	0.0000
Maximum	2.1171	+∞	+∞
Mean	1.3497	1.3497	1.3659
Mode	≈1.4538	1.2933	1.3020
Median	1.3624	1.3310	1.3367
Std Dev	0.2739	0.2759	0.2912
Skewness	0.2071	0.4089	1.0986
Kurtosis	3.6510	3.2508	7.4588
Left X	0.802	0.802	0.802
Left P	2.5%	1.2%	1.1%
Right X	1.863	1.863	1.863
Right P	97.5%	95.9%	94.8%
Dif. X	1.0616	1.0616	1.0616
Dif. P	95.0%	94.7%	93.7%
1%	0.7557	0.7916	0.7900
5%	0.8658	0.9301	0.9543
10%	0.9387	1.0103	1.0395
15%	1.1107	1.0671	1.0960
20%	1.1668	1.1137	1.1406
25%	1.1894	1.1548	1.1788
30%	1.2158	1.1926	1.2132
35%	1.2393	1.2283	1.2453
40%	1.2823	1.2628	1.2761
45%	1.2929	1.2969	1.3063
50%	1.3624	1.3310	1.3367
55%	1.4062	1.3657	1.3678
60%	1.4252	1.4015	1.4002
65%	1.4526	1.4392	1.4348
70%	1.4652	1.4797	1.4728
75%	1.4852	1.5242	1.5158
80%	1.5531	1.5748	1.5665
85%	1.5821	1.6352	1.6303
90%	1.7045	1.7132	1.7189
95%	1.8621	1.8334	1.8724
99%	2.1171	2.0732	2.2618

Figure 3.10 Statistical Distribution Fit Comparison for Tons of Straw Removed per Acre

Further investigation into which distribution yielded the best fit for the data gives Table 3.25 produced by the @Risk software. The table shows the ranking by fit statistic, distribution statistics, Information Criteria test results, and Chi-Squared test results. As is shown in the table, the AIC method ranked best (lowest) on the Gamma distribution, whereby the LogLogistic and Lognorm were ranked second and third, respectively. Therefore, the Gamma distribution was selected to represent the straw yield input in the model.

Table 3.25 Straw Yield Fitted Distribution Results



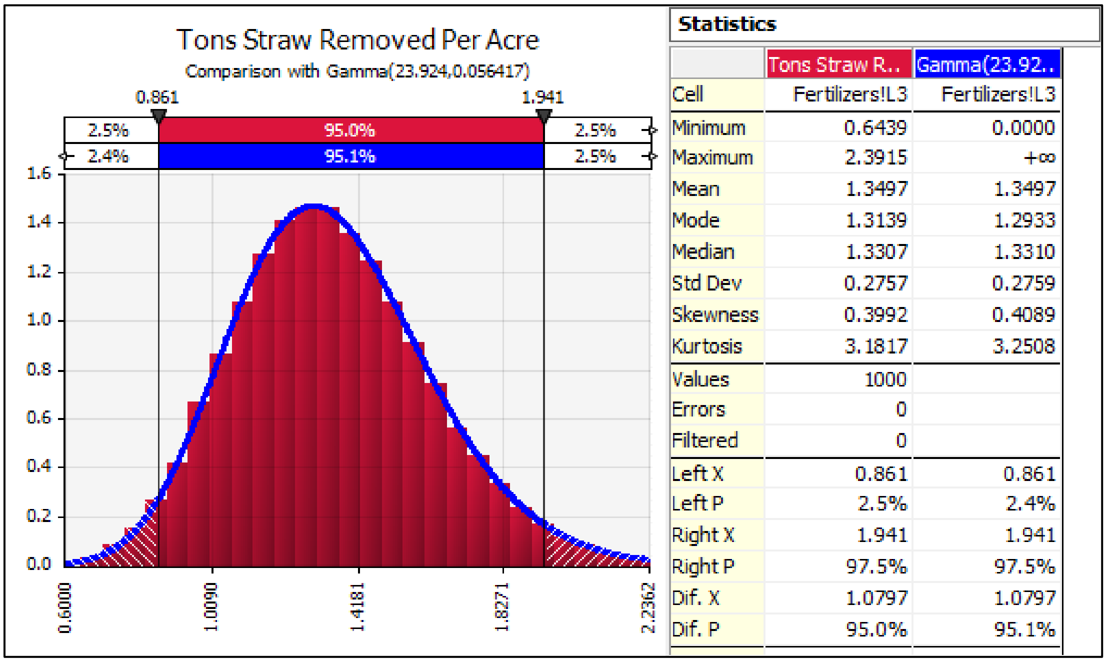
@RISK Fit Results

Performed By: Michael A Hagan

Date: Sunday, December 14, 2014 1:00:41 PM

	Input	Gamma	LogLogistic	Lognorm	InvGauss	Weibull
Fit						
Rankings By Fit Statistic [12 Valid Fits]						
Akaike (AIC)		#1	#2	#3	#4	#5
Bayesian (BIC)		#1	#2	#3	#4	#5
Chi-Sq Statistic		#5	#3 (Tie)	#1 (Tie)	#1 (Tie)	#3 (Tie)
K-S Statistic		#1	#2	#3	#4	#7
A-D Statistic		#2	#1	#3	#5	#4
Parameters - [* Values estimated using a bootstrap with 1000 resamples.]						
Distribution Statistics						
Minimum	0.76	-	-	-	-	-
Maximum	2.12	+Infinity	+Infinity	+Infinity	+Infinity	+Infinity
Mean	1.35	1.35	1.37	1.35	1.35	1.34
Mode	1.4538 [est]	1.29	1.30	1.27	1.26	1.40
Median	1.36	1.33	1.34	1.32	1.32	1.36
Std. Deviation	0.27	0.28	0.29	0.29	0.29	0.29
Skewness	0.21	0.41	1.10	0.64	0.63	(0.29)
Kurtosis	3.65	3.25	7.46	3.74	3.67	2.92
Percentiles						
Information Criteria						
Akaike (AIC)		15.53	15.56	16.84	16.97	17.97
Bayesian (BIC)		19.01	19.03	20.32	20.45	21.45
Chi-Squared Test - [* Values estimated using a bootstrap with 1000 resamples.]						
Chi-Sq Statistic		7.67	6.67	6.33	6.33	6.67
P-Value*		0.19	N/A	0.31	0.31	0.27
Cr. Value @ 0.750*		3.00	N/A	3.00	3.00	3.00
Cr. Value @ 0.500*		4.67	N/A	4.67	4.67	5.00
Cr. Value @ 0.250*		7.00	N/A	7.00	7.00	7.00
Cr. Value @ 0.150*		8.67	N/A	8.67	8.67	8.67
Cr. Value @ 0.100*		9.33	N/A	9.33	9.33	9.33
Cr. Value @ 0.050*		11.00	N/A	11.00	11.00	11.00
Cr. Value @ 0.025*		12.67	N/A	12.67	13.00	12.67
Cr. Value @ 0.010*		15.00	N/A	15.00	15.00	15.00
Cr. Value @ 0.005*		16.00	N/A	16.00	16.00	17.00
Cr. Value @ 0.001*		17.33	N/A	17.33	17.33	18.67

After the Monte Carlo simulation runs, the actual input into the simulation is shown in Figure 3.11. Figure 3.11 shows the statistical input for straw yield (tons per acre) with the same Gamma theoretical distribution that was determined above (blue curve). The red histogram now depicts the simulated result based on 1000 iterations. As can be seen in the figure, the mean and standard deviations of the simulated result are still very close to the actual raw data input. This method was used to determine the best fit for all field data used in the analysis.

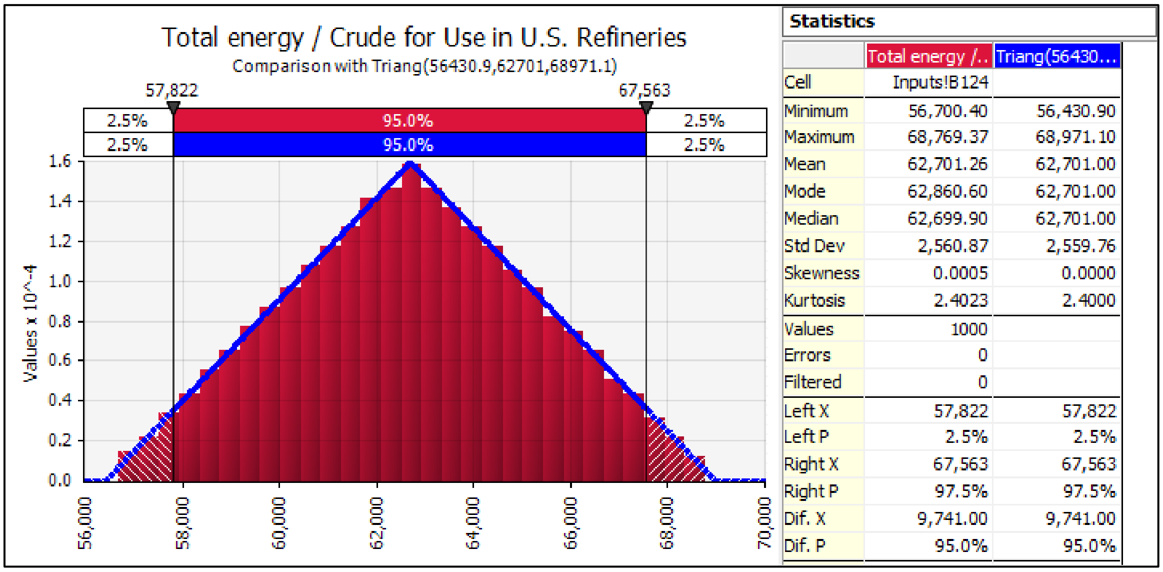


	Tons Straw R..	Gamma(23.92..
Cell	Fertilizers!L3	Fertilizers!L3
Minimum	0.6439	0.0000
Maximum	2.3915	+∞
Mean	1.3497	1.3497
Mode	1.3139	1.2933
Median	1.3307	1.3310
Std Dev	0.2757	0.2759
Skewness	0.3992	0.4089
Kurtosis	3.1817	3.2508
Values	1000	
Errors	0	
Filtered	0	
Left X	0.861	0.861
Left P	2.5%	2.4%
Right X	1.941	1.941
Right P	97.5%	97.5%
Dif. X	1.0797	1.0797
Dif. P	95.0%	95.1%

Figure 3.11 Simulated Data for Straw Yield based on Gamma Distribution

3.4.2 *Triangle Distribution Data*

For inputs where only point values were found in the literature, a +/-10% variation was added as the uncertainty factor and a triangle distribution was developed based on the corresponding minimum, most likely, and maximum values. Several inputs fell under this category, while only the total energy for crude oil extraction for use in US refineries is illustrated here as example. Total energy for the crude extraction was taken from the GREET model and determined to be 62,701 BTU per mmBTU of fuel. Since this can vary depending on the source of crude, how hard it is to extract, transportation distances, etc. and since it is a significant input into the analysis, a triangle distribution was used. Applying the +/-10% yields 56,431 and 68,971 BTU per mmBTU of fuel as the minimum and maximum, respectively. Selecting the triangle distribution function in @Risk yields the resulting distribution shown in Figure 3.12.



Statistics

	Total energy /..	Triang(56430...
Cell	Inputs!B124	
Minimum	56,700.40	56,430.90
Maximum	68,769.37	68,971.10
Mean	62,701.26	62,701.00
Mode	62,860.60	62,701.00
Median	62,699.90	62,701.00
Std Dev	2,560.87	2,559.76
Skewness	0.0005	0.0000
Kurtosis	2.4023	2.4000
Values	1000	
Errors	0	
Filtered	0	
Left X	57,822	57,822
Left P	2.5%	2.5%
Right X	67,563	67,563
Right P	97.5%	97.5%
Dif. X	9,741.00	9,741.00
Dif. P	95.0%	95.0%

Figure 3.12 Triangle Distribution Input for Total Energy for Crude Oil Extraction for use in US Refineries (BTU per mmBTU of fuel)

Using an identical format as above with the fitted data, the blue curve represents the theoretical input based on the triangle distribution defined. The red histogram depicts the simulated results based on 1000 simulations and yields results very close to the theoretical distribution.

3.4.3 *@Risk Output Data*

To view the @Risk Monte Carlo output result for a particular cell, the cell must be defined as an output cell with @Risk. Defining the output cell is simple, and the @Risk software will then take any statistical inputs, perform any calculations in the cell with that statistical distribution, and store the results in the output cell. The results in the output cell are reported in much the same way as the inputs are defined, with additional options for analyzing data. Figure 3.13 shows the results of the Total Energy from the Double Pass process during wheat harvest. As illustrated in the figure, the typical probability density is graphed with statistical data in the right columns. The particular results show a mean energy use of 2,294 MJ/hour, with a 397 MJ/hour standard deviation. Therefore, by integrating the stochastic analysis, conclusions can be based off not only the means but the distributions of the results.

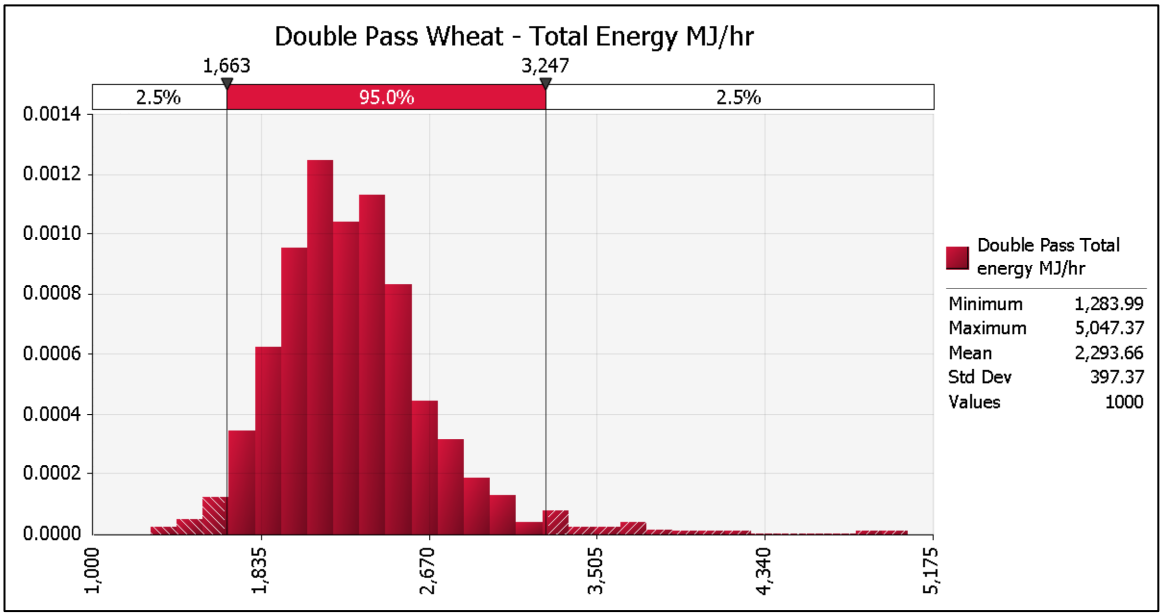


Figure 3.13 Example @Risk Output from the Wheat Double Pass Harvesting Process

Figure 3.14 depicts the Tornado Regression Coefficient graph for the same Total Energy from the wheat Double Pass harvest. The Tornado graph is another option of analyzing data made available through the @Risk software. It depicts all the inputs and their regression coefficients, meaning it shows the contribution that each input had on the output result.

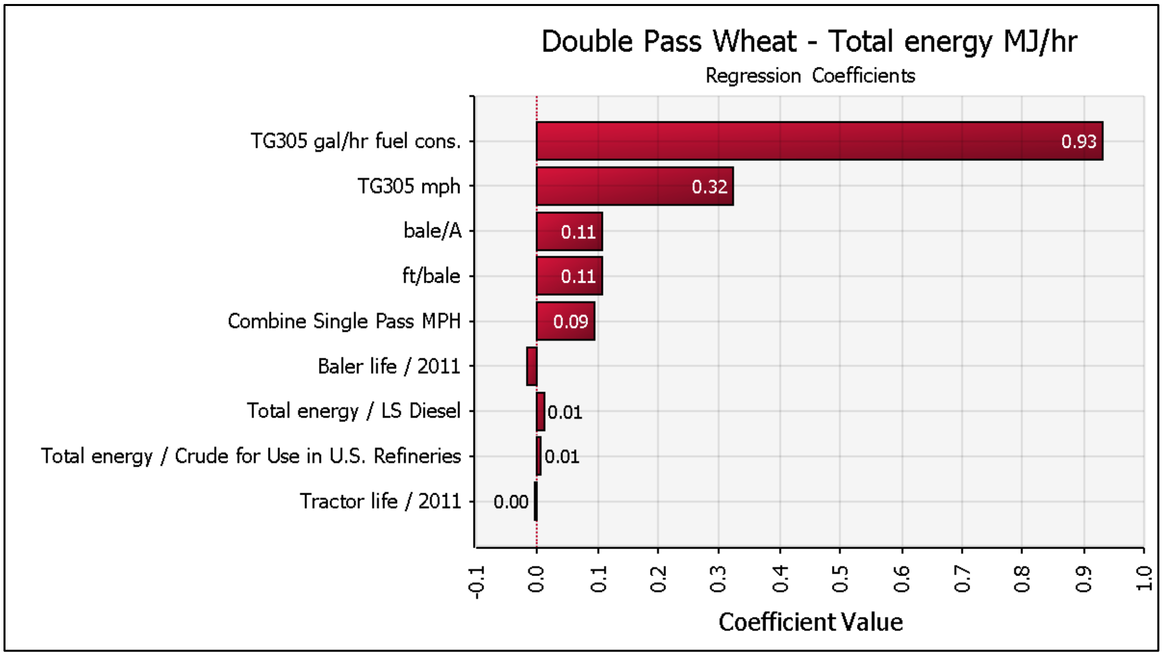


Figure 3.14 Tornado Regression Coefficient Graph of Total Energy in Double Pass Wheat Harvest

As can be viewed in Figure 3.14, the TG305 tractor fuel consumption had by far the biggest impact on the resulting total energy output of the process, followed by the TG305 tractor speed and bales per acre. This provides an easy means of illustrating the significant inputs of a process, whereby conclusions can be made to focus on methods to reduce their energy or emissions impact.

CHAPTER 4 : RESULTS AND DISCUSSION

4.1 Overview

To satisfy Objectives 1 and 2 of the project: develop a comprehensive LCA model of the agricultural residue development process; and utilize stochastic simulation to improve model robustness, respectively; each of the major equipment inputs and process step results are presented. On results with stochastic inputs, the Monte Carlo output of that result is also presented. The effects of varying methods of co-product handling are also reviewed, along with the results of each process step. To satisfy Objective 3: Evaluate the specific energy input and environmental emission differences between Single Pass and Double Pass Harvesting, an overall summary of each process step in both wheat and corn crops is presented. The total energy and emissions resulting from the ag residue harvest process is given in the Life Cycle Assessment section.

4.2 Equipment Results

As was detailed in the goal and scope of the project, the functional unit of MJ per hour or grams per hour was chosen as a means to eliminate most of the co-product issues that arise in an agricultural setting since this initial energy and emissions investment is spread over many uses of the equipment on farm. However, since the energy and emissions must first be tabulated for each piece of equipment before normalizing per hour of equipment life, it is noteworthy to report on the results of the equipment manufacture alone. Due to the vast amount of data produced from the model, the specific results of the Puma Tractor manufacture will only be detailed, with summary tables in Section 4.2.6 capturing the manufacture results of all the equipment. The normalized results per hour of equipment life will also be reported in a similar format.

Since greater than 80% of the resulting energy and emissions of the equipment was attributed to field operations, each specific equipment section below will review the LCA model results for equipment operation per hour. Equipment use in field was determined to have the largest impact on model results, and is what the cutoff criteria for the model was developed from.

4.2.1 *Puma Tractor*

The four primary categories used to report on the equipment and component manufacture were Material Components, Battery, Fluids, and Equipment Assembly. As review, the Material components category captures the raw materials used to make the equipment, while the Battery and Fluids categories encompass both the raw materials required to make the component and factors in the additional replacements from normal maintenance, such as oil changes. Note that the fluids are included in the equipment manufacturing part of the LCA and not in the operation since no fluids are theoretically consumed during operation. Therefore, all the fluids that would be used over the equipment life, based on manufacture's recommended service intervals, are included here. Equipment Assembly captures the specific energy and emissions that result from the manufacturing process. The corresponding energy and emissions results of each category are presented in Figure 4.1, Figure 4.2 and Figure 4.3, along with the total.

