Life Cycle Analysis of Hybrid Poplar Trees for Cellulosic Ethanol

by

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ABSTRACT

The main purpose of this paper is to assess the energy and environmental benefits of cultivating hybrid poplars as a biomass crop for cellulosic ethanol. A "Life Cycle Assessment" (LCA) methodology is used to systematically evaluate the hybrid poplar's energy input and output as well as greenhouse gas (GHG) emissions. The system boundary is divided into three sections, agriculture, transportation, and ethanol processing. In this LCA, only energy from fossil fuels is accounted for, and only energy yield from ethanol yield is considered. Energy demands and associated emissions for all operations are divided equally over the total biomass harvested over a 10 year timeline.

Ultimately, the net energy ratio, the amount of clean energy produced over the amount of fossil fuels consumed, and the amount of carbon dioxide emitted during the cultivation process is compared to those of current forms of fuel and other renewable resources. The net energy ratio was calculated to be in the range of 5.82 to 8.55, which was found to be higher than both gasoline and corn ethanol. The carbon dioxide emission was calculated to be in the range of 2.42 to 3.55 grams CO_2 per MJ output, and was lower than the net emissions of both gasoline and corn ethanol. However, in comparing to other renewable resources, such as solar and wind, hybrid poplars were evaluated to be less optimal in energy efficiency and GHG emissions.

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List of Acronyms

BFDP	Biofuels Feedstock Development Program
CHP	Combined Heat and Power
DOE	Department of Energy
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
RFS	Renewable Fuel Standard
SRWC	Short Rotation Woody Crops

Chapter 1: Introduction and Background

1.1 Introduction

There is a finite amount of fossil fuels, the world's primary energy source, available on Earth. However, while the world's limited energy resources are diminishing every year, the world's consumption of energy is increasing. Thus the demand for alternatives to fossil fuels is becoming ever more urgent.

Recently, the U.S. government has increased its support on the issues of environmental and energy sustainability. Bush has stated a goal of replacing 75% of Middle East oil imports by 2025 [1]. However, in order to achieve this goal, the U.S. needs to produce more energy locally. Thus, in the search for new sources of renewable clean energy, much focus has been on biomass crops. Biomass energy systems have the potential to not only decrease the nation's dependence on foreign energy supplies, but also mitigate greenhouse gases and support agricultural development opportunities. These biomass crops can be converted into multiple energy and industrial products such as, electricity, heat, chemicals, and fuels. Biomass programs have received much funding from both private and government institutions, and most of the focus has been on producing biomass crops for ethanol, a liquid transportation biofuel.

The U.S. transportation sector consumes about two-thirds of the nation's oil demand, most of which is imported from foreign countries [2]. Consequently, ethanol is an extremely important renewable energy product as it is a safe alternative to standard transportation fuel. Ethanol is currently being produced mostly from corn and sugar, but new technologies have diversified the types of biomass that can be used to produce ethanol. This new form of ethanol, cellulosic ethanol, can be produced from a variety of organic materials, such as agricultural and forestry residues, trees, and grasses. It has a greater potential to reduce greenhouse gas emissions, improve energy security, and become a sustainable form of alternative fuel over the current corn ethanol because it does not release carbon dioxide during the conversion process, produces more ethanol per acre of land, and also does not compete with the food market.

The process for producing cellulosic ethanol is still being refined, but scientists believe in the next decade it will surpass corn ethanol as the leading form of alternative fuel. The U.S. government has announced fiscal support to make cellulosic ethanol production competitive by 2012 [1]. Nevertheless, not only does more research need to go into the processing of cellulosic ethanol, but also research needs to be conducted to ascertain the optimal biomass crops for producing cellulosic ethanol.

The main purpose of this paper is to assess the energy and environmental benefits of growing hybrid poplars as a biomass crop. I will quantify the total fossil fuel used to produce ethanol from hybrid poplars using the "Life Cycle Assessment" (LCA) approach. The final analysis will determine the energy efficiency of cultivating hybrid poplars for cellulosic ethanol.