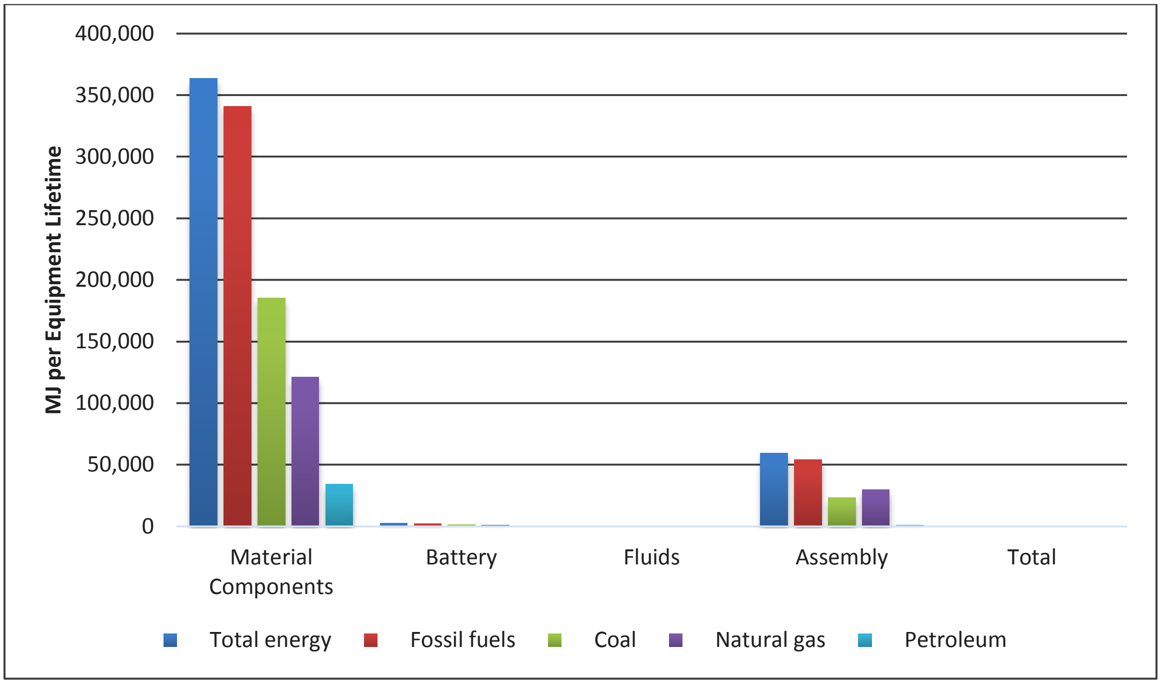


Figure 4.1 MJ Energy Use for Manufacture of Puma Tractor – Not Including Energy Used During Operation

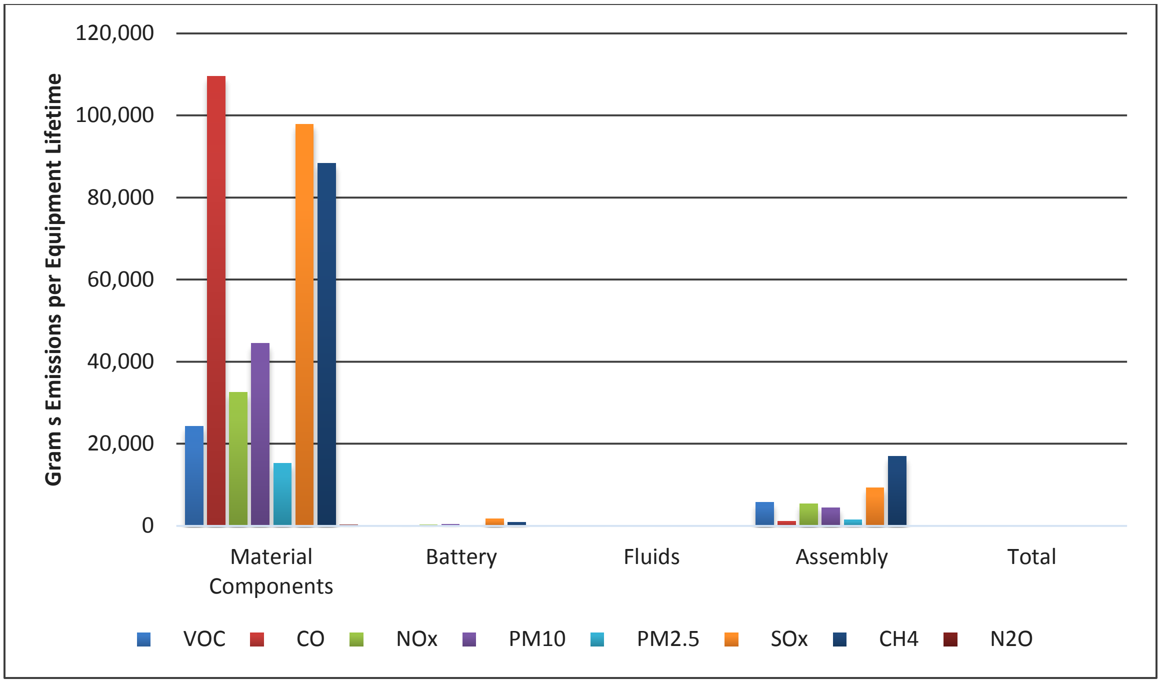


Figure 4.2 Grams Emissions from Manufacture of Puma Tractor – Not Including Emissions During Operation

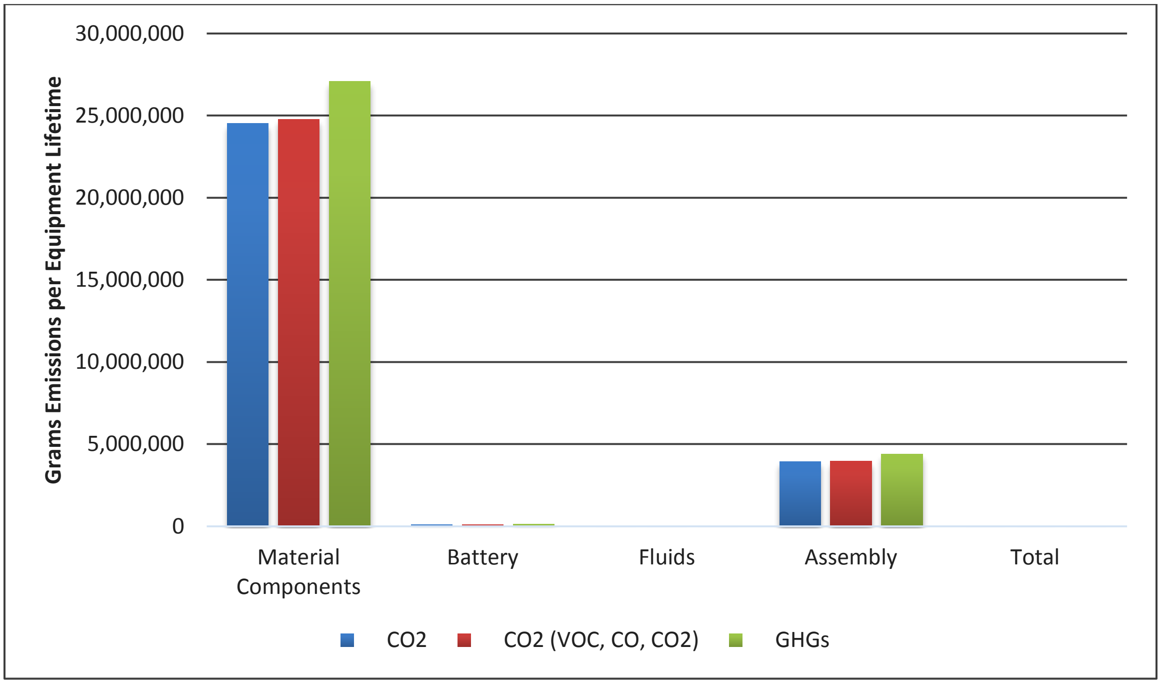


Figure 4.3 Grams of CO_2, CO_2+Carbon and CO_2 Equivalent GHG Emissions from the Manufacture of the Puma Tractor – Not Including Emissions During Operation

As illustrated in the Figures 4.1 - 4.3, the material components category represented the majority of both energy and emissions results for the Puma Tractor. Not surprisingly, Fossil Fuels accounted for over 93% of the energy for Material Components and 100% of the energy for the Fluids component. The Battery component contributed very little to the overall energy and emissions of the equipment. Total Energy use for the Puma Tractor was 513,000 MJ and the Total GHG emissions were 37,260,300 grams.

Normalizing these results per hour of tractor life and incorporating stochastic analysis yields the results shown in Figure 4.4 for Total Energy and Figure 4.5 for GHG emissions. As reviewed in Section 3.4, the @Risk software produces frequency or probability distributions for the Monte Carlo analysis results shown in the figures.

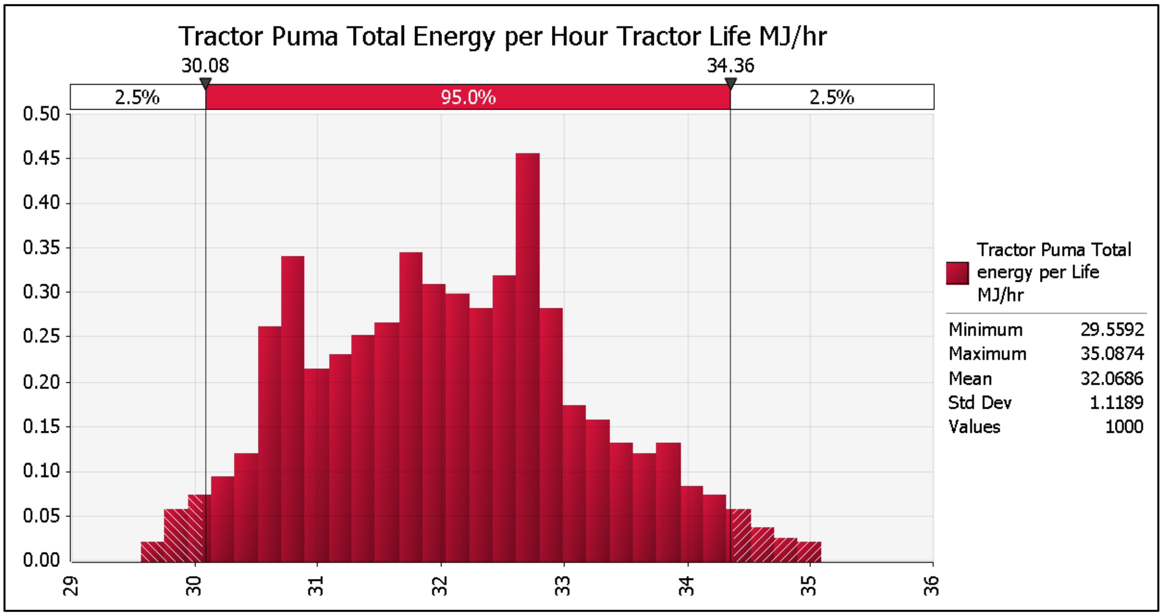


Figure 4.4 Normalized Total Energy for Manufacture of Puma Tractor – Not Including Energy Used During Operation

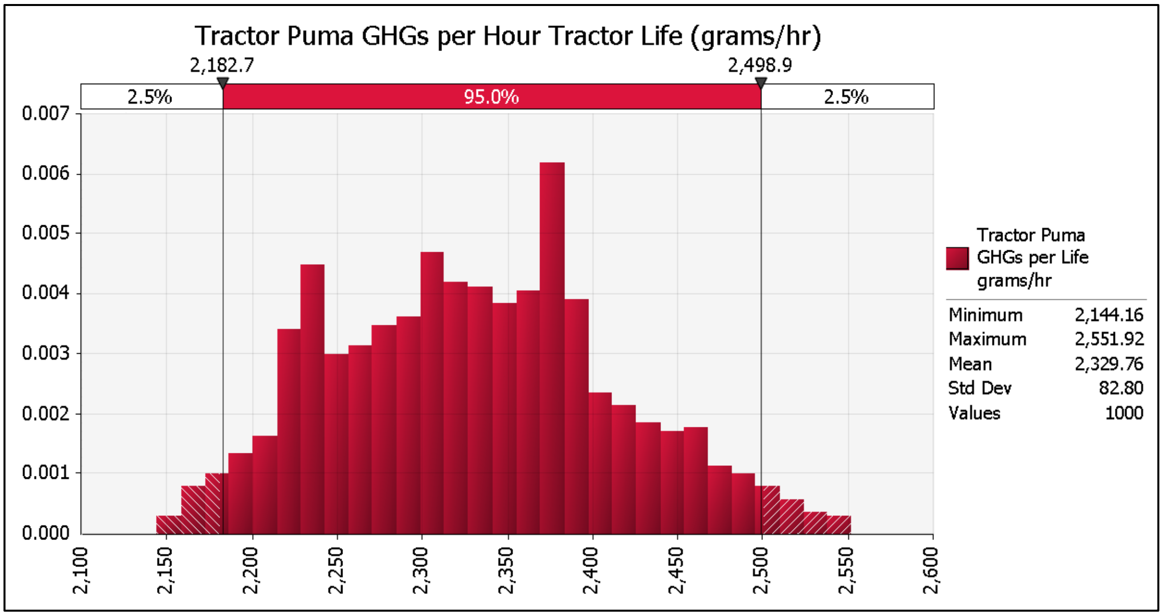


Figure 4.5 Normalized GHG Emissions Result for Manufacture of Puma Tractor – Not Including Emissions During Operation

Normalizing the results per hour of equipment life spreads the large initial energy and emissions out, greatly reducing the impact on a per hour machine use basis. The machine use of the equipment takes into consideration the raw crude extraction, the transportation and conversion to fuel, and finally the energy and emissions that result from the fuel consumption itself by the equipment. DEF fluid consumption is also included but comprised a very small percentage of the total. Figure 4.6 and Figure 4.7 show the resulting energy use and emissions output from the Puma Tractor operation alone, and does not include the results of the manufacturing energy and emission reviewed above.

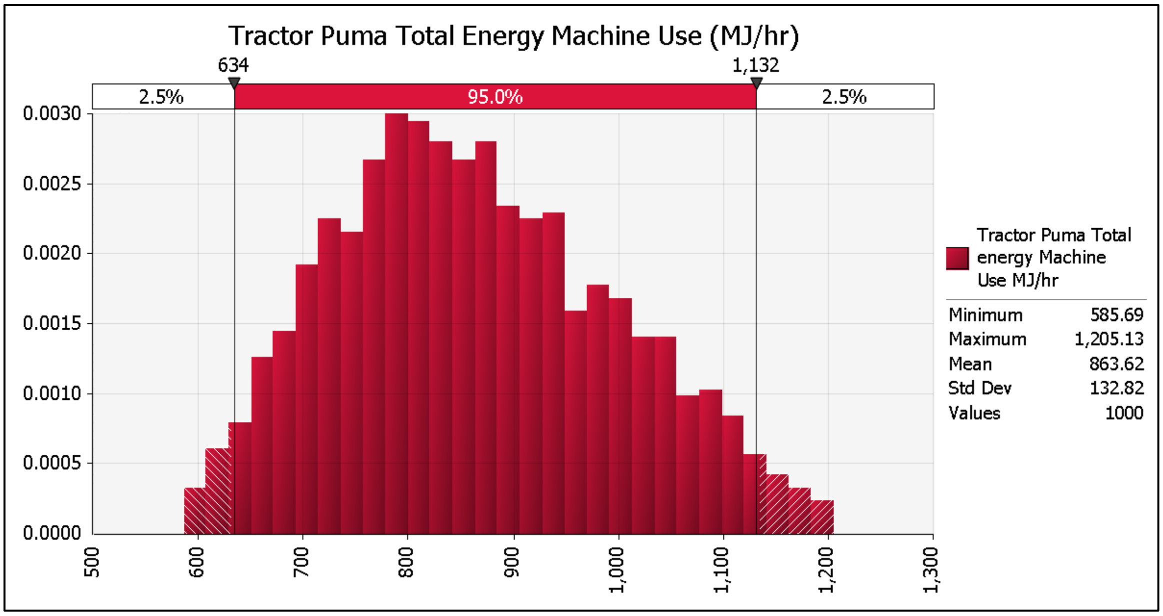


Figure 4.6 Total Hourly Energy Used During Puma Tractor Operation – Not Including Energy of Equipment Manufacture

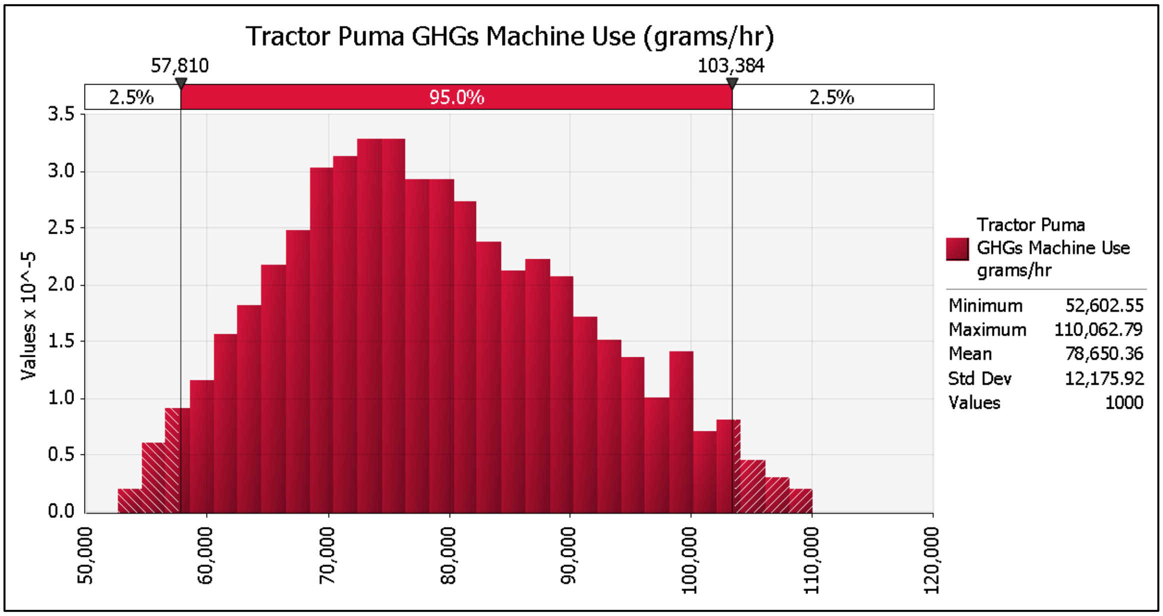


Figure 4.7 Total Hourly GHG Emissions from Puma Tractor Operation – Not Including Emissions of Equipment Manufacture

As illustrated in the figures, utilizing stochastic analysis produced a mean Total Energy use of 864 MJ per hour and Total GHG emissions of 78,650 grams per hour operation. As compared with the normalized manufacturing Total Energy of 32 MJ per hour and 2,330 MJ per hour GHG emissions, machine operation accounted for over 95%

of the total. Since field fuel consumption data was not available for the Puma Tractor, a +/-10% variation was used as the stochastic input on fuel consumption. Coupled with triangle distributions used on the crude oil extraction and refining inputs explains why the resulting energy and emissions output resembles the triangle distribution. Nevertheless, the results illustrated the potential variation present in the process.

4.2.2 *TG 305 Tractor*

The TG 305 Tractor Energy and Emissions manufacturing results are very similar to the Puma Tractor, albeit generally larger due to the heavier weight of the equipment. Energy and emissions resulting from the TG 305 machine operation are shown in Figure 4.8 and Figure 4.9. Mean energy use was 1,033 MJ per hour and GHG emissions were 94,190 grams per hour.

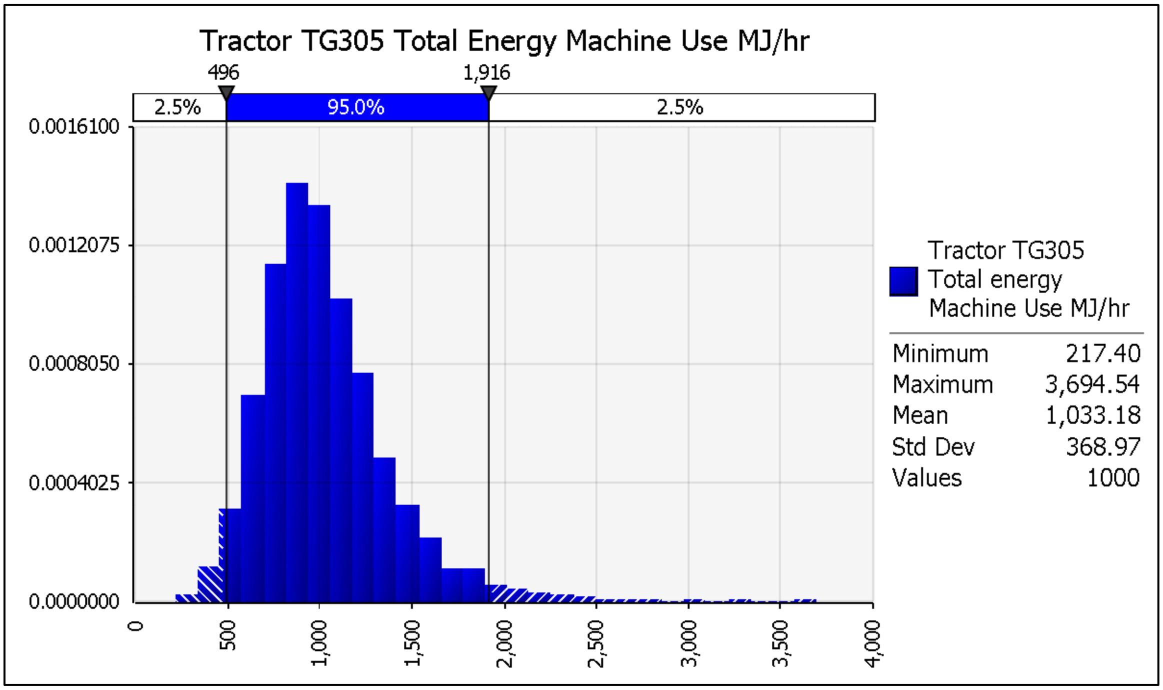


Figure 4.8 Total Hourly Energy Used During TG 305 Tractor Operation – Not Including Energy of Equipment Manufacture

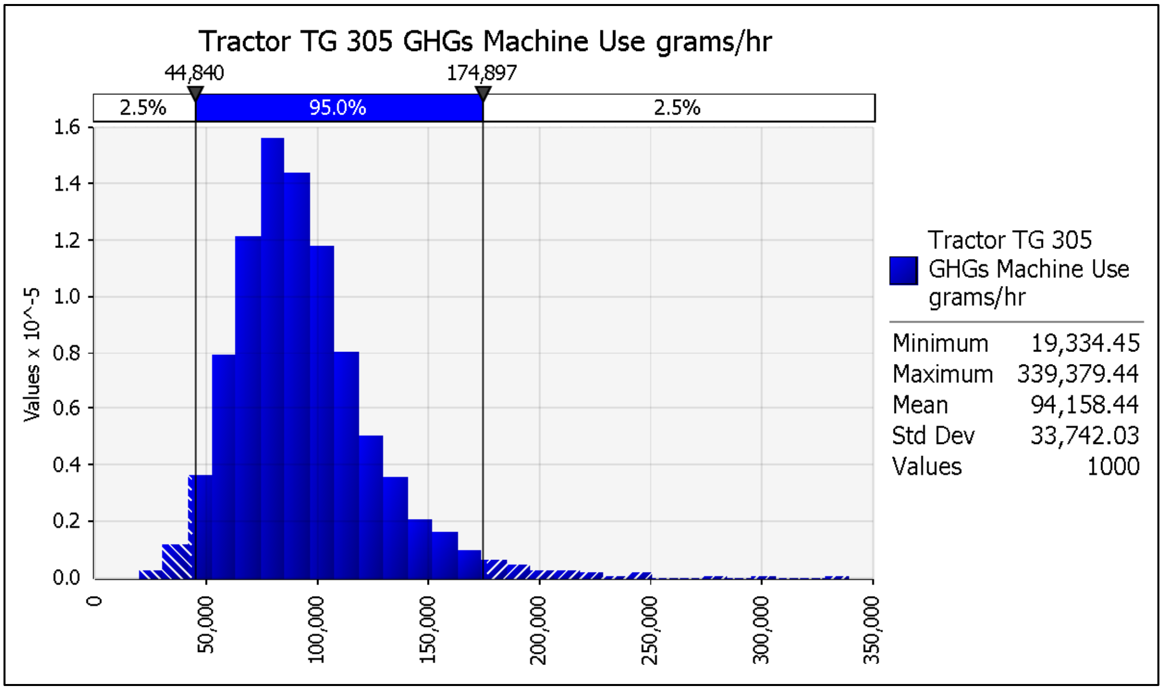


Figure 4.9 Total Hourly GHG Emissions from TG 305 Tractor Operation – Not Including Emissions of Equipment Manufacture

Since field fuel consumption data was available for the TG 305 tractor, the resulting outputs more closely resemble the distribution for fuel consumption since this was by far the most significant in input. Figure 4.10 depicts the tornado regression coefficient graph for the three statistical inputs for total energy, clearly showing that fuel consumption was the major input.

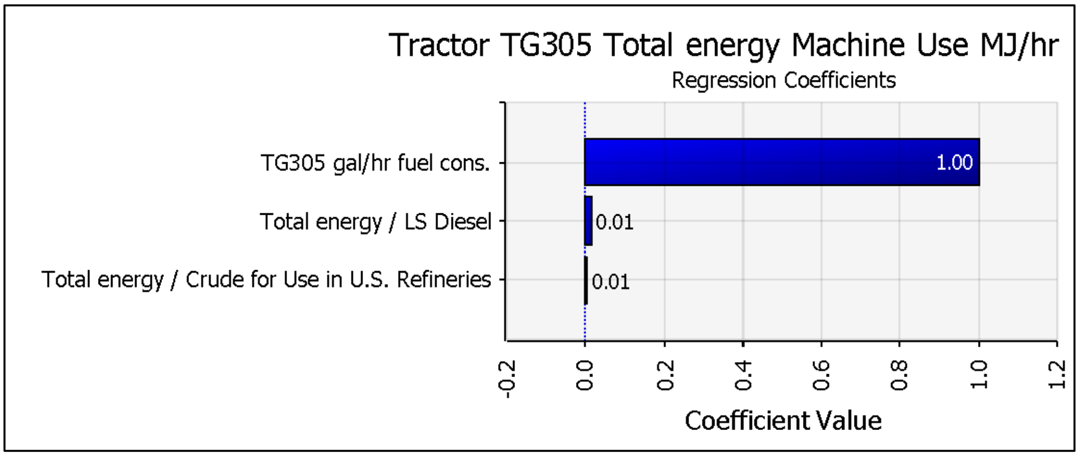


Figure 4.10 Tornado Regression Coefficient Graph for TG 305 Operation, Total Energy Inputs – Not Including Equipment Manufacture

4.2.3 *Combine*

The combine is the one piece of equipment that is used in multiple process steps; that is for both conventional grain harvest and the simultaneous grain and biomass harvest during single pass operation. In keeping with the goal and scope of the study, the LCA model only considers the process steps to produce baled biomass that are above and beyond conventional grain harvest, since grain harvest is assumed to be the primary output of the process and occurs regardless if the biomass is baled. The LCA model is designed such that all the inputs from single pass harvesting with the combine are considered in the Combine LCI database, and co-product handling techniques are applied in the Wheat and Corn worksheets to separate the energy and emissions that are attributed to normal grain harvest. Therefore, the total energy and emissions reported in Figure 4.11 and Figure 4.12 below are from the whole single pass harvest process, including both the grain harvest and biomass harvest. The separation of the energy and emissions attributed to grain harvest or biomass harvest alone will be covered in detail in Section 4.4 below.

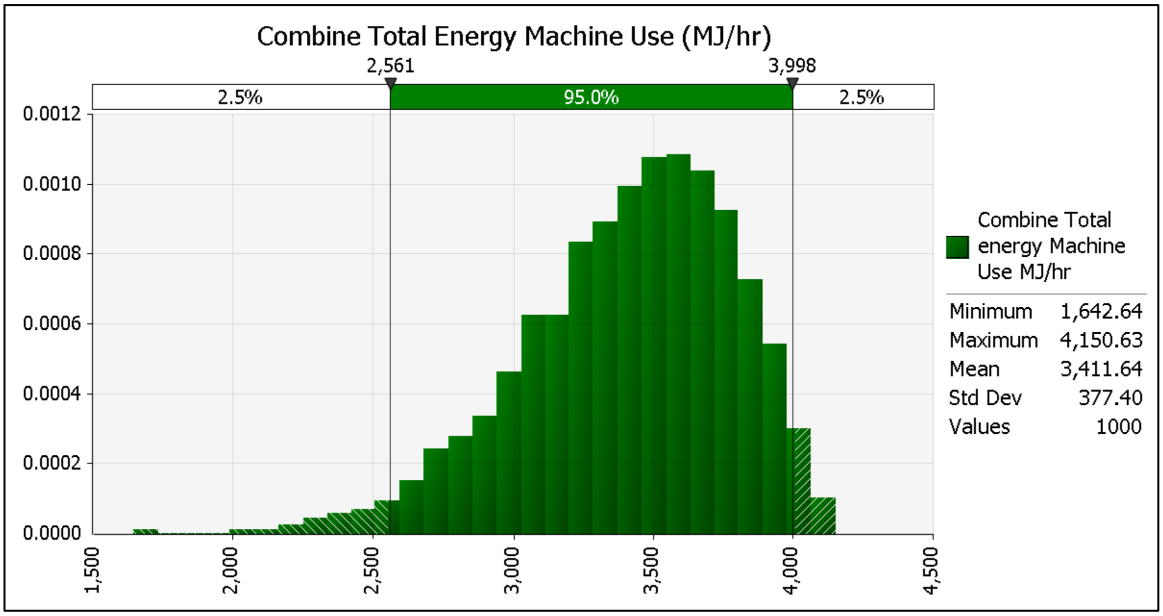


Figure 4.11 Total Hourly Energy Used During Combine Operation in Single Pass Harvest – Not Including Energy of Equipment Manufacture

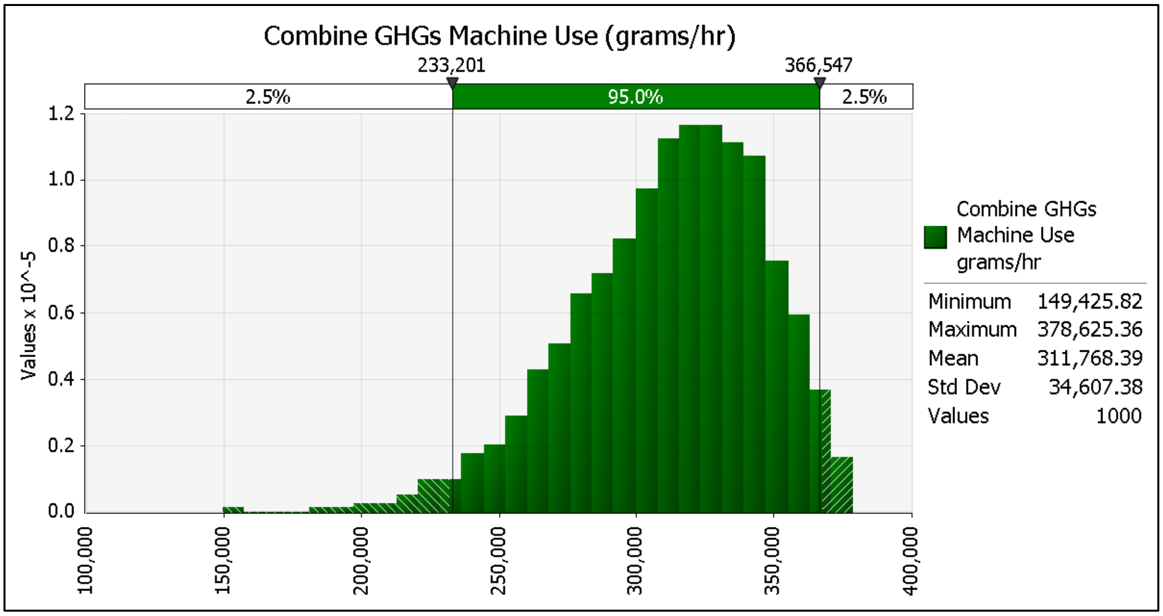


Figure 4.12 Total Hourly GHG Emissions from Combine Operation in Single Pass Harvest – Not Including Emissions of Equipment Manufacture

4.2.4 *Baler*

The Baler field operation differs in that fact that it does not burn diesel fuel, but rather uses baling twine. This twine usage rate was calculated based on field data for the number of biomass bales produced per hectare, length of twine per bale and average baler speed. The resulting twine usage rate is illustrated in Figure 4.13 with a mean of 1,429 meters per hour (4,688 feet per hour).

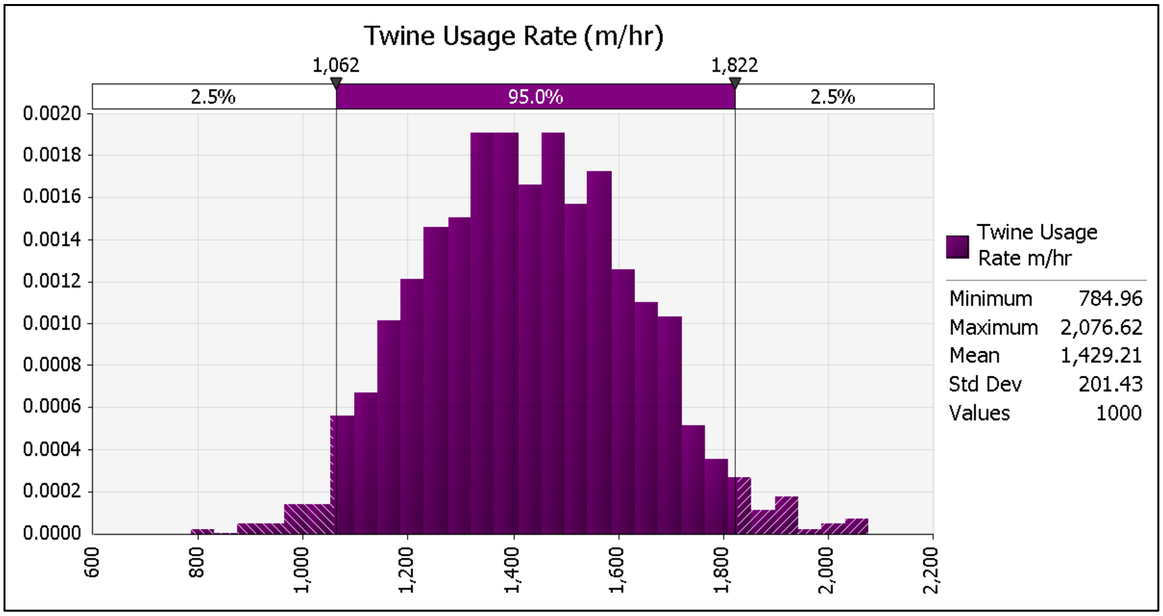


Figure 4.13 Baler Twine Usage Rate (meters per hour)

The resulting energy and emissions resulting from the twine usage are illustrated in Figure 4.14 and Figure 4.15. Note that this is the only input for the baler operation since it does not have fuel or DEF consumption of its own. Manufacture energy and emissions are not included in the figures.

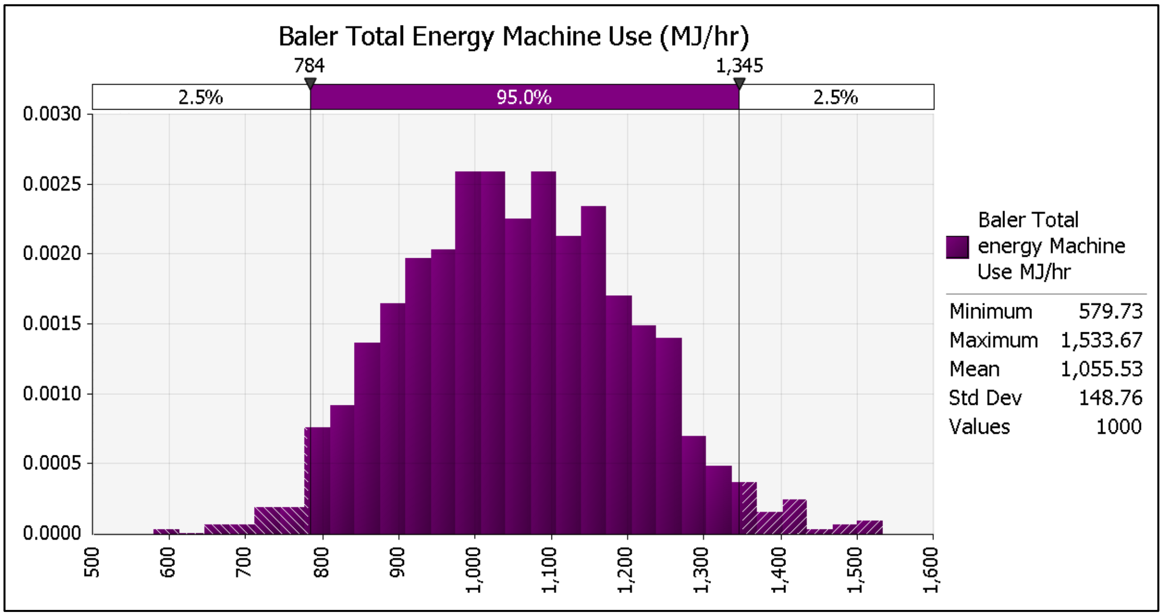


Figure 4.14 Total Hourly Energy Used During Baler Operation – Not Including Energy of Equipment Manufacture

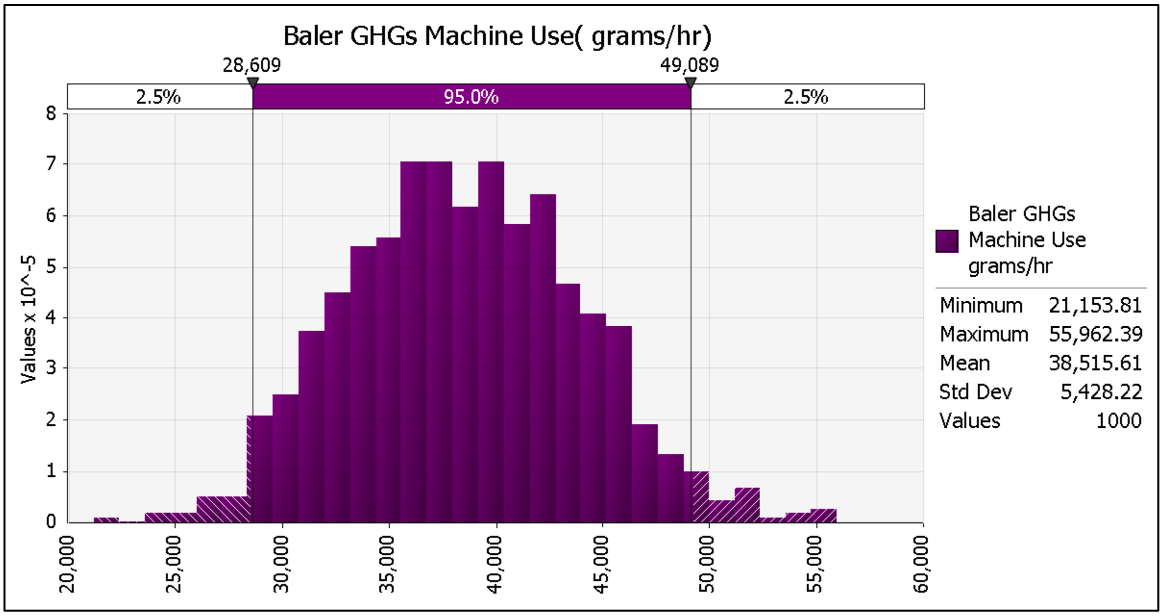


Figure 4.15 Total Hourly GHG Emissions from Baler Operation – Not Including Emissions of Equipment Manufacture

4.2.5 *Semi*

Consistent with the other equipment, the semi fuel consumption was the most significant input effecting the energy and emissions results. Since field fuel consumption data was not available for the semi, and most public fuel consumption data was for on-road applications, the on-road fuel consumption data (liters per kilometer) was referenced. To convert this into an hourly rate, an equivalent speed was assumed. Since most biomass transport would occur in short distances at slow speeds on rural roads, a triangle distribution was used with minimum, mean and maximum speeds of zero, 40.3 and 80.5 kilometers per hour (0, 25, and 50 miles per hour). The calculated fuel consumption results are shown in Figure 4.16.

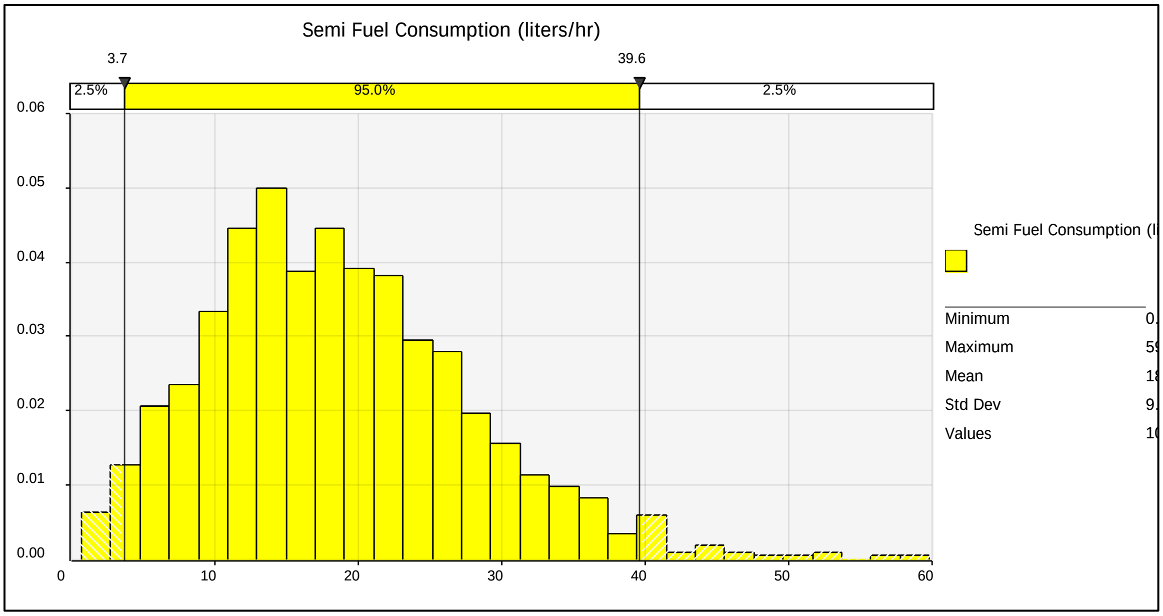


Figure 4.16 Semi Fuel Consumption Input into the Model

As shown in Figure 4.16, a mean of 18.7 liters per hour (4.9 gallons per hour) was used for the semi fuel consumption. A relatively large standard deviation of 9.2 liters per hour (2.4 gallons per hour) illustrate the fuel consumption variation that is present during the semi operation due to varying speeds and fuel consumption rates under load. The Total Energy and GHG emissions from the semi use are shown in Figure 4.17 and Figure 4.18.

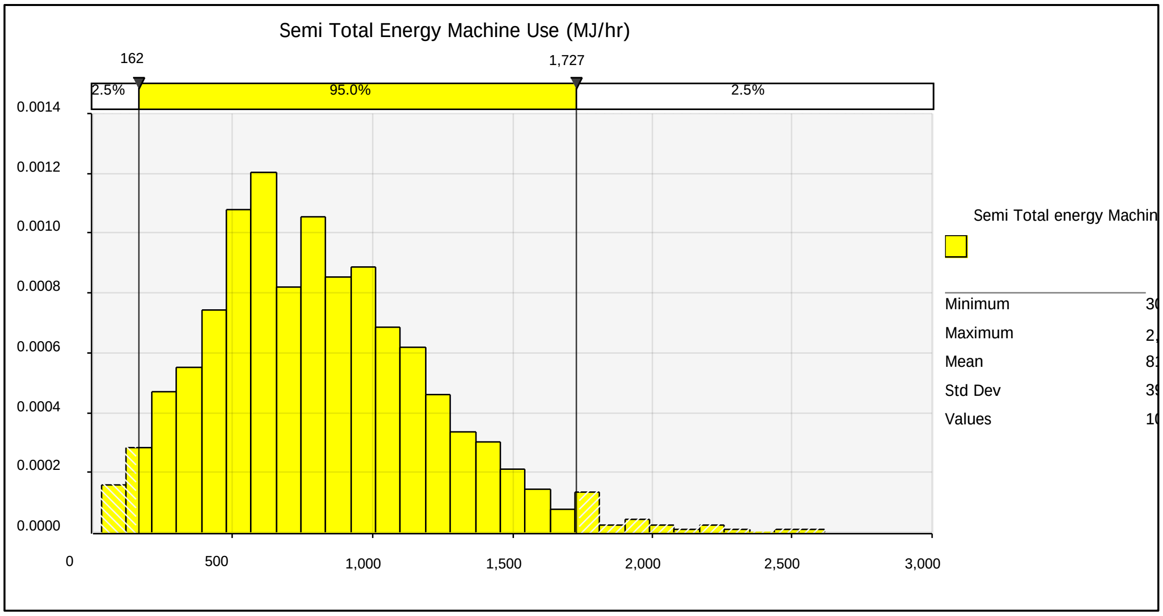


Figure 4.17 Total Hourly Energy Used During Semi Operation – Not Including Energy of Equipment Manufacture

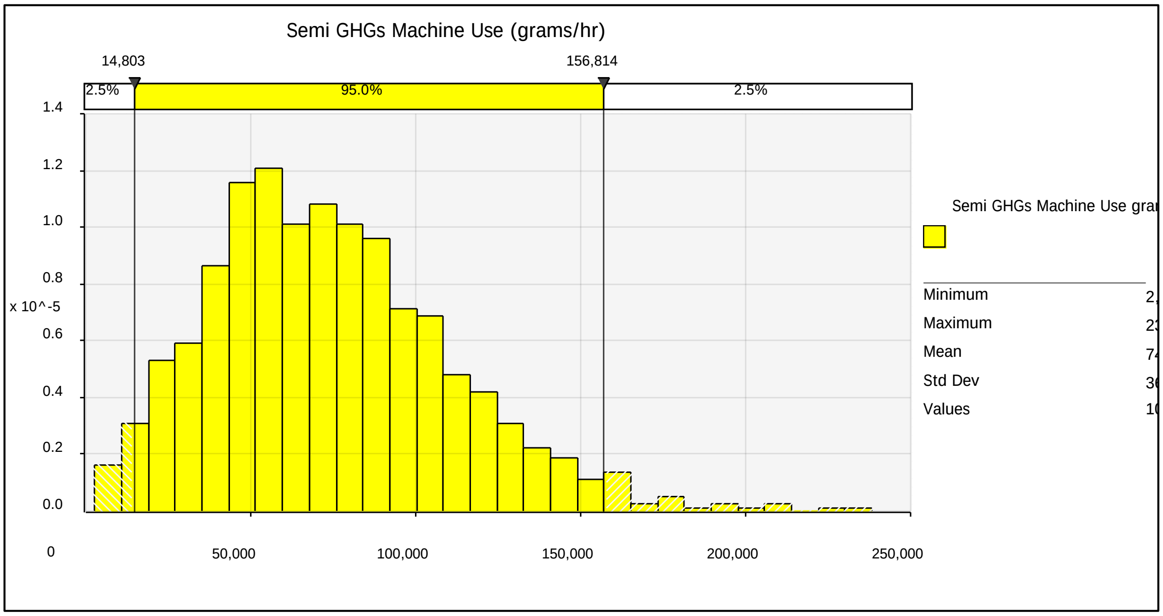


Figure 4.18 Total Hourly GHG Emissions from Semi Operation – Not Including Emissions of Equipment Manufacture

4.2.6 *Equipment Summary and Discussion*

The LCA model produces a vast amount of data just for the equipment alone. While it is important to review the results for single pieces of equipment or processes, it is particularly helpful to analyze the data on a comparative basis. The compiled results of the energy use and emissions of each piece of equipment are shown in Table 4.1, Table 4.2 and Table 4.3.