1.2 Background of Ethanol

1.2.1 Current Market

Many new forms of renewable clean energy have been developing in the past decade, but due to the surge in gasoline prices, ethanol has been receiving the most public attention. Ethanol has been the primary focus of non-foreign energy supply for over 20 years. The demand for ethanol has increased exponentially over the past few years largely as a result of federal and state policies. The ethanol market was most significantly affected by the recent Energy Policy Act of 2005. The bill introduced the Renewable Fuel Standard (RFS), which requires U.S. fuel production to include a minimum amount of renewable fuels each year, starting at 4 billion gallons in 2006 and reaching 7.5 billion gallons by 2012. (Figure 1) The vast majority of the renewable fuel used will be ethanol, resulting in a doubling of the domestic ethanol industry in the next 6 years [2].

The use of ethanol as a clean liquid fuel alternative to fossil fuels, such as gasoline, has been increasing around the world. Ethanol is currently being blended into regular gasoline at different percent mixtures in hopes of eventually replacing gasoline as the primary transportation fuel. In America, the most popular blend is E10, which is a 10% ethanol and 90% gasoline mixture, which all automobiles are able to run on without engine modification. There are also over 4 million flex-fuel vehicles in America that can use E85, an 85% ethanol and 15% gasoline mixture [2].

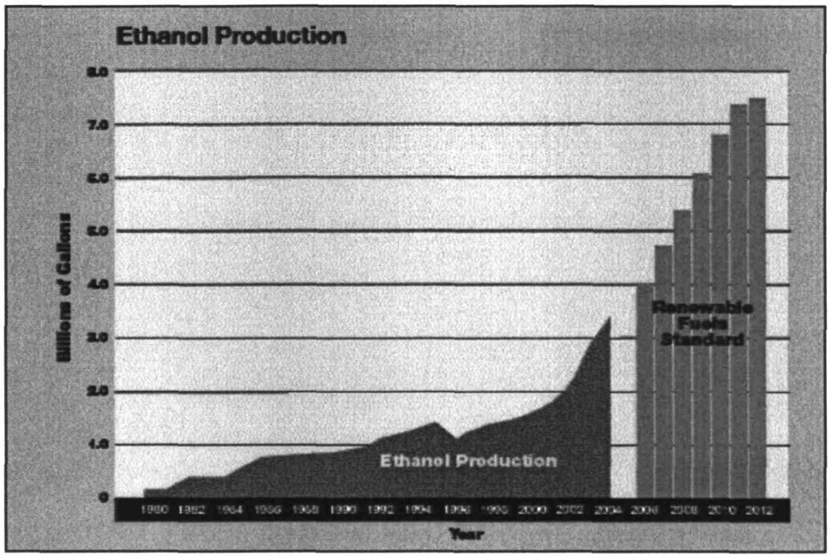

Figure 1: Ethanol Production in the US (Historic and Projected under the RFS) [2].

1.2.2 Ethanol Processing

Worldwide, ethanol is predominately being made from corn and sugar cane. In the U.S. nearly all fuel ethanol is produced from corn; however among the three main types of raw materials used to produce ethanol: sugars, starches, and cellulose, cellulose materials represent the most abundant global source of biomass. As stated in Lin and Tanaka (2005) [3], "The global production of plant biomass, of which over 90% is lignocellulose, amounts to about 200 billion tons per year, where about 8-20 billion tons of the primary biomass remains potentially accessible." The U.S. Department of Energy (DOE) has recently been promoting the development of cellulosic ethanol, as the next feedstock to replace corn.

Cellulosic ethanol's starting raw material is lignocellulose, a complex substrate composed of a mixture of cellulose and hemicellulose and lignin. While sugars can be fermented to ethanol directly with yeast, starches and cellulose must first be hydrolyzed with enzymes (or other forms of processing) into simple sugars before being converted to ethanol [3]. Lin and Tanaka's article illustrates the complex process to produce ethanol from lignocellulosic biomass: delignification to seperate cellulose and hemicellulose from the lignin, depolymerization of the carbohydrate polymers (cellulose and hemicellulose) to produce free sugars, and fermentation of simple sugars to produce ethanol [3]. Figure 2 below illustrates the process.