Table 4.1 Total Energy of Equipment Manufacture Over the Life of the Equipment

Total energy (MJ)	Material Components	Battery	Fluids	Assembly	**Total**
Puma	363,576	2,491	87,310	59,569	512,944
TG305	517,806	2,491	157,428	87,296	765,020
Combine	1,103,692	2,491	43,462	193,789	1,343,433
Baler	376,334	-	19,572	72,939	468,845
Semi	755,338	1,660	54,167	90,531	901,697

Table 4.2 Grams Emissions by Category of Equipment Manufacture Over the Life of the Equipment

VOC Emissions (grams)	Material Components	Battery	Fluids	Assembly	**Total**
Puma	24,219	66.7	5,553	5,722	35,561
TG305	34,086	66.7	5,729	8,385	48,266
Combine	71,315	66.7	3,290	18,613	93,285
Baler	22,680	-	423.0	7,006	30,109
Semi	51,113	44.5	2,151	8,696	62,004
CO Emissions (grams)					
Puma	109,543	121.2	1,700	1,074	112,438
TG305	156,842	121.2	2,928	1,574	161,465
Combine	337,565	121.2	892.1	3,493	342,071
Baler	117,727	-	349.7	1,315	119,392
Semi	168,037	80.8	1,010	1,632	170,760
NOx Emissions (grams)					
Puma	32,492	222.4	9,218	5,373	47,306
TG305	46,040	222.4	16,491	7,874	70,627
Combine	97,425	222.4	4,578	17,480	119,706
Baler	32,595	-	2,046	6,579	41,220
Semi	69,405	148.2	4,318	8,166	82,037
PM10 Emissions (grams)					
Puma	44,464	376.2	3,272	4,466	52,578
TG305	64,491	376.2	5,955	6,545	77,367
Combine	140,914	376.2	1,618	14,529	157,436
Baler	49,517	-	744.8	5,468	55,731
Semi	95,567	250.8	1,415	6,787	104,020
PM2.5 Emissions (grams)					
Puma	15,205	140.2	2,051	1,428	18,825
TG305	22,027	140.2	3,768	2,093	28,028
Combine	48,036	140.2	1,003	4,647	53,826
Baler	16,753	-	474.8	1,749	18,977
Semi	35,516	93.4	937.3	2,171	38,718
SOx Emissions (grams)					
Puma	97,831	1,764	11,513	9,328	120,436
TG305	140,144	1,764	20,663	13,669	176,241
Combine	301,658	1,764	5,787	30,345	339,554
Baler	107,954	-	2,555	11,421	121,931
Semi	177,650	1,176	4,652	14,176	197,654
CH4 Emissions (grams)					
Puma	88,403	836.6	12,212	17,010	118,461
TG305	124,584	836.6	19,487	24,927	169,835
Combine	261,956	836.6	6,600	55,336	324,730
Baler	89,259	-	2,215	20,828	112,302
Semi	170,614	557.7	12,654	25,851	209,677
N2O Emissions (grams)					
Puma	316.3	1.6	38.0	61.2	417.1
TG305	446.5	1.6	62.7	89.6	600.5
Combine	942.5	1.6	20.9	199.0	1,164
Baler	331.8	-	7.2	74.9	413.8
Semi	606.3	1.1	21.5	93.0	721.8

Table 4.3 Grams Emissions of CO_2 and GHGs of Equipment Manufacture Over the Life of the Equipment

CO2 Emissions (grams)	Material Components	Battery	Fluids	Assembly	**Total**
Puma	24,532,411	114,347	5,294,514	3,945,705	33,886,978
TG305	34,817,880	114,347	9,376,117	5,782,304	50,090,648
Combine	73,864,911	114,347	2,642,343	12,836,175	89,457,776
Baler	24,792,295	-	1,156,629	4,831,360	30,780,284
Semi	52,386,689	76,232	2,273,245	5,996,621	60,732,786
GHG Emissions (grams)					
Puma	27,084,363	136,134	5,631,113	4,408,700	37,260,310
TG305	38,418,249	136,134	9,904,443	6,460,807	54,919,634
Combine	81,447,421	136,134	2,825,226	14,342,389	98,751,170
Baler	27,378,313	-	1,216,022	5,398,279	33,992,614
Semi	57,256,065	90,756	2,604,287	6,700,273	66,651,380

Generally, the material components category comprised the majority of energy and emissions from the manufacture of the equipment, followed by the assembly and fluids. Not surprisingly, heavier equipment tended to be more energy or emissions intensive, considering the additional energy and emissions not only required during manufacture but also in raw material acquisition. Thus the combine required the most energy to produce and emitted the greatest amount of emissions in the process, followed by the semi, TG305 tractor, Puma tractor and baler. Battery manufacture comprised very little to the total for all pieces of equipment.

Surprisingly, the TG305 Tractor had a high energy and emissions result for the fluids component as compared with the other pieces of equipment. This was primarily due to the larger quantity of engine, transmission and hydraulic oil of the TG305 tractor but also due to the higher number of changes over its life as recommended by the manufacturer.

The stochastic GHG emission results of normalizing the equipment manufacture per hour of life are shown in Figure 4.19 below. Similar results for the normalization of Total Energy per equipment life were produced.

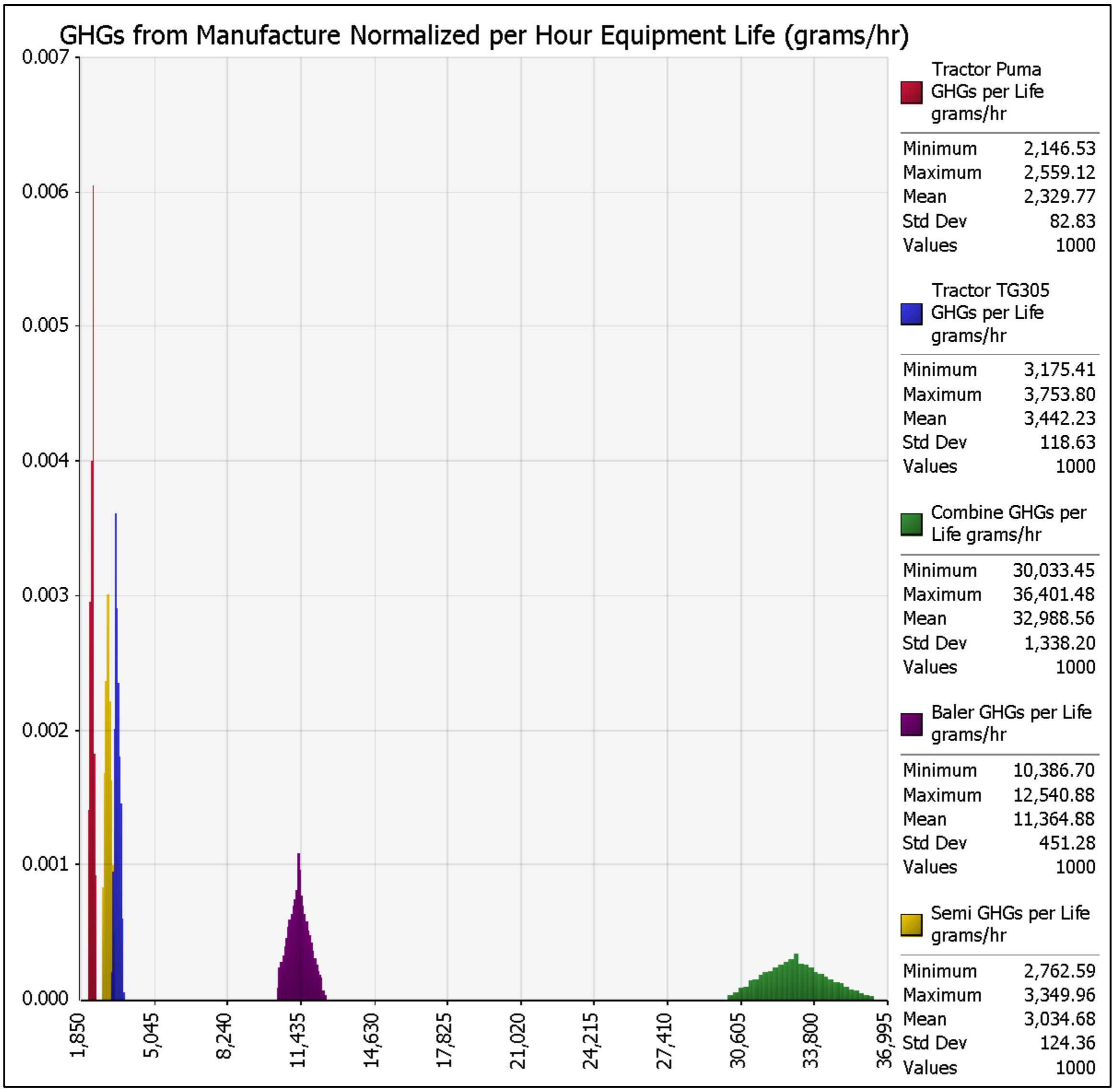
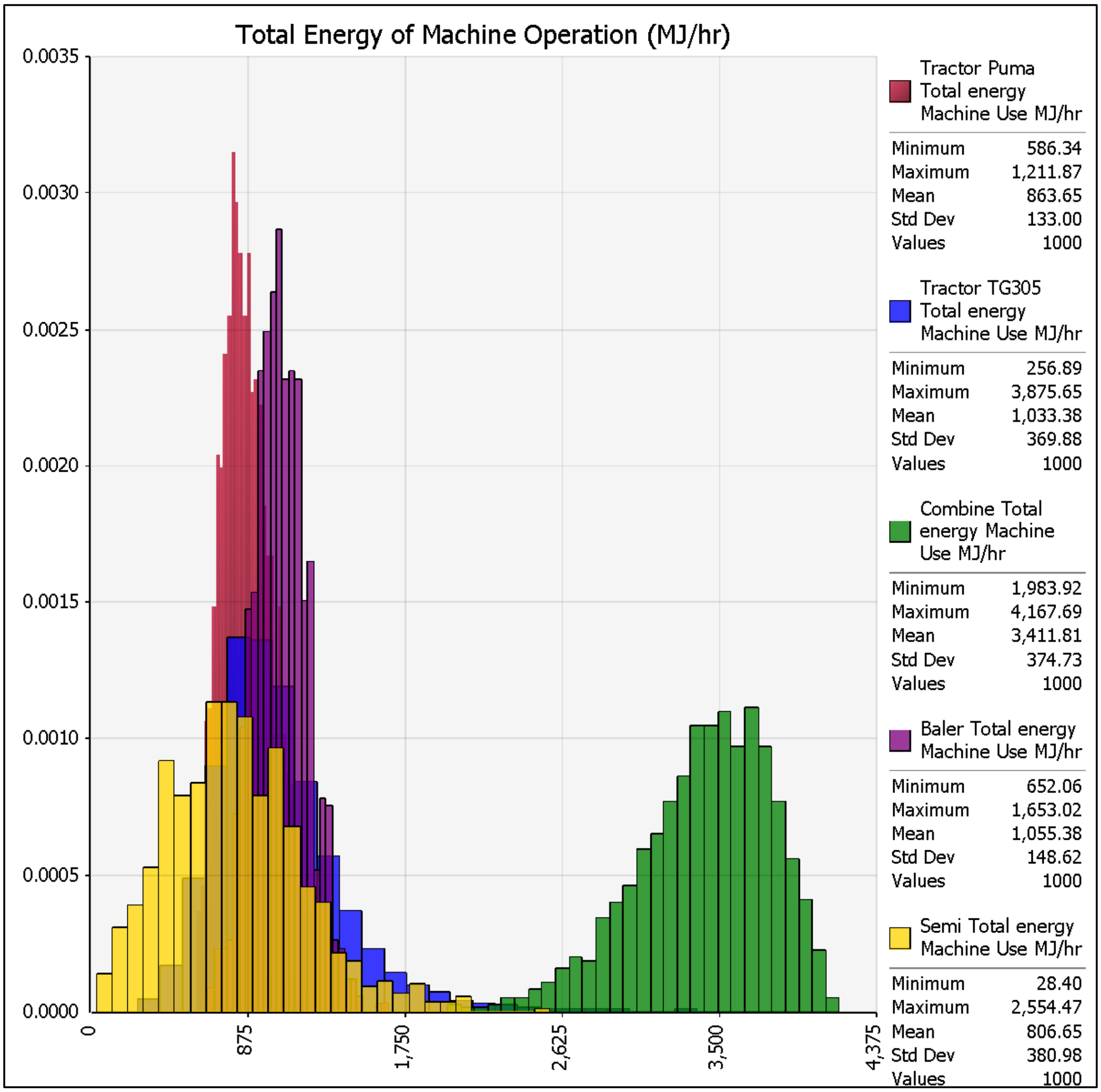


Figure 4.19 Stochastic Comparison for Hourly GHG Emissions of Equipment Used in the Process – Not Including Emissions During Operation

Illustrated in Figure 4.19, great differences are present in the GHG emissions after the equipment is normalized per hour of life. The combine had the largest emissions, due in combination to the high emissions produced during the manufacturing process and also to the low life (3000 hours). The baler is shown to have the second highest GHG emissions per hour of life, also due to the low life expectancy of 3000 hours as compared to the Puma and TG305 tractors life of 16,000 hours and the semi life of 22,000 hours.

Figure 4.20 illustrates the stochastic comparison for total energy per hour operation for each piece of equipment. Similar results for GHG emissions were also produced. From the figure, the combine yields the highest energy use in operation due to the higher fuel consumption (20.75 gallon per hour). While the baler does not have its own power source, i.e. it is pulled by a tractor or combine, it still represents a large energy use. In fact, the mean total energy (1,055 MJ per hour) for the baler operation was higher than that of the fuel consumption of the TG305 tractor (1,033 MJ per hour) due to the high rate of twine usage and the energy intense process of producing the twine.



	Tractor Puma Total energy Machine Use MJ/hr	Tractor TG305 Total energy Machine Use MJ/hr	Combine Total energy Machine Use MJ/hr	Baler Total energy Machine Use MJ/hr	Semi Total energy Machine Use MJ/hr
Minimum	586.34	256.89	1,983.92	652.06	28.40
Maximum	1,211.87	3,875.65	4,167.69	1,653.02	2,554.47
Mean	863.65	1,033.38	3,411.81	1,055.38	806.65
Std Dev	133.00	369.88	374.73	148.62	380.98
Values	1000	1000	1000	1000	1000

Figure 4.20 Stochastic Comparison for Total Hourly Energy of Equipment Operation – Not Including Energy of Equipment Manufacture

4.3 Additional Fertilizer

Removing wheat straw or corn stover from the field also removes nutrient values that could be used for the subsequent year's crop. The three macronutrients: nitrogen, phosphorus and potassium were considered in the LCA. However, since very little nitrogen is left in the soil year to year in Kentucky, the energy and emissions from additional nitrogen was considered zero (AGR-1, 2012-2013).

Expectedly, the variable contributing the most sensitivity to the results was the mass of biomass removed from the field. This data was collected in the field for both wheat straw and corn stover, and is shown in Figure 4.21. The mean straw weight was measured to be 3,026 kg per hectare (1.35 tons per acre) and mean stover weight was 2,314 kg per hectare (1.03 tons per acre). The data collected was at harvest moisture contents. The resulting energy and emissions output for the additional fertilizer is shown below in their respective sections.

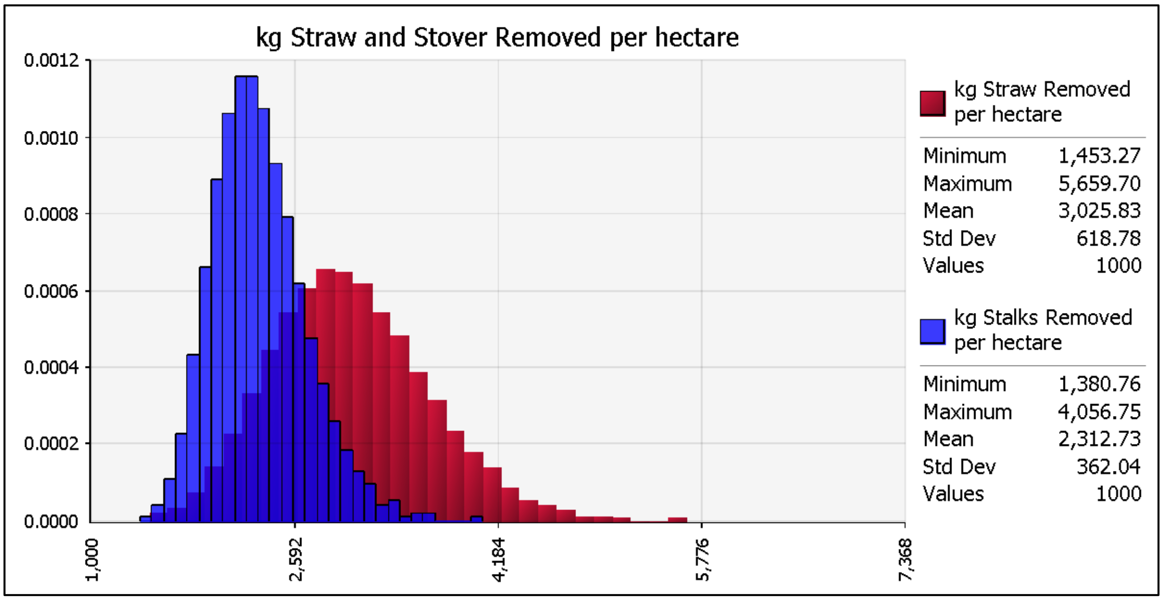


Figure 4.21 Mass of Straw and Stover Removed per Hectare

4.3.1 *Phosphorus*

The energy and emissions resulting from phosphorus fertilizer addition for both wheat straw and corn stover are shown in Figure 4.22 and Figure 4.23.

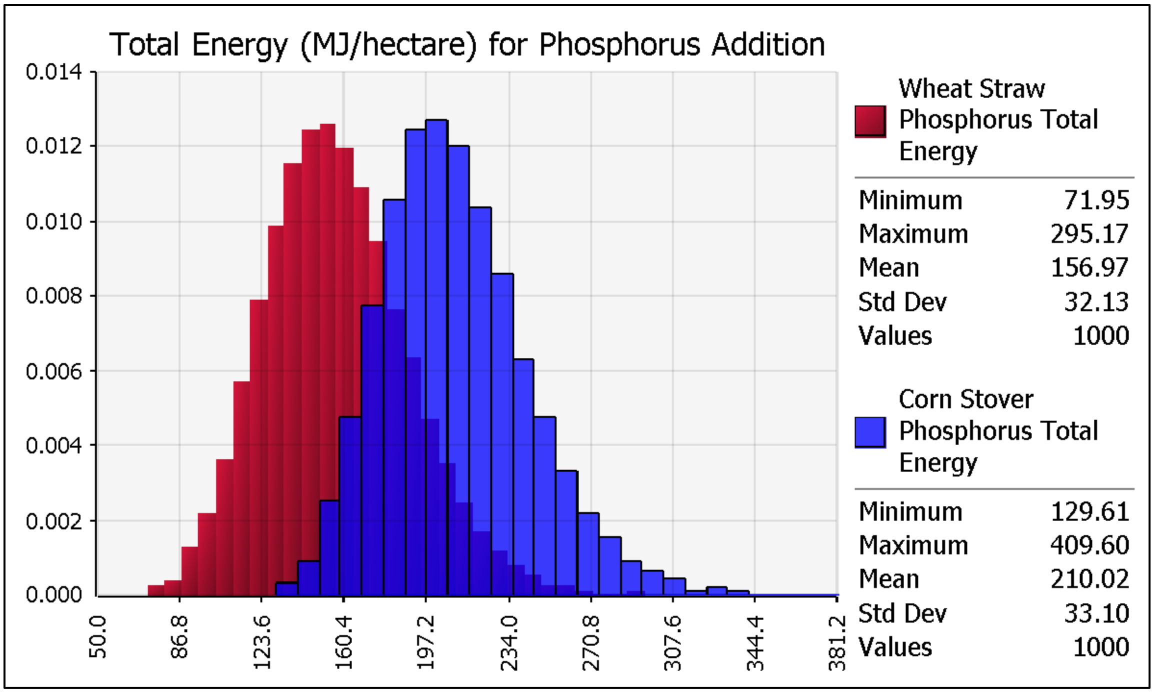


Figure 4.22 Total Energy Used for Additional Phosphorus Application

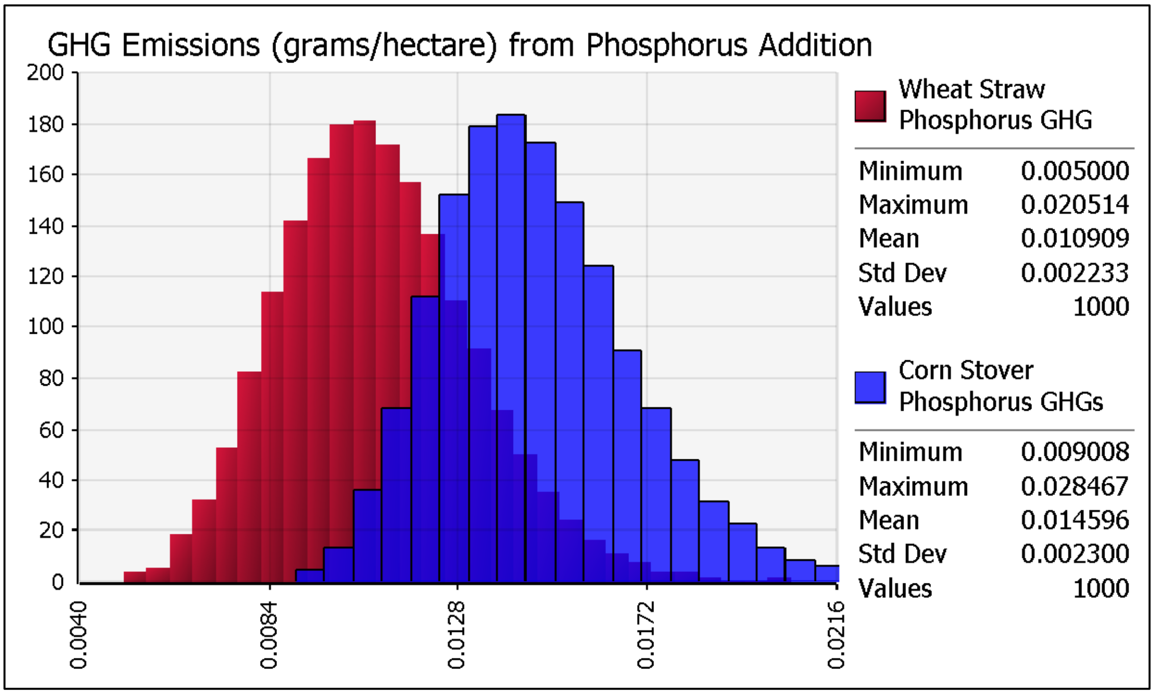


Figure 4.23 GHG Emissions Output from Additional Phosphorus Application

As illustrated in Figures 4.22 and 4.23, although a larger amount of straw mass is removed per hectare versus stover, the resulting energy and emissions to make up the nutrients from stover is higher due to the higher nutrient value of the stover that was removed (as compared to wheat). Although there are many overlapping regions of the probability curve, mean energy from phosphorus addition was 157 MJ/hectare for straw and 210 MJ/hectare for stover. GHG emissions were 0.011 and 0.015 grams/hectare for straw and stover, respectively.

4.3.2 *Potassium*

The energy and emissions results for the potassium addition are shown in Figure 4.24 and Figure 4.25. Similar to the phosphorus results, the corn stover required higher energy input and larger GHG emissions than straw due to the higher potassium nutrient value in the corn stalks as compared to wheat. The energy and emissions resulting from potassium addition were also determined to be greater than that from phosphorus. Although potassium has lower energy use and emissions outputs to produce as compared to phosphorus, the higher amount of potassium lost in the straw and stover as compared to phosphorus made up the difference.

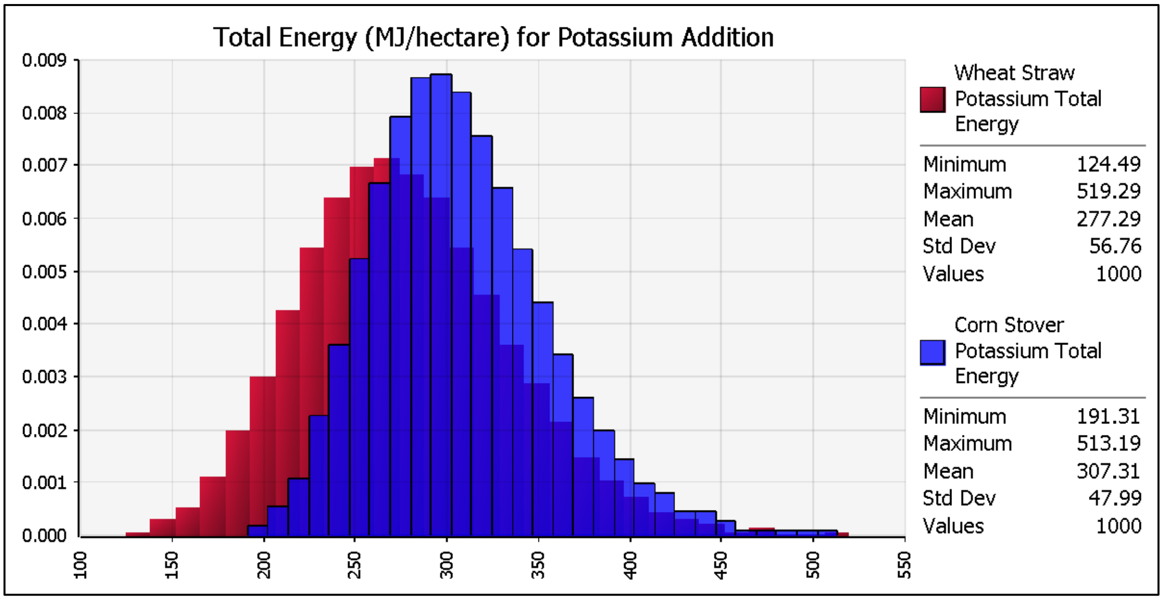


Figure 4.24 Total Energy Used for Additional Potassium Application

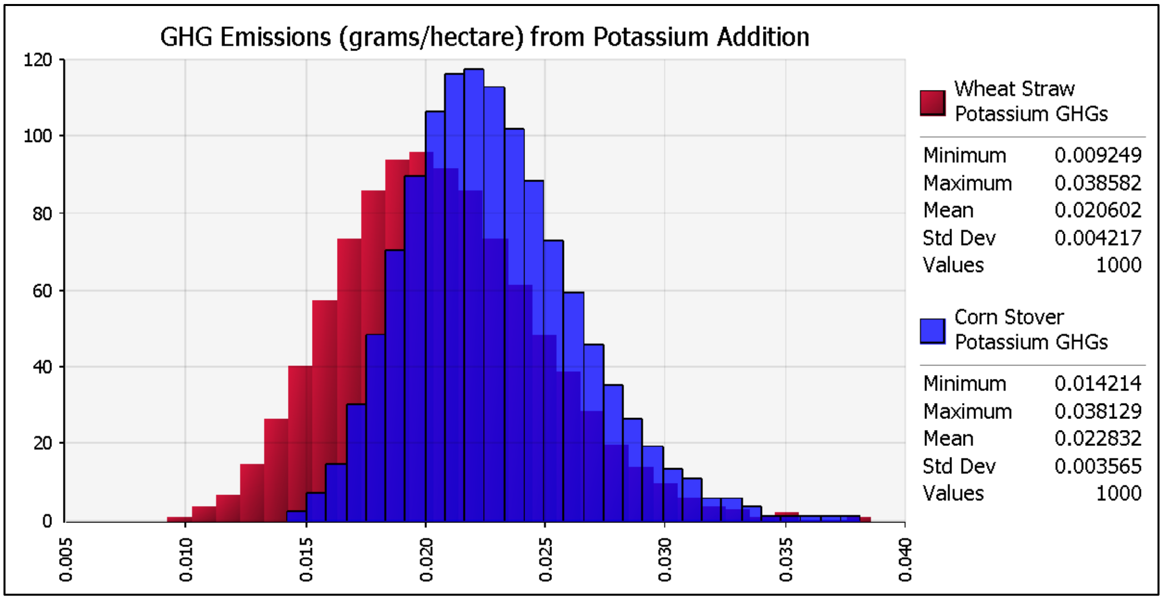


Figure 4.25 GHG Emissions Output from Additional Potassium Application

4.4 Co-Product Handling

As was previously mentioned, methods in which co-products are allocated can result in dramatically different results. The combine in single pass harvesting is the only process in which co-product analysis is concerned since results are normalized per hour operation and the combine produces both grain and biomass while operating. All other processes to harvest biomass are above and beyond normal grain operation and therefore the energy and emissions are considered to contribute 100% to the process.

When comparing the conventional co-product allocation methods of mass based and market based, as well as the additional method utilizing fuel consumption differences between a single pass combine operation and conventional operation, the total energy and GHG emissions results vary. Again, there was no difference between combine speeds during conventional harvest and single pass harvest, therefore the additional fuel consumption during single pass harvest was directly due to pulling the baler and thus attributed to the biomass. Figure 4.26 and Figure 4.27 show the variation between co-product handling methods for single pass operation in wheat, with each method overlaid on the graph. As the figures depict, market based allocation yields the lowest result for energy consumed, while fuel consumption based and mass based have progressively higher results. The 100% allocation of combine operation to biomass harvest is obviously the highest since the other methods are percentages of it, but is included in the figure for reference purposes.

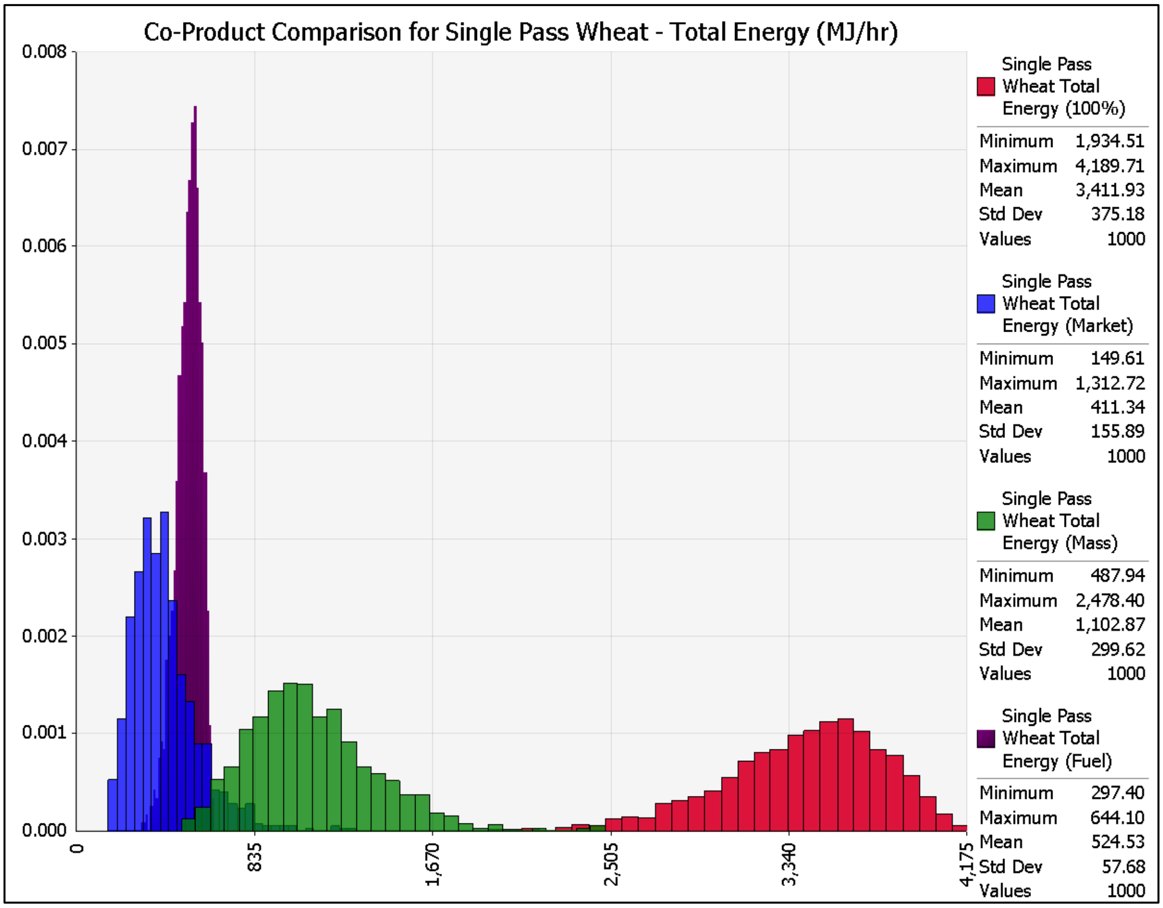


Figure 4.26 Co-Product Comparison Results for Wheat Straw-Single Pass Harvest Total Energy – Includes Combine Manufacture and Operation

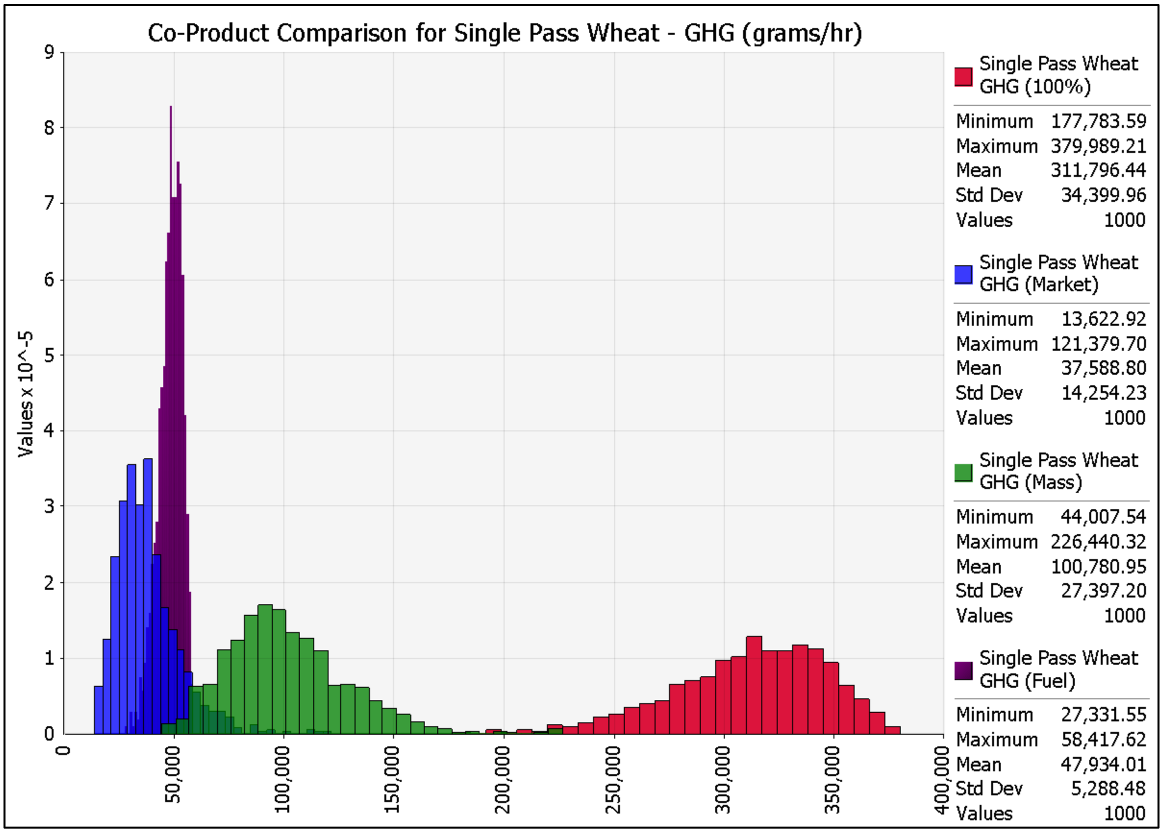


Figure 4.27 Co-Product Comparison Results for Wheat Straw-Single Pass Harvest GHG Emissions – Includes Combine Manufacture and Operation

There is some overlap of the distributions, but clearly three separate curves are present, with means of 411, 1,103, and 525 MJ/hour for the total energy in the market, mass and fuel consumption methods, respectively. GHG’s follow a very similar trend but with means of 37,590, 100,780, and 47,934 grams/hour emissions for the market, mass and fuel consumption methods, respectively. Similar trends are shown in Figure 4.28 and Figure 4.29 below for corn stover, although energy and emission attributed to the stover is even lower than that of the straw.

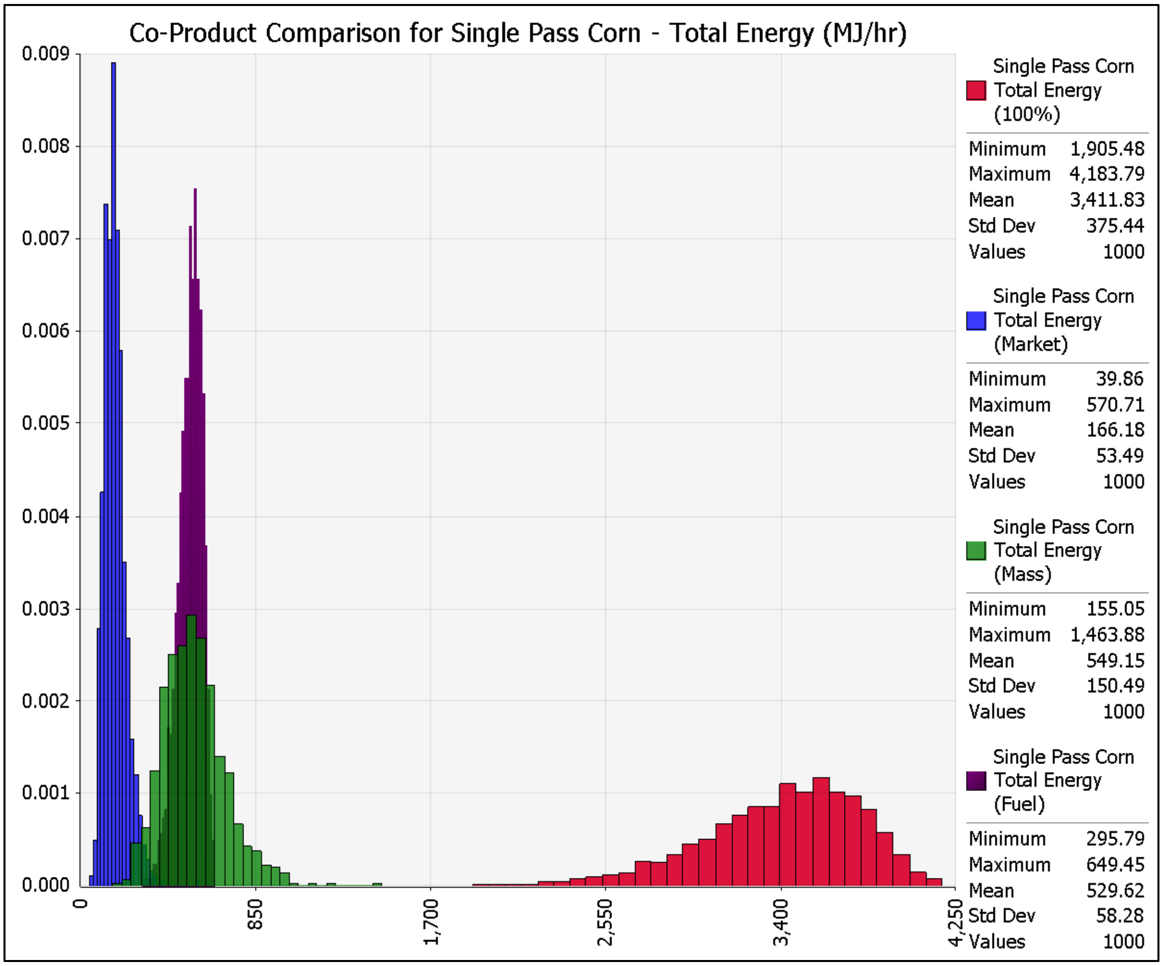


Figure 4.28 Co-Product Comparison Results for Corn Stover - Single Pass Harvest Total Energy – Includes Combine Manufacture and Operation

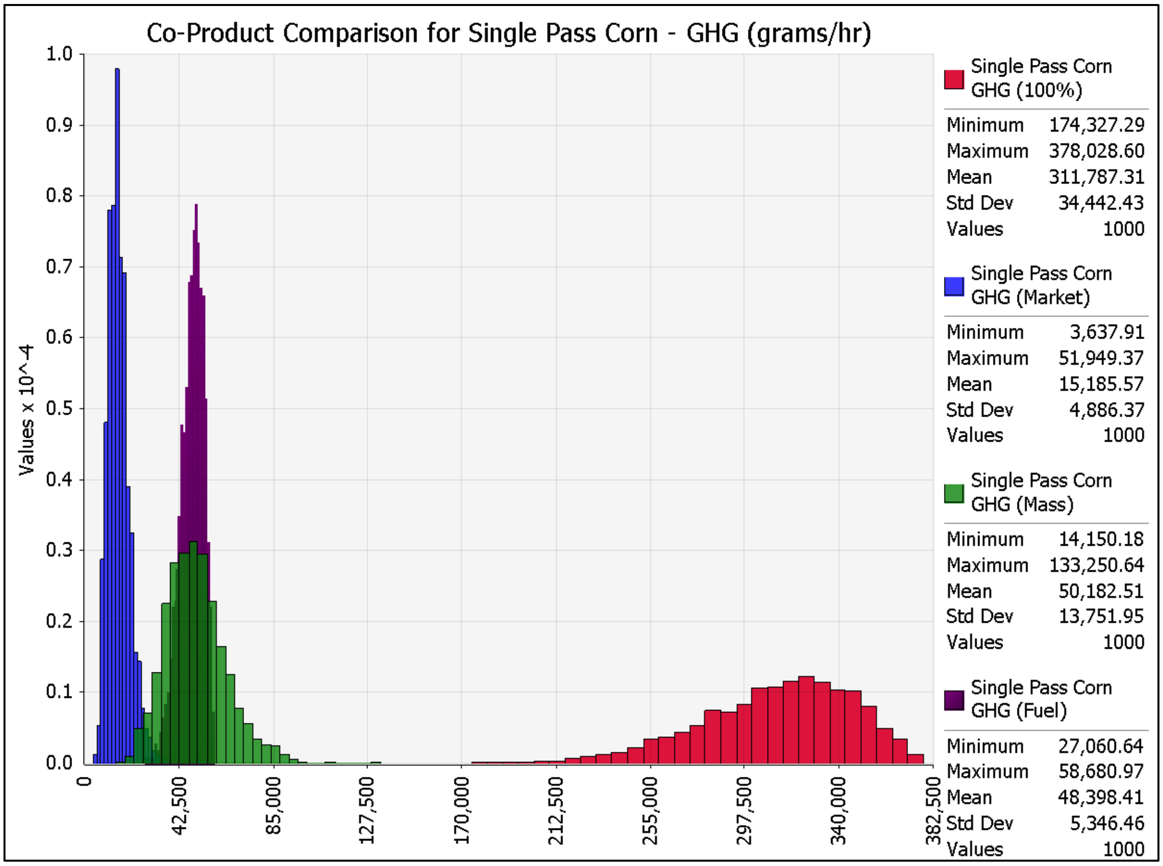


Figure 4.29 Co-Product Comparison Results for Corn Stover - Single Pass Harvest GHG Emissions – Includes Combine Manufacture and Operation

Subsequent results presented from the LCA are based on the fuel consumption method of co-product handling. This was chosen primarily because the fuel consumption method represents the most realistic way to analyze the additional energy and emissions from biomass harvest. Additionally, this method represents a balanced case for energy and emissions attributed to the biomass harvest during the single pass operation. In other words, the fuel consumption method attributes an intermediate result of energy use and emissions output to the biomass as compared to the other methods. In reality, if one choses to view the results utilizing the mass or market based methods, there would be a slight reduction or gain in total energy consumed or emissions released in the process.