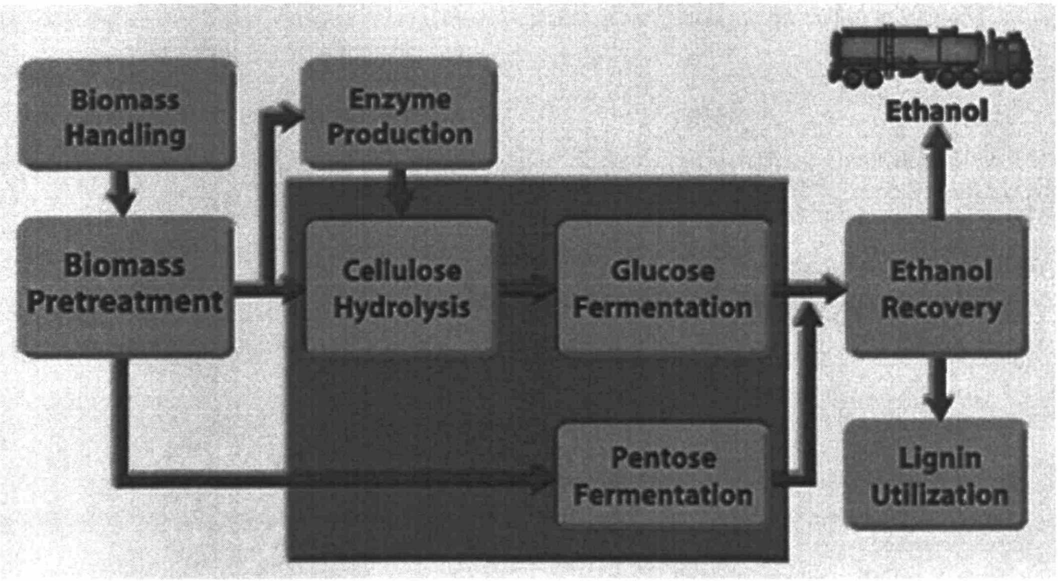

Figure 2: Cellulosic Process Description from U.S. Department of Energy [2].

The first phase, delignification (biomass pretreatment on figure), is the rate-limiting step and the foremost obstacle to widespread cellulosic ethanol commercialization. Private and government studies are currently investigating cost-effective pretreatment technologies to make cellulose in lignocellulosic biomass more accessible for enzymatic hydrolysis. As of yet, various cellulosic ethanol conversion experiments have been successful in laboratories and on a pilot-scale basis, but there has been no full-scale commercialized processing of lignocellulosic biomass to ethanol. [4] In particular, the National Renewable Energy Laboraty (NREL) has been researching the process design and economics of lignocellulosic ethanol plants for the past 20 years in hopes of making cellulosic ethanol economically feasible. [5]

1.2.3 Benefits of Ethanol

Domestic production and use of ethanol as an alternative to fossil fuels can not only decrease dependence on foreign oil, but also help the environment by reducing greenhouse gasses (GHG), and help the agricultural economy. Adding ethanol to petroleum products allows the fuel to combust more completely and this reduces air pollution [2]. When fossil fuels are burned, they release carbon dioxide, which contributes to the buildup of GHG. On the other hand, when biomass energy is burned, those emitted GHGs are not counted, as that GHG had originally been absorbed from the air during plant-growth. According to US Department of Energy, cellulosic ethanol reduces GHG by 85% over regular gasoline, while corn ethanol, which uses fossil fuels to provide energy for the process, reduces GHG emissions by 18% to 29% over gasoline [2]. Ethanol from biomass can contribute to sustainable development and resources are available across the nation.

1.3 History of Hybrid Poplars

There are various types of biomass resources available: wood residues, municipal solid waste, agriculture, and dedicated energy crops. Since 1978, the U.S. Department of Energy has supported biomass energy crop development through the Biofuels Feedstock Development Program (BFDP) at Oak Ridge National Laboratory (ORNL). The BFDP has researched a variety of annual and perennial plants species: 34 herbaceous species and 125 tree species [6]. Recently the BFDP has been focusing on switchgrass and short rotation wood crops (SRWCs). SRWCs are a promising source of biomass because of their ability to obtain numerous harvests from a single planting and their potential to be produced in large quantities in many locations. The United States has over 40 million hectares (approximately 100 million acres) of land that SRWCs, such as hybrid poplars, can be produced on [7].

Hybrid poplars (Populus spp.) are mainly hybrids between black poplars (Populus Aeigeros) and balsam poplars (Populus Tachamahaca) [8]. Hybrid poplars are attractive because of their fast growth rate, ease of breeding, and ability to resprout after multiple harvests [9]. They can be vegetatively propogated, which allows fast growing of clonal populations since they capture genetic improvements more quickly than seedling-propagated trees [8]. Hybrid poplars can be produced throughout most of the continental U.S, but most commonly in the Midwest and Northwest.

Growing poplars, mostly as windbreaks for farmers, can be traced back to the 1600s; however, commercial planting of hybrid poplar did not begin until the 1970s [10]. The BDFP started growing poplars in 1979, and working with other government and private entities has enhanced hybrid poplar's genome in order to raise adaptability, growth rates, and pest resistance. The program also assessed costs and environmental impacts of cultivating hybrid poplar, and has resulted in successful planting of approximately 90,000 acres of hybrid poplar and cottonwoods [10]. The lake states and specifically, Minnesota, has been the most popular site for test plantation of hybrid poplars [8].

Hybrid poplars grown under intensive silviculture can produce between 4 to 10 dry tons of wood/acre/year and achieve a height of 60 feet in as little as six years, while naturally grown poplars yields less than 1 dry ton/ac/yr [10]. Hybrid poplar stands are planted at spacing ranging from 2 x 2 feet to 12 x 12 feet. The production cycle can be short (5 to 10 years) rotations or long (15 years) rotations [11]. Although hybrid poplars are capable of resprouting immediately after harvest, a reestablishment period is recommended to reduce potential insect and disease problems [10]. Hybrid poplars also need proper site preparation, weed control, pesticide control, and other maintenance. However, compared to other crops, hybrid poplar's chemical and fertilizer applications are considerably lower and also provide more year-round habitat for birds and small mammals [10].

Chapter 2: Life Cycle Assessment

Life cycle assessment (LCA) methodology is intended to be a comprehensive systems-based analysis of the energy and environmental impact of a product or process' entire life cycle. The assessment is obtained through quantification of the energy from raw material acquisition through production, use and disposal [12].

In this paper, a LCA model was developed to evaluate the energy performance and greenhouse gas (GHG) emissions of hybrid poplar tree production for cellulosic ethanol. The system boundary includes the agricultural sector, transportation sector, and ethanol processing sector. (Each of these sections will be discussed in detail.) Energy demands and associated emissions for all operations are divided equally over the total biomass harvested over a 10 year timeline [12]. The assessment does not include energy from the production of the ethanol plant and farming machinery, as well as human labor, due to the insignificance and ambiguity of these amounts [12]. As for environmental impact, GHG emission will be evaluated throughout the production cycle. For the purpose of this paper, carbon dioxide will be the only GHG gas accounted for.

2.1 Agriculture Sector

The agriculture sector includes all farming activity from planting to harvest. For this paper, poplars have been assumed to be harvested over a 10 year period, with two 5 year rotations.

2.1.1 Overview of Agriculture Sector

Sites are plowed to a depth of 10 inches and 10-inch cuttings from two-year old trees are used to establish the plantation site [10]. The dormant cuttings are planted in May, with a spacing of typically 4x4 or 8x8 feet (around 4400 cuttings per hectare). The first year, a pre-emergent herbicide is applied once after planting [13]. Additional herbicide may be needed a few years; however, once the poplar trees grow tall enough to form a canopy, the canopy shade protects the hybrid poplars from additional weed control [10]. Hybrid poplars have been bred to be very pest resistant, so little or no pest management is needed. Fertilizer application is also relatively minimal, although, nitrogen, phosphorous and potassium levels in the soil must be maintained for favorable growth [13]. In some sites only nitrogen fertilizer is needed.