4.5 Single Pass Harvest

Utilizing the fuel consumption based method of co-product allocation for the combine, the total results for the single pass harvest operation are shown below for both wheat straw and corn stover. The equipment included in this process are the combine and baler. Figure 4.30 details the energy consumed while Figure 4.31 and Figure 4.32 detail the emissions for the process.

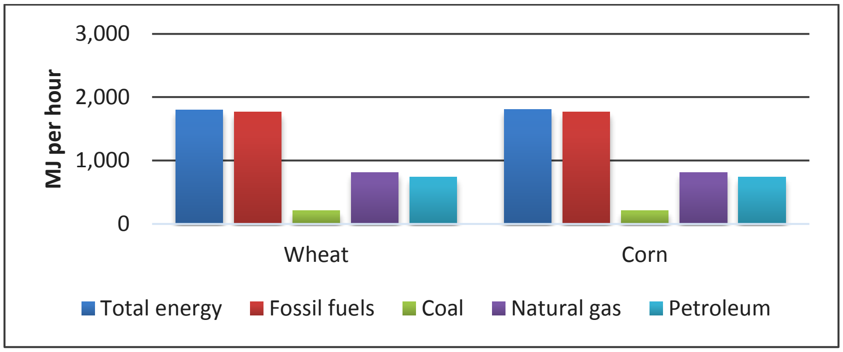


Figure 4.30 Energy Use of Single Pass Harvest of Wheat and Corn - Includes Equipment Manufacture and Operation

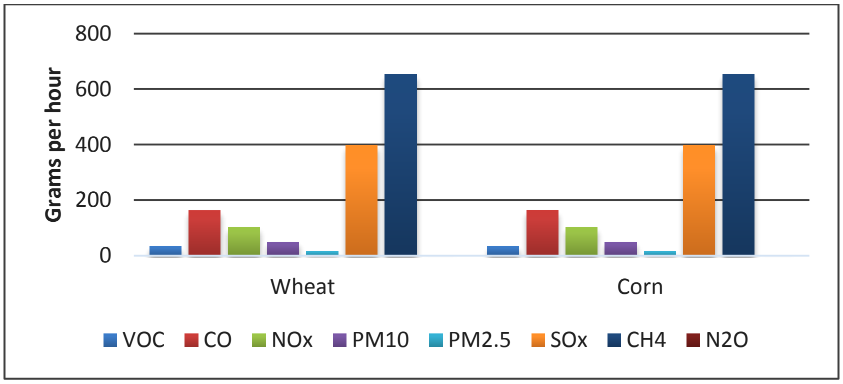


Figure 4.31 Grams per Hour Emissions Output of Single Pass Harvest of Wheat and Corn - Includes Equipment Manufacture and Operation

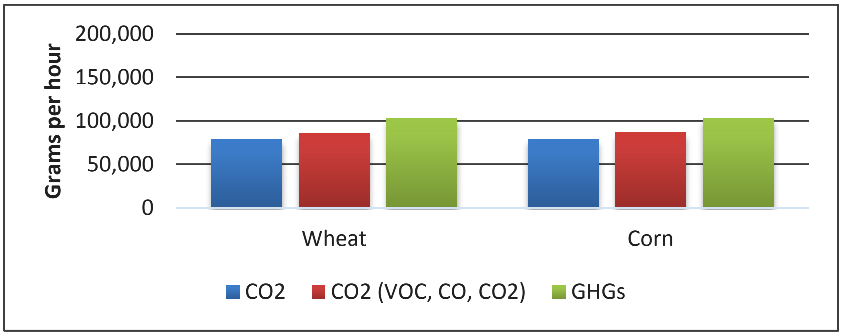


Figure 4.32 Grams per Hour of CO_2, CO_2+Carbon and CO_2 Equivalent GHG from Single Pass Harvest of Wheat and Corn - Includes Equipment Manufacture and Operation

As illustrated in Figures 4.30 - 4.32, both energy use and emissions output are very similar for the single pass harvest processes in both wheat and corn. Fossil fuels dominate the energy use mix, due to the heavy petroleum used (diesel fuel consumption) during the field operations but also an unexpectedly high natural gas usage. The natural gas component was primarily a result of the high twine usage of the baler and the large amount of natural gas energy required to produce the polypropylene based twine. In fact, the baler had greater total energy use as compared to the combine after co-product methods had been applied. Coal comprised a smaller share of the total energy, primarily appearing in the energy use during the equipment manufacturing process but otherwise non-existent for field operations.

Emissions output are also very similar for the two crops. Nitrous oxides emissions are lower as compared with the other emissions for the process, with only 1.55 and 1.56 grams per hour emissions for wheat and corn, respectively. SO_x and methane emissions comprise the majority of non-CO_2 emissions, with 400 grams per hour SO_x emitted and 650 grams per hour of methane emitted. CO_2 was the primary GHG emitted and represented the bulk of emissions for the process, being greater than a factor of 10 as compared to the other emissions of the process. Total equivalent GHG's were approximately 103,000 grams per hour for both wheat straw and corn stover processes.

4.6 Double Pass Harvest

Double pass harvesting involved the TG 305 tractor and the baler. The combine operation for grain harvest was not considered due to the assumption that grain harvest would occur regardless of biomass harvest. However, the energy and emissions from combine operation alone is detailed in Section 4.9 for comparison purposes.

For the double pass harvesting step, both wheat straw and corn stover are assumed to have the same energy use and emissions outputs. In reality there would be slight differences in the process energy and emissions for each crop due to the differing densities, biomass per hectare, fuel consumption, etc. The results for energy use and emissions output are shown in Figure 4.33, Figure 4.34 and Figure 4.35, respectively.

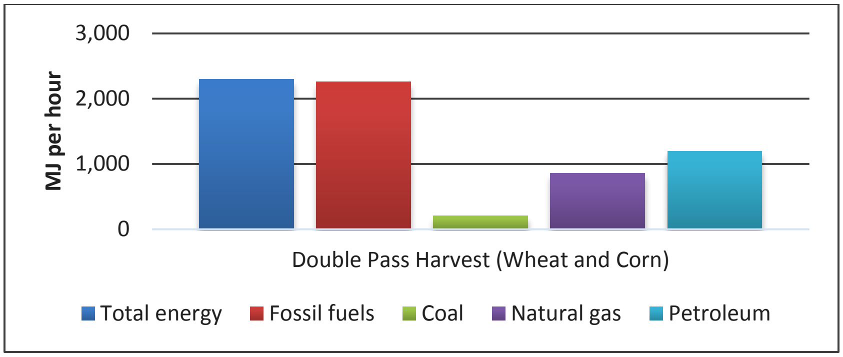


Figure 4.33 Energy Use of Double Pass Harvest - Includes Equipment Manufacture and Operation

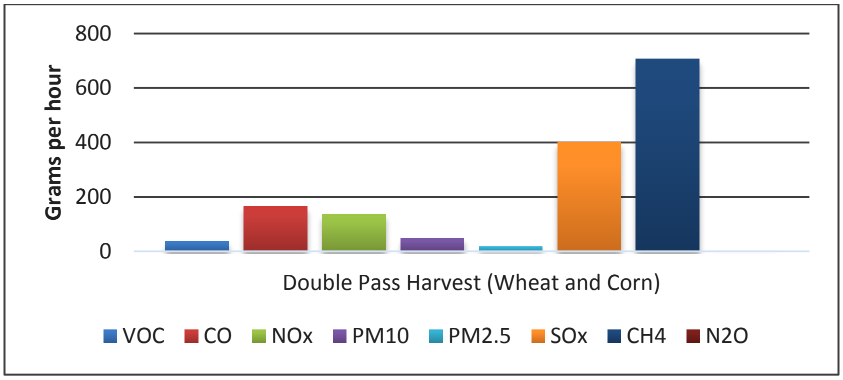


Figure 4.34 Grams per Hour Emissions Output of Double Pass Harvest - Includes Equipment Manufacture and Operation

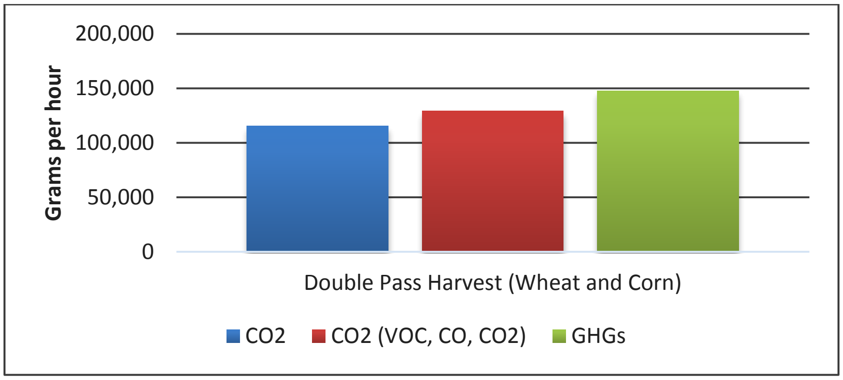


Figure 4.35 Grams per Hour of CO_2, CO_2+Carbon and CO_2 Equivalent GHG from Double Pass Harvest - Includes Equipment Manufacture and Operation

As illustrated in Figures 4.33 – 4.35, Total Energy of the process is 2300 MJ per hour and is comprised primarily of fossil fuels. Petroleum energy is higher than that of natural gas, which is opposite than what was seen in the single pass harvest process. This is primarily due to the higher fuel consumption (and thus petroleum use) of the tractor as compared with the biomass co-product share of the combine. The natural gas energy still comprised a large share of the fossil fuel energy, again due to the high twine usage rate of the baler and the large share of natural gas used in the production of twine. The baler operation contributed the highest total energy use during the process (1055 MJ per hour), slightly greater than the fuel consumption of the TG305 Tractor (1034 MJ per hour).

Emissions output of nitrous oxides are again very low as compared with the other emissions, at 2.42 grams per hour. CO2 and GHG emissions comprised 115,500 and 147,485 grams per hour, respectively.

In comparing the results to single pass harvest, very similar overall trends are shown, however an increase in energy and emissions for the double pass harvest process is present. Section 4.7 details this difference further.

4.7 Single Pass versus Double Pass Harvesting

A critical process difference exists between single pass harvesting versus double pass harvesting. In fact, Objective 3 of the project is to simply understand this difference. While the end result may not influence a producer’s primary decision making in selecting the single pass or double pass method, the energy and emissions results do change depending on the method selected. This could have implications when applying the results on a larger scale. The results for the wheat and corn crops are reviewed below.

The total energy for single pass harvest in both wheat and corn had a lower mean energy and tighter standard deviation as compared to double pass harvest, as illustrated in Figure 4.36. In some simulations, double pass harvesting actually has a lower energy value than single pass, which is to be expected based on the inherent variation assumed in the process. In simple terms, there is overlap in the probability distributions. In the vast majority of simulations, however, the single pass harvesting process shows a slightly lower energy consumption than double pass.

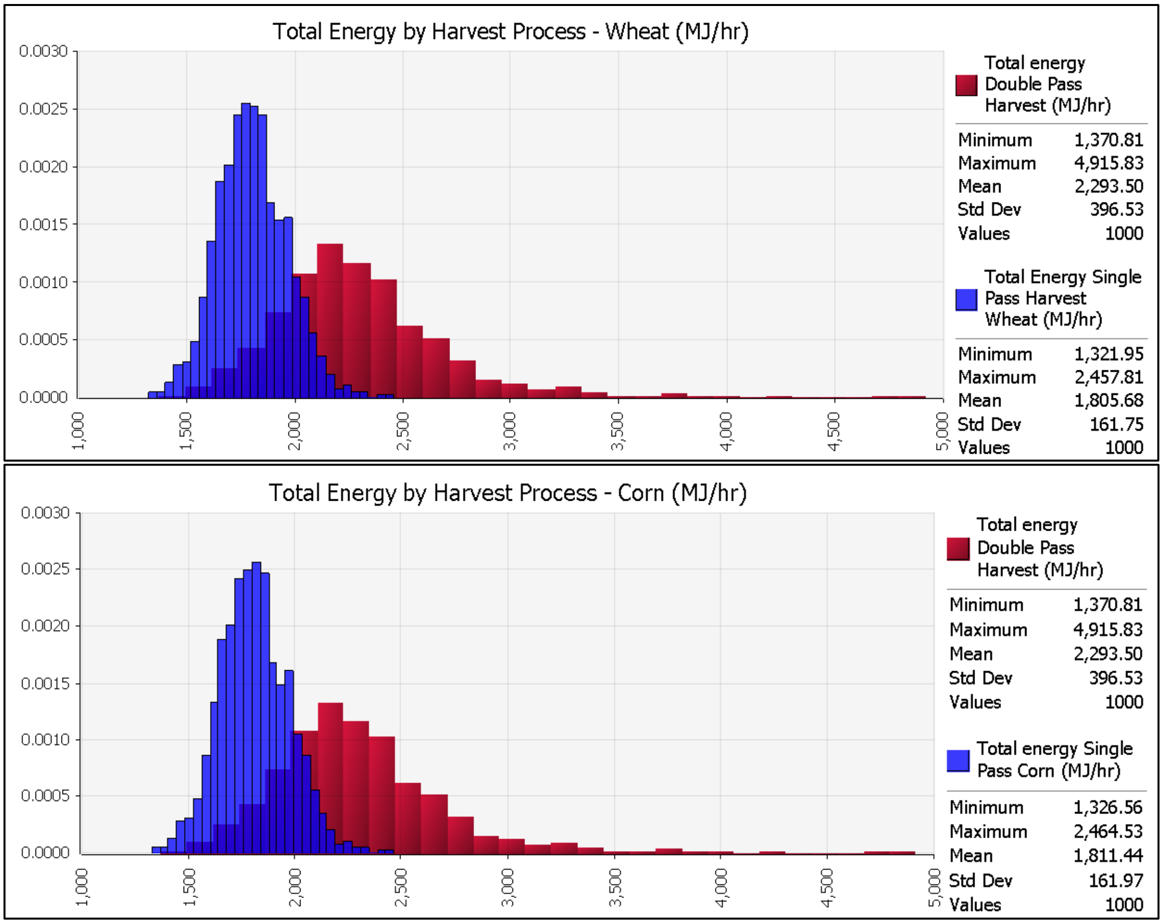


Figure 4.36 Total Energy by Harvest Process – Wheat and Corn Crops - Includes Equipment Manufacture and Operation

GHG emissions output of the model shows that single pass harvesting also has lower emissions than double pass harvesting, with both having a lower mean and tighter standard deviation (Figure 4.37). Again, curve overlap is present showing that in optimal conditions GHG emissions could actually be lower with double pass harvesting, but in the majority of simulations single pass harvest emits fewer GHG emissions than double pass. Both wheat and corn crops show very similar results, which is to be expected since very minor differences exist in the fuel consumption differences of the combine in both crops.

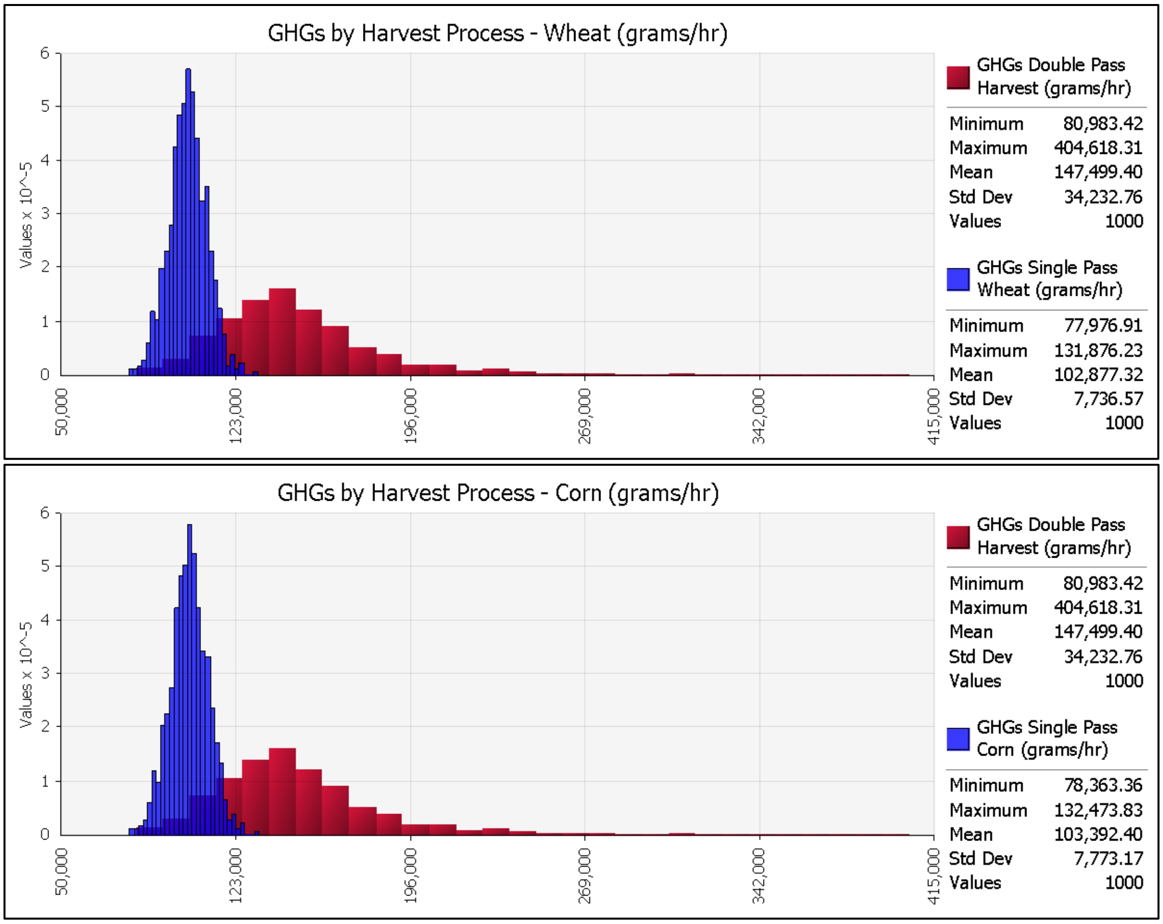


Figure 4.37 GHG Emissions by Harvest Process – Wheat and Corn Crops - Includes Equipment Manufacture and Operation

Co-product allocation methods are critical when comparing the two processes. While the above results utilize the fuel consumption method of co-product allocation, if one were to select a different method such as mass based, the end result would change. In mass based allocation, single pass harvesting has higher average total energy and GHG emissions than double pass. For practical purposes, there is not a large difference between single pass and double pass harvesting LCA results.

4.7.1 *Energy and Emissions per Area*

Since the speed of the tractor in double pass harvesting is greater than the combine in single pass harvest, evaluating the differences of the two processes on an hourly rate can be slightly misrepresentative since the biomass throughput is different. In other words, more biomass can be processed per hour in double pass operation than in single pass. For this reason it is helpful to compare single pass and double pass harvesting on a per area basis. Utilizing the field data of the TG305 tractor and combine, the total energy and emissions "per hour" can be converted to "per hectare." Comparison results for total energy and GHG emissions in wheat straw and corn stover are shown in Figure 4.38 and Figure 4.39.

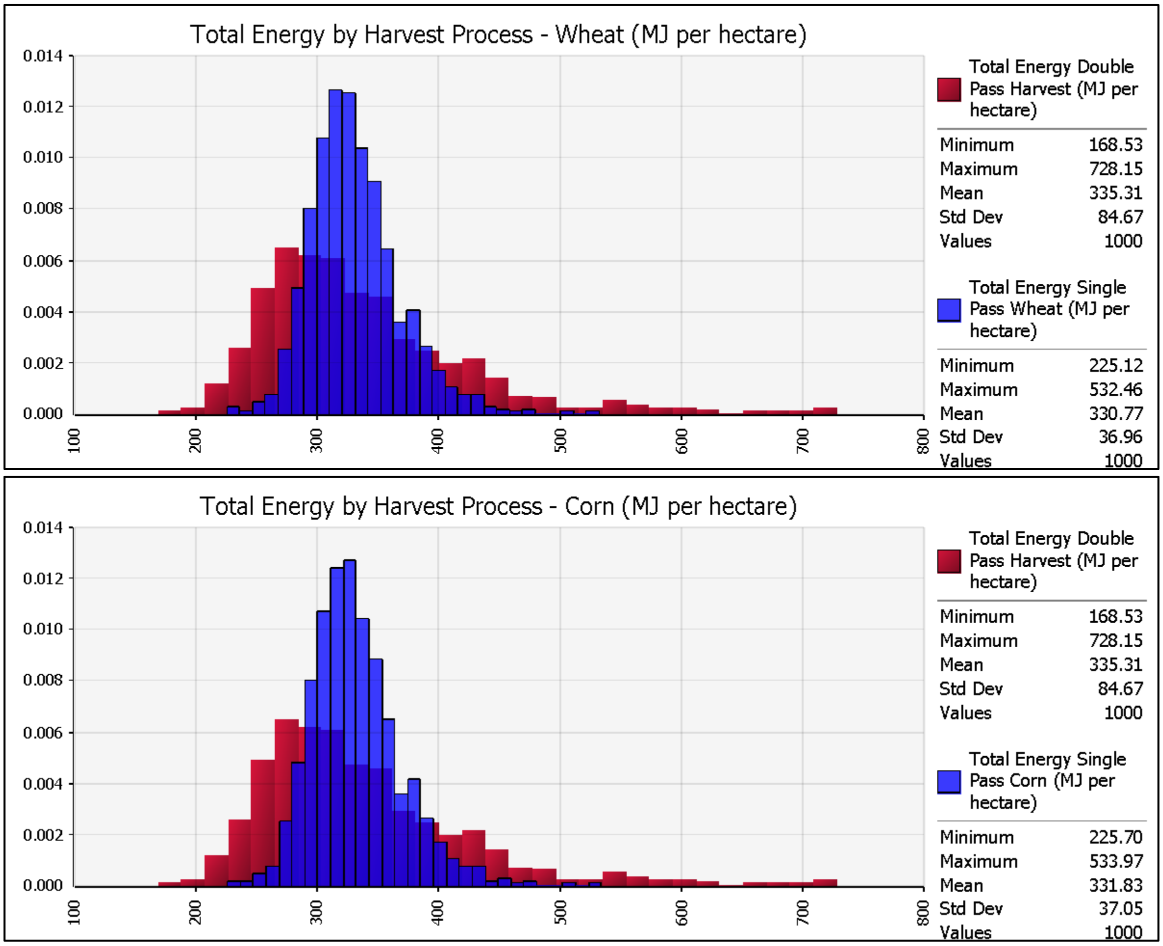


Figure 4.38 Total Energy per Hectare by Harvest Process – Wheat and Corn Crops - Includes Equipment Manufacture and Operation