The trees are typically 15-20 cm in diameter and 12-14 meters tall when they are ready for harvest in the fall of the fifth year. The trees are harvested with a harvesting machine that grabs the tree and cuts it off at the base, and then loaded onto a large trailer [13]. After thorough literature review, the average annual yield for hybrid poplars across the nation was calculated to be 5.41 dry ton per acre[1].

Figure 3: Hybrid Poplar after 1-year of growth[2]

2.1.2 Energy Calculations

The largest energy input in this section is from fertilizers. Both energy from the fertilizer application rate and energy from the fertilizer production, packaging, and transportation were considered. All the numbers represented are averages from three different sources in order to diminish variances particular to individual sites. The same approach was applied to herbicides as well.

Table 1: Energy from fertilizer[3]

Type of Fertilizer	Fertilizer Application (lbs/acre/yr)	Energy to produce Fertilizer (MJ/lb)	Fertilizer Production Energy Input (MJ/dry ton/yr)
Nitrogen	66.2	33.0	403.9
Phosphorous	13.4	8.4	20.6
Potassium	13.4	2.8	7.0
		Total	**431.5**

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[1] Appendix A, Table A-1

[2] Virginia's Department of Public Utilities Website: http://www.vpuc.com/biomass.htm.

[3] Appendix A, Table A-2a and Table A-2b: Total energy from fertilizer calculated from multiplying the fertilizer spread with fertilizer production energy.

Table 2: Energy from herbicide[4]

Type of Herbicide	Herbicide Application (lbs/acre/yr)	Energy to Produce Herbicide (MJ/lb)	Herbicide Production Energy Input (MJ/dry ton/yr)
Herbicide (General)	.3	12.0	2.2

The last part of the agriculture sector assessed the average total fossil fuels used in farming machinery. The average annual diesel consumption was determined to be 291.6 MJ/dry ton hybrid poplar[5]. This number only reflects the direct energy used in the farming activity, such as harvesting or plowing, but does not include the energy used to produce the actual machine.

In summary, the total yearly energy input for agriculture is 725.3 MJ/ dry ton. This number was calculated from the sum of the three main energy components: energy from fertilizer, energy from herbicide, and energy from farming machinery. The break down of the energy inputs are as follows:

Table 3: Total agriculture energy inputs

Total Energy Input from Agriculture Sector (MJ/dry ton/yr)	
Fertilizer	431.5
Herbicide	2.2
Farming Diesel	291.6
Total	**725.3**

2.1.3 Greenhouse Gas Emissions

In assessing the GHG emissions for the agriculture sector, the carbon dioxide (CO_2) release in the burning of fuel for operation farming machinery and in the production of fertilizers was taken into account. The GHG emissions from herbicide production have been ignored due to the insignificant amount of weed treatment used. Also, the carbon dioxide intake by the hybrid poplars is not accounted for because when

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[4] Appendix A, Table A-3a and Table A-3b: Total energy from herbicide calculated from multiplying the herbicide spread with herbicide production energy.

[5] Appendix A, Table 4

ethanol is consumed, all the carbon dioxide absorbed during photosynthesis will be released.

In order to calculate the GHG emissions from diesel consumption by operating machinery, the carbon dioxide emission factor of diesel was multiplied with the total amount of fuel used per dry ton of poplar.

Table 4: Carbon dioxide emission from farming machinery

	Emission Factor[6] (g CO_2/MJ Diesel)	Total Emission (g CO_2/dry ton)
CO_2 from Farming Diesel	20.8	6065.3

The same methodology was applied to determine the emission from production of each type of fertilizer.

Table 5: Carbon dioxide emission from production of fertilizer

	Emission Factor[7] Fertilizer Product (g CO_2/ kg)	Average Fertilizer Application (kg Fertilizer/dry ton)	Total Emission for Fertilizer (g CO_2/ dry ton)
$CO_2$from Nitrogen Fertilizer (Ammonia)	1223	5.6	6785.7
$CO_2$from Phosphate	165.1	1.1	184.7
$CO_2$from Potassium	165.1	1.1	184.7

Lastly, combining the total amount of GHG emission from diesel consumption and from fertilizer production, the overall carbon dioxide emission was calculated to be 13,220.5 grams CO_2 per dry ton hybrid poplar.