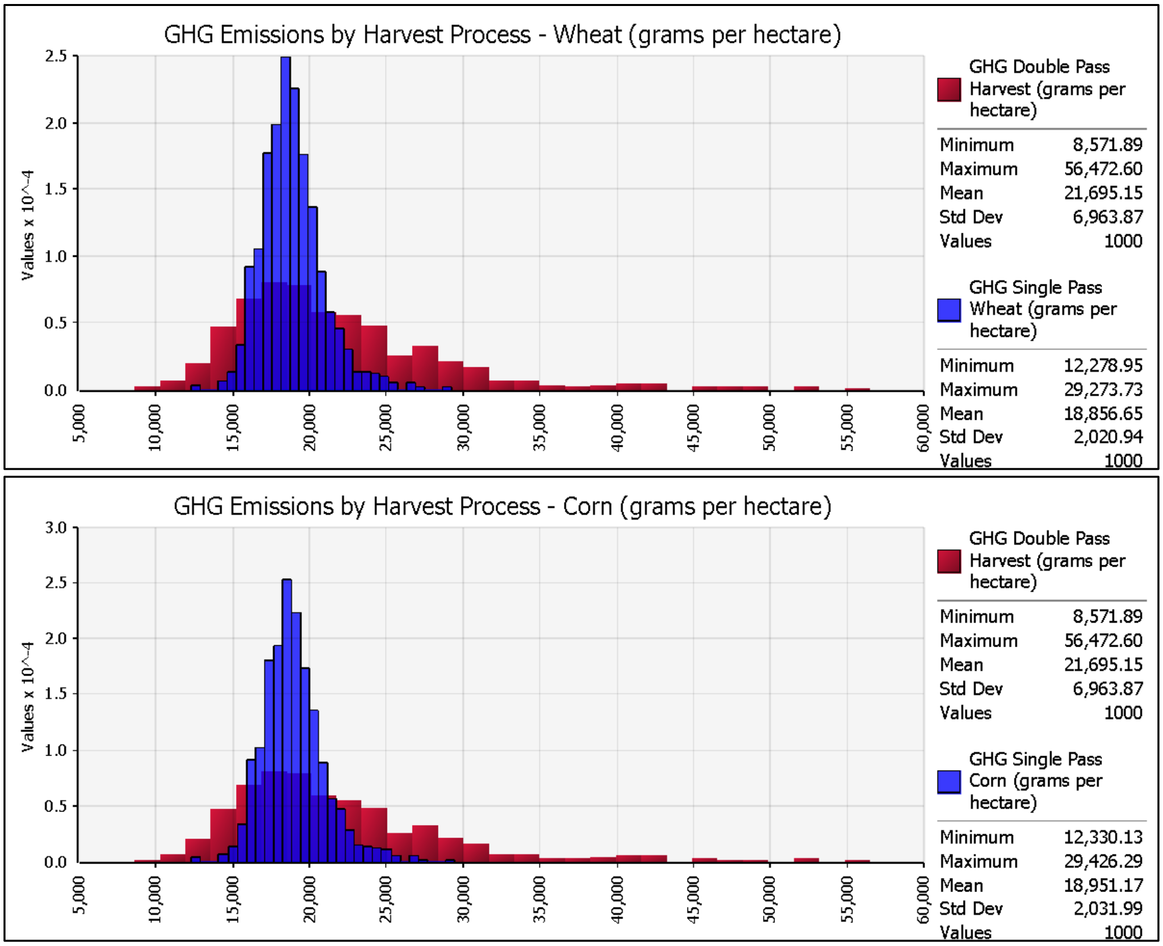


Figure 4.39 GHG Emissions per Hectare by Harvest Process – Wheat and Corn Crops - Includes Equipment Manufacture and Operation

Illustrated in the figures, there is little difference in the means of total energy between single pass and double pass harvest when they are compared on a per hectare basis. However, the standard deviation of double pass is roughly twice that of single pass harvesting. Similar trends exist in the GHG emissions when single pass and double pass harvest are compared on a per hectare basis, with means of single pass harvesting still slightly lower than double pass, and with double pass having more than twice the variation.

Comparing the LCA results on a per area basis provides another insight into the energy and emissions difference between single pass and double pass harvesting. The end result being that, on average, there is practically no difference in the results, however the difference in variation between both processes was similar compared to the hourly rate results.

4.8 Transport to the Processing Facility

Transport from the field to the processing facility is the final step in producing a bale of wheat straw or corn stover ready to be stored and converted into biofuel. The Puma Tractor and Semi are the equipment used in this process. Similar to double pass harvesting, the energy use and emissions of transporting wheat straw and corn stover are assumed to be the same. While minor differences still exist in the crops, this is primarily a result of the differing biomass yields of the crops, and thus the different weight of the bales and distance between bales. Section 4.9 below analyzes the results per kilogram of biomass to gain insight in the differences in the crops. Figure 4.40, Figure 4.41 and Figure 4.42 show the results of the process, per hour of operation.

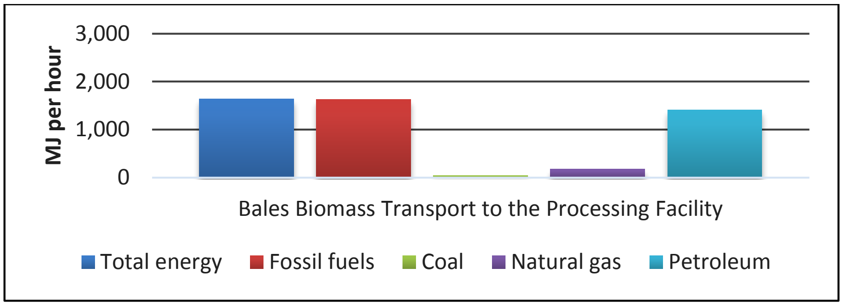


Figure 4.40 Energy Use during Transport - Includes Equipment Manufacture and Operation

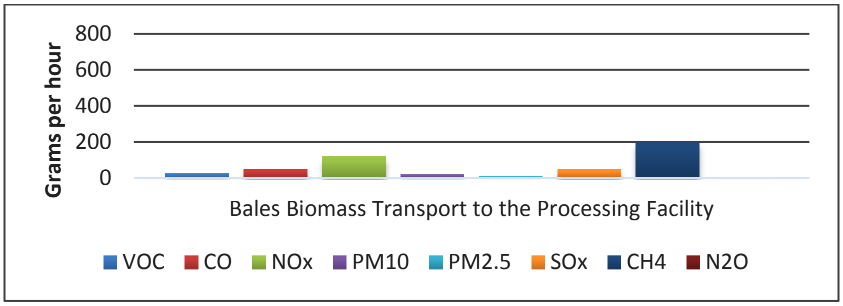


Figure 4.41 Grams per Hour Emissions Output during Transport - Includes Equipment Manufacture and Operation

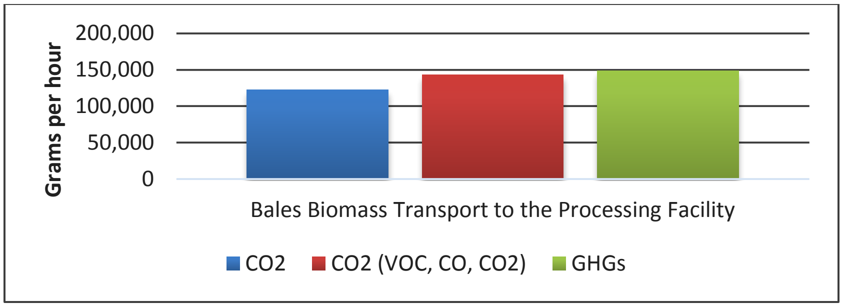


Figure 4.42 Grams per Hour of CO_2, CO_2+Carbon and CO_2 Equivalent GHG during Transport - Includes Equipment Manufacture and Operation

Reviewing the stochastic results for Total Energy and GHG Emissions for the transport process yields Figure 4.43 and Figure 4.44.

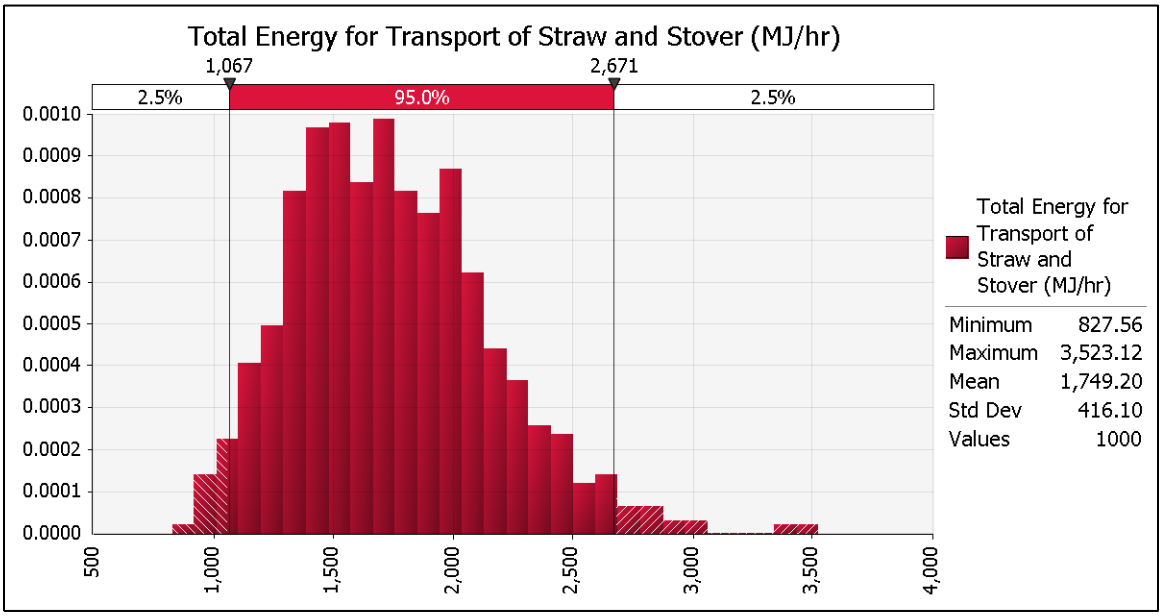


Figure 4.43 Stochastic Analysis for Total Energy Use during Transport - Includes Equipment Manufacture and Operation

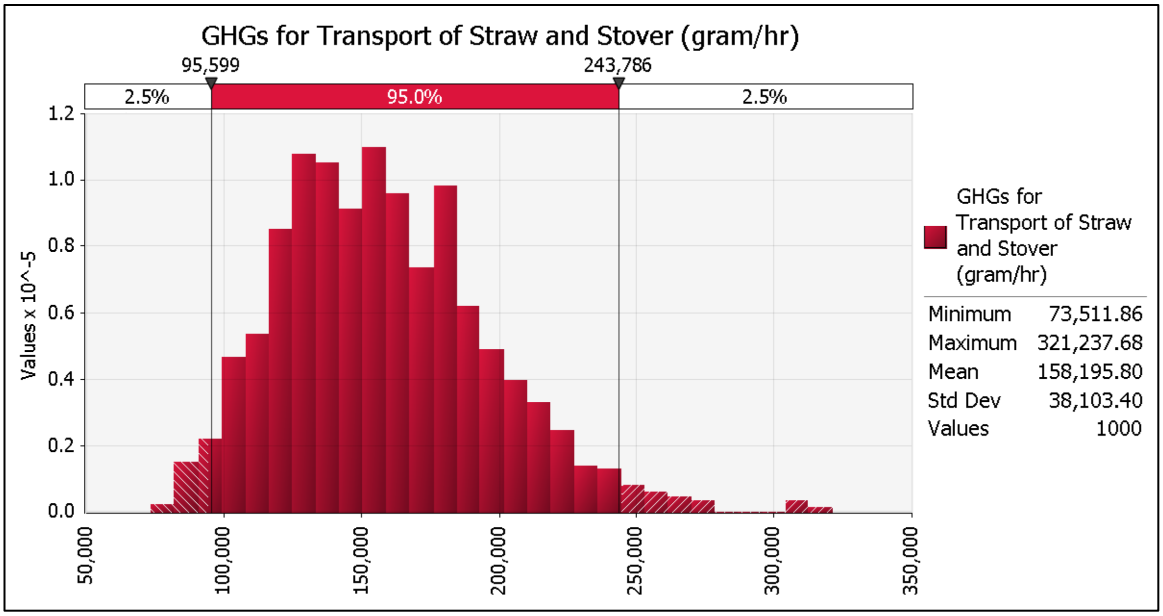


Figure 4.44 Stochastic Analysis for GHG Emissions during Transport - Includes Equipment Manufacture and Operation

Reviewing the total energy and emissions resulting from the transportation of the biomass to the processing facility, total energy has a mean of 1,749 MJ per hour and GHGs have a mean of 158,200 grams per hour. A longer tail to the right of the distributions indicates the potential for even greater energy use or emissions if the transportation speed or fuel consumption of the Puma tractor or Semi was on the high end. Figure 4.45 depicts the tornado graph for Total Energy showing the regression coefficients of the inputs with the most significant results.

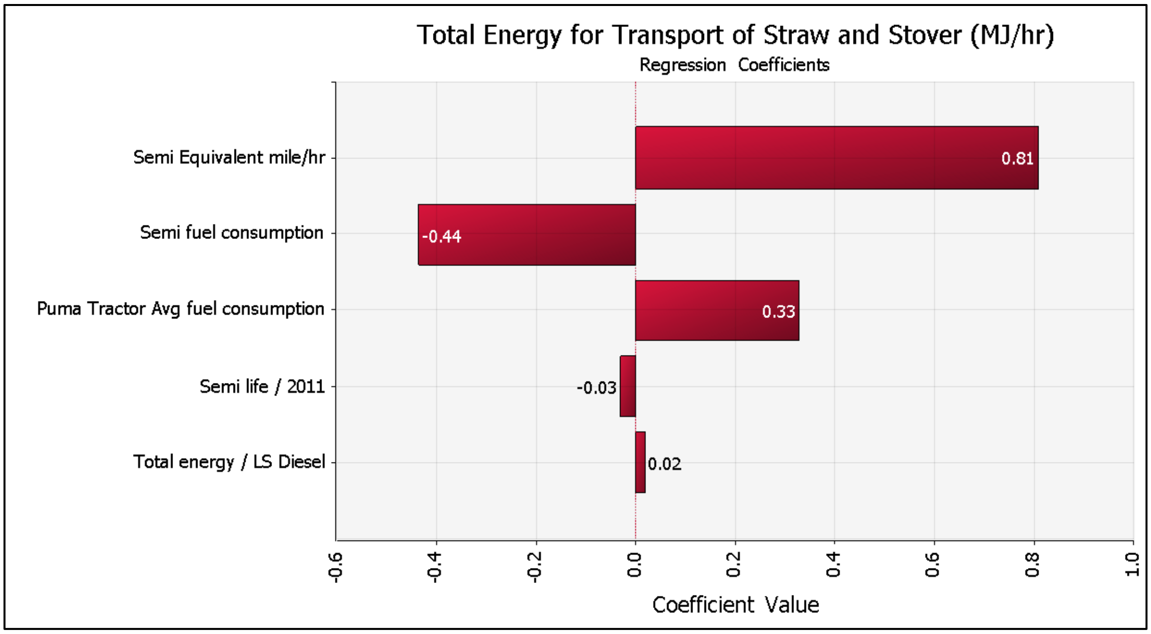


Figure 4.45 Tornado Regression Coefficient Graph of the Significant Inputs of the Transportation Process - Includes Equipment Manufacture and Operation

4.9 Life Cycle Impact Assessment

Having reviewed the individual equipment and process steps that make up the biomass harvest process as a whole, the process steps are now combined to evaluate the total life cycle impact assessment. The combined results are reviewed, as well as a comparison to normal grain harvest. This comparison serves to provide perspective on the energy and emissions of biomass harvest as compared to the standard practice of grain harvest as it exists today, which adds practical insight to the LCA results.

4.9.1 *Total Process Energy and Emissions Result*

The LCA results of each critical process step (Double Pass Harvest, Single Pass Harvest, and Transportation) as well as the totals when adding each step together are given in Table 4.4 for wheat and Table 4.5 for corn.

Table 4.4 LCA Results by Process and Totals for Wheat Straw

	Double Pass	**Single Pass**	**Transport**	**Total Double Pass**	**Total Single Pass**
Energy use: MJ per hour					
Total energy	2,293	1,805	1,645	**3,938**	**3,450**
Fossil fuels	2,255	1,767	1,635	**3,891**	**3,402**
Coal	202.2	210.9	49.6	**251.8**	**260.5**
Natural gas	857.4	814.5	177.9	**1,035**	**992.4**
Petroleum	1,196	741.2	1,408	**2,603**	**2,149**
Total Emissions: grams per hour					
VOC	39.5	34.9	23.9	**63.4**	**58.8**
CO	167.5	163.7	48.7	**216.2**	**212.4**
NOx	137.7	103.1	118.6	**256.3**	**221.7**
PM10	50.2	49.8	19.2	**19.2**	**69.0**
PM2.5	18.7	17.5	9.5	**9.5**	**27.1**
SOx	401.9	397.6	49.2	**451.1**	**446.8**
CH4	706.5	652.7	198.8	**905.2**	**851.5**
N2O	2.4	1.6	2.8	**5.2**	**4.4**
CO2	115,509	78,952	122,605	**238,114**	**201,558**
CO2 (VOC, CO, CO2)	129,103	86,052	142,848	**271,951**	**228,901**
GHGs	147,484	102,834	148,652	**296,136**	**251,486**

Table 4.5 LCA Results by Process and Totals for Corn Stover

	Double Pass	**Single Pass**	**Transport**	**Total Double Pass**	**Total Single Pass**
Energy use: MJ per hour					
Total energy	2,293	1,811	1,645	**3,938**	**3,456**
Fossil fuels	2,255	1,772	1,635	**3,891**	**3,407**
Coal	202.2	211.3	49.6	**251.8**	**260.9**
Natural gas	857.4	815.2	177.9	**1,035**	**993.1**
Petroleum	1,196	745.8	1,408	**2,603**	**2,153**
Total Emissions: grams per hour					
VOC	39.5	35.0	23.9	**63.4**	**58.9**
CO	167.5	164.0	48.7	**216.2**	**212.7**
NOx	137.7	103.5	118.6	**256.3**	**222.1**
PM10	50.2	49.9	19.2	**19.2**	**69.1**
PM2.5	18.7	17.6	9.5	**9.5**	**27.1**
SOx	401.9	397.9	49.2	**451.1**	**447.1**
CH4	706.5	653.5	198.8	**905.2**	**852.2**
N2O	2.4	1.6	2.8	**5.2**	**4.4**
CO2	115,509	79,380	122,605	**238,114**	**201,985**
CO2 (VOC, CO, CO2)	129,103	86,546	142,848	**271,951**	**229,394**
GHGs	147,484	103,349	148,652	**296,136**	**252,001**

When evaluating the life cycle results of each individual process, the double pass harvest process represents the highest energy consumption per hour, however the transport from the field to the processing site represents the largest emission source. The baler primarily accounts for the higher total energy during double pass harvesting as compared to transportation, since the twine usage contributes a higher energy percentage but relatively low emissions as compared to that emitted during fuel combustion. Total life cycle impact for double pass harvest is shown to be higher than for single pass harvest, for both total energy and GHG emissions in wheat straw and corn stover. Figure 4.46 and Figure 4.47 show the stochastic results for wheat straw by process step and also the total per process for Total Energy and GHG emissions, respectively. The corn stover process had very similar results.

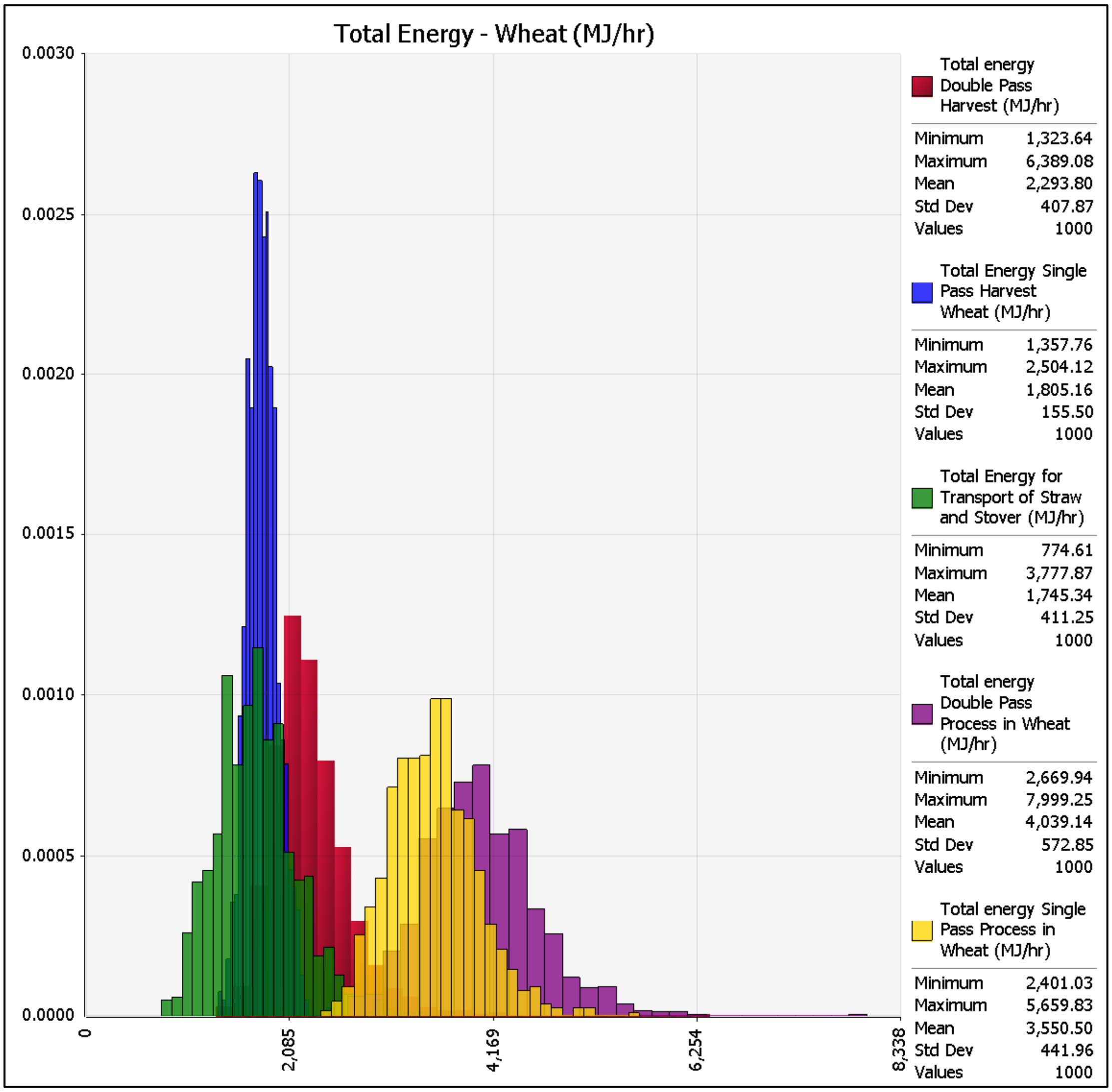


Figure 4.46 Stochastic Results for Total Energy for the Process - Includes Equipment Manufacture and Operation

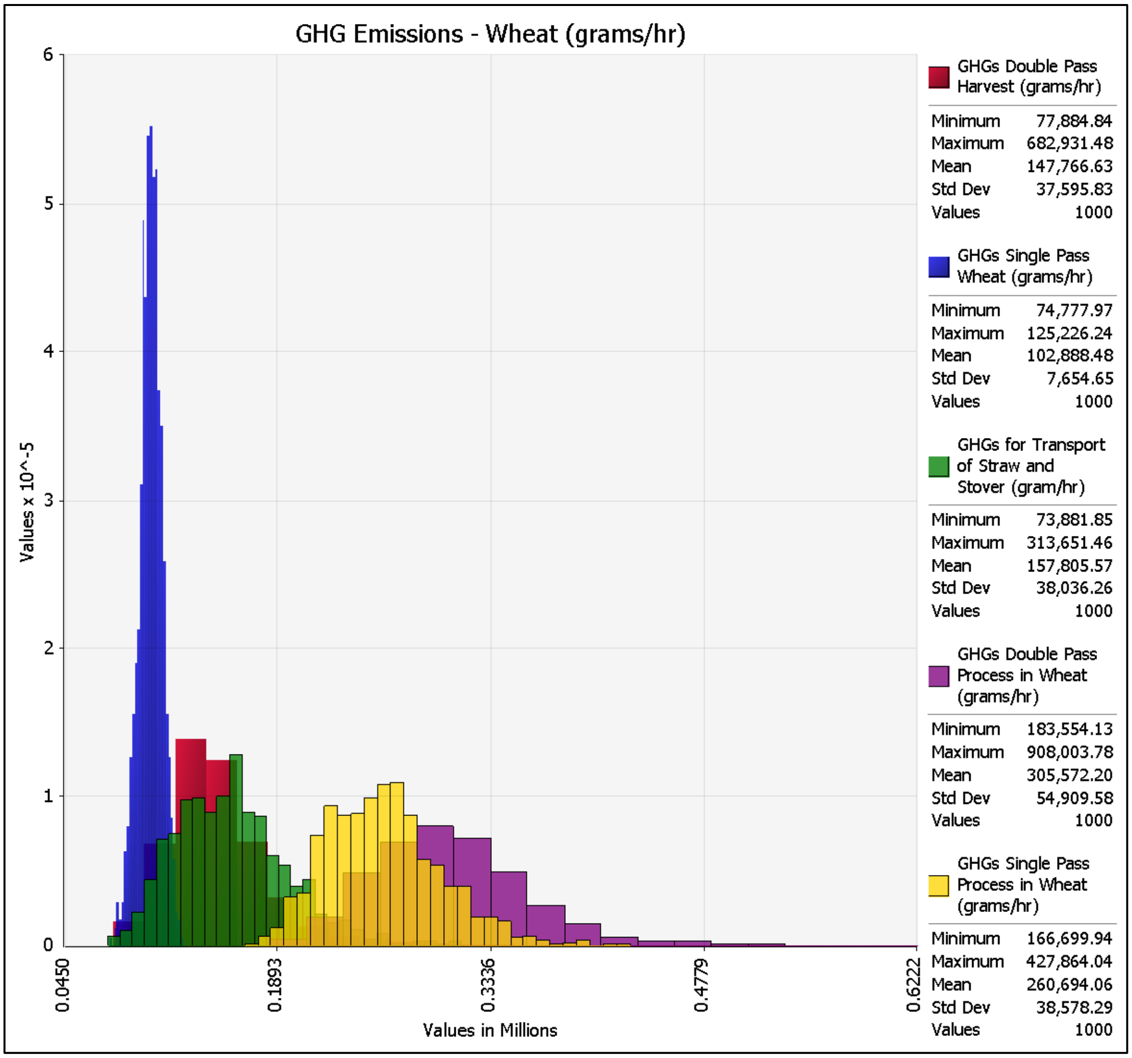


Figure 4.47 Stochastic Results for GHG Emissions for the Process - Includes Equipment Manufacture and Operation

While evaluating the energy and emissions results between process steps on an hourly basis provides an equal and consistent comparison, in reality there are differences in total processing time between the individual processes. Therefore, the LCA evaluation of the rates provides one insight into the energy and emissions of the process, and future studies could tally the time in each process step to determine the energy and emissions total of each process step.

4.9.2 *Total Energy and Emissions Difference as Compared to Traditional Grain Harvesting Alone*

Utilizing co-product methods to separate the energy and emissions of the combine attributed to biomass harvest satisfies the primary objectives of the project; however, it is also interesting to review the energy and emissions results of the combine in conventional harvest since the results are readily available after applying the co-product methods. Comparing the results of the combine in conventional harvest gives perspective to the biomass harvest results. In other words, how much more energy is needed or emissions produced as compared to the normal process of grain harvest can be determined. Results for Total Energy and GHG Emissions are illustrated in Figure 4.48 and Figure 4.49 below. Again, corn stover produced very similar overall results as wheat straw.

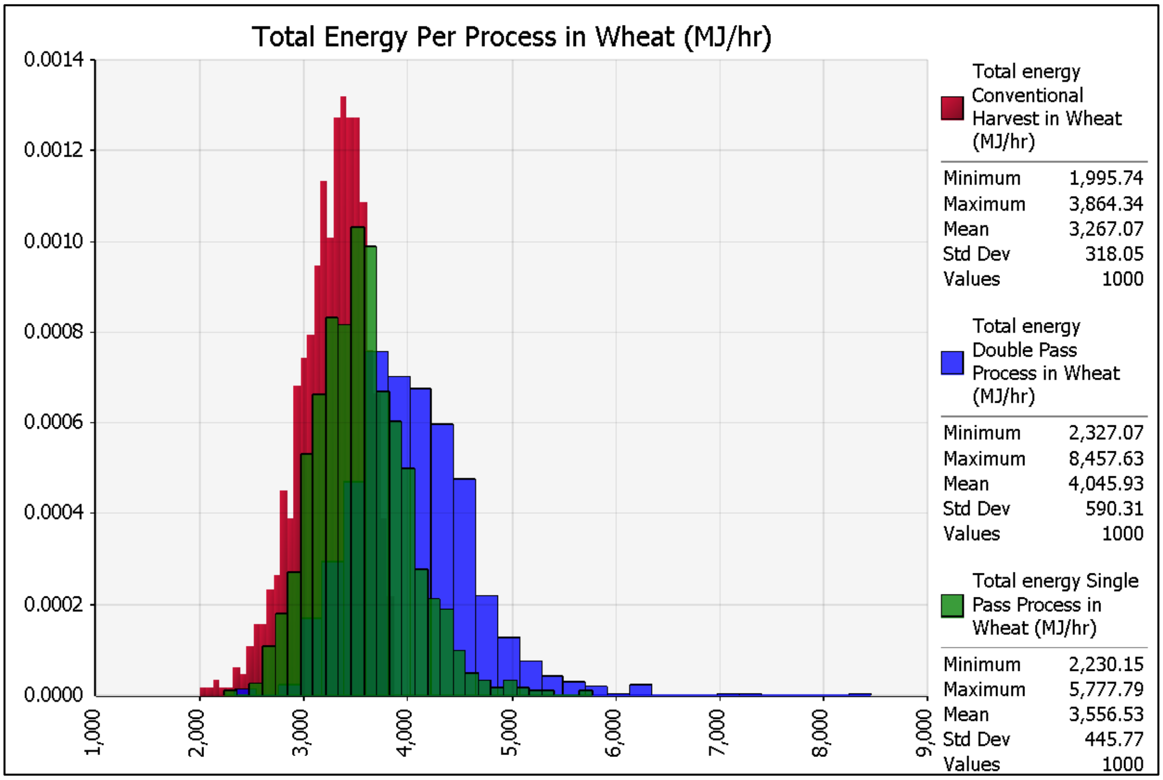


Figure 4.48 Total Energy per Process as Compared to Conventional Grain Harvest - Includes Equipment Manufacture and Operation

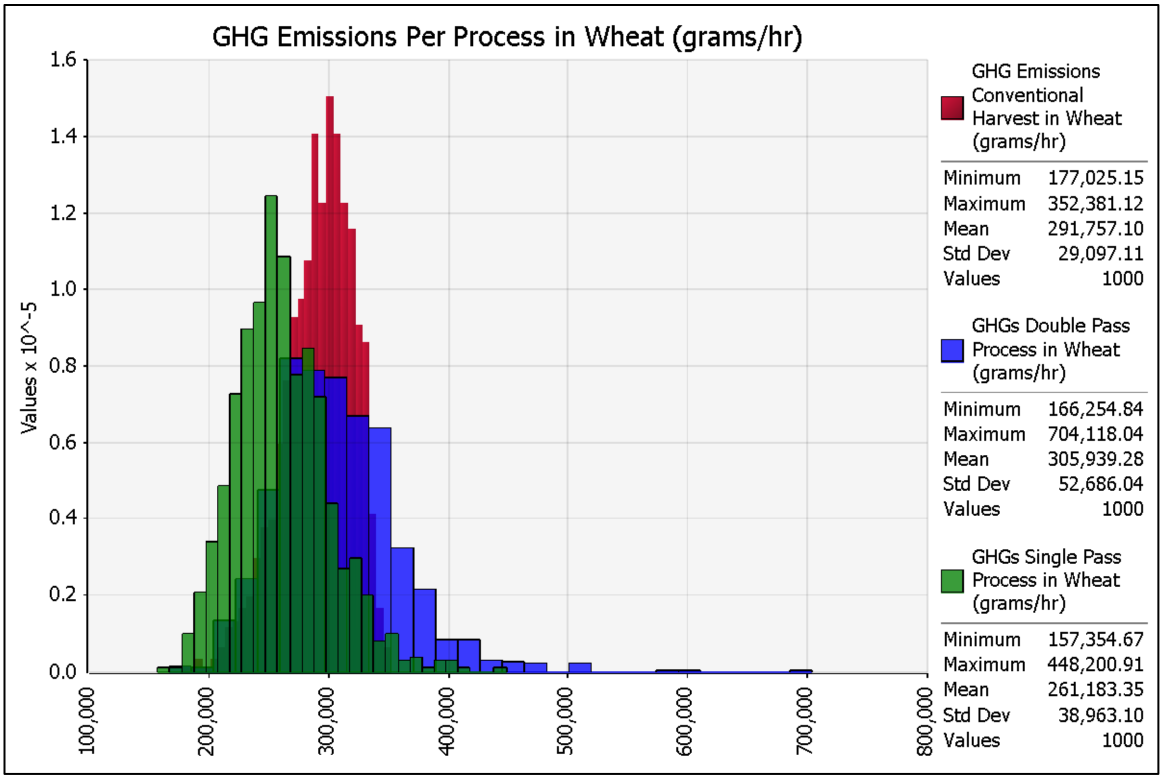


Figure 4.49 GHG Emissions per Process as Compared to Conventional Grain Harvest - Includes Equipment Manufacture and Operation

As illustrated in the figures, total energy and GHG emissions of the conventional harvest alone are approximately equivalent to that of both double pass and single pass harvesting of biomass. Therefore, adding the biomass harvesting process to the grain harvest more or less doubles the energy used and emissions released than would have normally been the case for grain harvest alone.

CHAPTER 5 : SUMMARY AND CONCLUSIONS

As part of the USDA-BRDI *On-Farm Biomass Processing: Towards an Integrated High Solids Transporting/Storing/Processing System* project, the primary goal of this thesis was to evaluate the energy consumed and emissions produced during the Feedstocks Development phase of the project. More specifically, the harvest and transport of the agricultural residues wheat straw and corn stover were investigated. A life cycle assessment (LCA) approach was utilized since the method takes a holistic accounting of the energy inputs and emissions outputs of every aspect of the process. To achieve the goal of the project, three specific objectives were developed:

1. Develop a comprehensive LCA model of the agricultural residue collection process
2. Utilize stochastic simulation to improve model robustness
3. Evaluate the specific energy input and environmental emission differences between single pass and double pass harvesting

Several methods of conducting the LCA were evaluated. While many commercially available LCA software packages and databases were considered, a Microsoft Excel model was developed due to the transparency in data input and calculation. The specific process steps evaluated were: fertilizer addition, single pass harvest, double pass harvest, and transport to the processing facility. Only the inputs or process steps for biomass collection that were above and beyond normal grain harvest were considered, since grain harvest was assumed to the be primary product of the process.

While the process steps to harvest and transport the agricultural residues were few, the inputs into the LCA model were enormous. Argonne National Laboratory's GREET model provided an excellent data framework that was used in the model and provided much of the input data referenced to form the energy and emissions impact of the agricultural machinery manufacture. The equipment used in the various process steps included in the model were: CaseIH Puma 160 Tractor, New Holland TG305 Tractor, CaseIH 9120 combine, CaseIH LB433 Baler, and Volvo VN Series Semi. The combine exhibited the greatest energy used (1,343,400 MJ) and emitted emissions (98,751,000 grams of CO2 equivalent greenhouse gas emissions (GHG)) during manufacture of all the equipment. This was primarily due to its heavier weight and thus correspondingly more energy needed and emissions produced during the raw material acquisition and combine assembly. Since fluid changes over the life of the equipment were included as part of the equipment manufacture, the TG305 tractor exhibited the largest energy use and emissions output in the fluids category, 157,430 MJ and 9,904,000 grams GHG emissions, respectively. This was due to the longer estimated tractor life and larger number of manufacturer recommended fluid service changes.

Since the agricultural machinery used in the process is typically used for many other functions on farm, the functional units of MJ per hour energy use and grams per hour emissions were selected for the LCA. Therefore, the large energy and emissions impact during equipment manufacture were normalized over the life of the equipment. When compared to in-field equipment operation, the normalized energy and emissions from equipment manufacture was less than 20% of the total (in fact, it generally comprised less than 10% of the energy and emissions total). Therefore, hourly field operation of the equipment had a much higher impact on energy use and emissions output than the equipment manufacture when spread out over the life of the equipment.

When analyzing the in-field operational results of the equipment, fuel consumption was the single most contributing factor to both the overall energy and emissions of the equipment. Since the baler had no fuel consumption of its own, the twine usage was the most significant input. Surprisingly, the large amount of twine used in the process (1430 meters per hour) and the energy intensive process of producing the polypropylene based twine made the baler operation a larger energy user than all other equipment other than the combine.

To address the uncertainty in the model, stochastic simulation was incorporated by utilizing the @Risk software. Since field operations were determined to be the most significant inputs, field data was incorporated into the model via distribution fitting functions of @Risk; and Monte Carlo techniques were used to simulate hundreds of data output scenarios to address the various uncertainties of the inputs. While the mean or average results of the stochastic analysis were generally close to the point values used in the model, the stochastic analysis clearly illustrated the large amount of variation present in all of the process steps.

The functional unit of MJ per hour energy use and grams per hour emissions eliminated most of the co-product issues that arise in LCA practice, except for the combine in single pass harvesting. To separate the energy and emissions of the combine to that which should be attributed to grain harvest and biomass harvest, several methods of co-product allocation were evaluated. This included a market based, mass based, and process-purpose based allocation of fuel consumption difference in single pass operation versus conventional combine operation. The fuel consumption allocation method was chosen as the most applicable to the process, and represented a balanced result as compared to the market based and mass based methods.

After utilizing the fuel consumption co-product allocation method, single pass harvesting is shown to have lower overall energy consumption and greenhouse gas emissions per hour than double pass harvesting in both wheat and corn crops. Choice of co-product allocation method was critical in this comparison, when utilizing the mass based allocation method the results were reversed. Since there are different biomass throughput rates in double pass versus single pass harvesting, a per hectare comparison provided additional insight into the processes. Evaluating the energy and emissions of the two processes per hectare showed practically no difference in the average stochastic results, although the double pass harvest exhibited twice the variation as compared to single pass harvest.

Of the process steps to produce baled biomass, transportation from the field to the processing facility was determined to have the lowest energy impact, with a mean of 1,645 MJ per hour as compared to 2,293 MJ per hour in double pass harvest, 1,805 MJ per hour in single pass wheat and 1,810 MJ per hour in single pass corn. These results were due to the higher energy use of the baler (twine) in single pass or double pass operation as compared to transport. The results were reversed however for GHG emissions, where emissions were the lowest in single pass harvesting (102,830 grams/hour in wheat, 103,350 grams/hour in corn), followed by double pass harvest (147,480 gram/hour) and then transport (148,650 grams/hour). In short, the energy in baling twine caused the harvest operations to have a larger energy impact, while the lower emissions of twine as compared to the fuel consumption of both the tractor and semi in transport was cause for the transport step to emit a greater amount of GHG emissions.

The additional fertilizer required to replace that which is lost through the biomass was low as compared to typical field fertilization levels. However, since the process to produce fertilizer is very energy intense, the per hectare total energy results were comparable to that of the harvest operations. Phosphorus results were 157 and 210 MJ/hectare in wheat and corn, respectively. Potassium additions contributed 277 MJ/hectare in wheat and 307 MJ/hectare in corn. This is compared to 322 MJ/hectare in double pass operation and 329 and 330 MJ/hectare in single pass wheat and corn, respectively. GHG emissions of the fertilizer addition were negligible, however.

It is clear in the LCA that fossil fuels dominate as the energy source for the process. The single greatest factor in all simulations of the model is the fuel consumed by the machinery. Although renewable energies such as wind and solar power will help decrease energy use during the equipment manufacturing process, the LCA shows that, for mobile equipment, the manufacturing component represents a relatively small portion of the total energy and emissions over the equipment life. Therefore, to help reduce the fossil fuel use of mobile equipment, it is critical that the biofuels discussed in this paper are incorporated into the process.

While the primary impact categories of this project were energy use and GHG emissions of the process, the LCA produced an enormous amount of data to which many other comparisons and conclusions could be ascertained. Many of the individual emission components were briefly reviewed, but could represent major impacts to certain environmental metrics. The results of this LCA could be utilized for many other comparisons or as input into further studies.

CHAPTER 6 : FUTURE WORK

6.1 Particle Size Reduction and Incorporation into *On-farm Biomass Processing* Model

As was mentioned in Chapter 1, this project is a small part of the *On-Farm Biomass Processing* project. Particle size reduction or grinding of the biomass is the next step in the Feedstocks Development phase of the project. While the grinding process was specifically stated to be outside the scope of the project, it is the last highly mechanical step in preparing the biomass for chemical conversion into biofuels and could be easily added to the model. Furthermore, to completely assess the *On-Farm Biomass Processing* life cycle, the LCA results of this project should be combined with that of the Biofuels and Biobased Products Development LCA. This would give a complete understanding of the life cycle impacts of the process.

6.2 Equipment LCA's

One model limitation is the availability of agricultural equipment specific emissions and manufacture data. The GREET models were used extensively as the foundation of the model for this analysis, however where passenger car and light duty truck information is available, large agricultural equipment data was not. The scaling up of the energy and emissions used in this analysis was likely not fully representative of the true energy and emissions of the equipment. Therefore, further work is needed to research and develop true energy and emissions numbers for large agricultural equipment.

6.3 Fertilizer and Land Use Change

Fertilizer addition was expected to increase as a result of the *On-Farm Biomass Processing* process that was covered in the model. While the increase is small compared to normal crop fertilization rates, fertilizer development is energy intensive and will likely not have significant advances in efficiency any time soon. However with the wide spread use of precision agriculture, it is anticipated that field mapping will lead to a more accurate understanding of nutrient loss as well as the ability to put the nutrients back where they are needed. Future work will be needed to refine this LCA to account for this efficiency improvement, as well as consider improvement in crop genetics, etc. Differences in straw and stover collection between single pass and double pass harvesting may contribute to a difference in fertilizer addition that may be worth future investigation.

Land use change and its effect on the environment was not discussed in this project since the agricultural residues are a byproduct of grain production, and millions of acres of ground are already in grain production that could be used as feedstock. However, the number of acres in crop production varies each year depending on market conditions and it is conceivable that an additional market for biofuels from biomass production could lead to more crop acres being planted where they currently are not on some farms. Land use change would be a logical addition to the model in these specialized circumstances.

6.4 Changing Data

Performing a sensitivity analysis on the LCA model shows that machine fuel consumption per hour is a major parameter that impact model results. Although the values used in the analysis are accurate representations of the equipment used in the field, it is expected that future field efficiency improvements will be developed to make the process more efficient. Whether from the use of alternative fuels, lighter weight components or more efficient engines, the model will need to be updated in the future to account for these improvements.

Co-product allocation was another cause for great variation in the model results, and could completely change the results depending on the assumptions used. Since the methods of co-production allocation were derived from market data, mass yield data and fuel consumption differences of the combine, any significant shifts in those data sets will require corresponding updates in the model to determine if they impact the results.

While regularly updating data sets is necessary for any LCA, it is especially important with the above parameters since they heavily influence model results.

APPENDICES

Appendix A. GREET Software Copyright Statement

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model.

Software: GREET 1, Version 2011. Copyright © 1999 UChicago Argonne, LLC

Software: GREET 2, Version 2.7. Copyright © 2007 UChicago Argonne, LLC

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EXPERIENCE

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- Part Time Farming Business, Philpot, KY. May 2011 - Present
- Aftertreatment Integration Senior Engineer, Cummins Inc., Columbus, IN. September 2010 – May 2011.
- Product Engineer/Rapid Problem Solving Team Leader, Cummins Inc., Columbus, IN. July 2008 – September 2010.
- High Horsepower Marine Mechanical Development Internship, Cummins Inc., May 2007 – August 2007
- Undergraduate Research Assistant, Biosystems and Agricultural Engineering Department, University of Kentucky, Lexington, KY. January 2006 – May 2008. Supervisor: Dr. S. A. Shearer.
- Mechanical Engineering Internship, Weyerhaeuser Corporation, Hawesville, KY. May 2005 – August 2005

AWARDS/LICENSURE

- Registered PE since 2012, Kentucky #29097
- Certified Energy Manager since 2011, #17630
- Six Sigma Green Belt Certification, Cummins Inc. 2010
- New Faces of ASABE recognition, 2013
- UK College of Engineering Commencement Speaker, 2008
- Awarded the Senior Leadership Award and the Maurice A. Clay Award for outstanding graduating senior from the UK College of Engineering for service and achievements in the college, 2008
- Member of senior design project team which placed 3rd in the nation in the ASABE annual competition for the project: “Agricultural Implement Guidance System.” 2008