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[6] Weiss et al. (2000) [15]

[7] Wood (2004)

2.2 Transportation Sector

Due to the fact that there are no current large-scale ethanol processing plants, the data collected for this section is an approximation of a near-future site.

2.2.1 Overview of Transportation

This section includes the transportation of the harvested hybrid poplar from the hybrid poplar farm to the ethanol processing plant. The method of transportation was estimated to be similar to paper transportation and corn-stover transportation. Based on previous research papers on biomass, the distance of the harvesting site and the ethanol plant was assumed to be 50 miles apart. Data was collected from two types of vehicles: diesel truck and 40-feet van. All of the energy calculated for this sector was based from fuel consumption of the vehicle.

2.2.2 Energy Calculations

Table 6: Diesel fuel consumption in poplar transport[8]

Type of Vehicle	Diesel Truck	40-feet van	Diesel Truck
Btu/dry ton	146,500	189,000	150000
MJ/dry ton	154.6	199.4	158.3

In order to determine the energy consumed by the 40-feet van, I found the fuel consumption rate for a loaded and unloaded vehicle and determined the total fuel demand for the 100 mile roundtrip. This total was then divided by the load (total dry ton poplar per trip). For the two diesel trucks, these calculations were already made. The average energy demand from the three different sources was calculated to be 170.7 MJ/dry ton[9].

2.2.3 Greenhouse Gas Emissions

The GHG emission is estimated by the carbon dioxide released from the burning of gasoline and diesel:

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[8] Appendix B

[9] Appendix B

Table 7: Average carbon dioxide released in the transportation process

	Emission Factor [10] (g CO_2/MJ)	Total GHG Emission (g CO_2/dry ton)
Diesel	24.1	3769.3
Gasoline	24.5	4885.2

The actual total was calculated from averaging the two diesel truck emissions and the 40-feet van, and was determined to be 4,327.3 grams CO_2 per dry ton poplar.

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[10] Wood (2004)

2.3 Ethanol Processing Sector

Biomass crops are composed of three main components: cellulose, hemicellulose, and lignin. Cellulose, a polymer of glucose sugar molecules, and hemicellulose, a component consisting of four different sugar polymers, can be fermented to ethanol after pre-treatment and hydrolysis. Lignin, however, is a complex polymer that cannot be used to produce ethanol and instead can be converted to electricity and heat to provide energy for the ethanol production process itself [14]. This use of lignocellulosic biomass is still being developed or large-scale commercialization, but many successful experiments have been demonstrated with corn stovers. Thus the data collected in this section reflects literature review mostly of corn stover to ethanol processing plants; although one documented case, Pan et al. (2006) [4], of poplar conversion to ethanol is referenced.

2.3.1 Overview of Lignocellulosic Processing

The major concern in converting lignocellulosic biomass, such as poplars, to ethanol is the pretreatment step needed to efficiently release all of the sugars contained in the hemicellulose and cellulose components of the biomass. In sugarcane to ethanol or corn to ethanol production, the simple sugars are either readily accessible from the sugarcane directly or after hydrolysis of starch from corn. However, attaining fermentable sugars from lignocellulosic biomass is a more tedious task due to the crop's biomass composition. The fermentable sugars from cellulose and hemicellulose are not directly accessible and consequently require costly pretreatment and hydrolysis steps.

Pan et al. (2006) documented a successful organsolv pretreatment process for hybrid poplar conversion to ethanol. In the organsolv pretreatment, hybrid poplar chips are alternated being cooked in aqueous ethanol, with sulfuric acid as a catalyst, in a four-vessel, rotating digester and using mechanical methods (nylon mesh and flat screen slits) to filter and separate the sugars, lignin, and other residue. The final screened remainder is comprised of a water-soluble fraction containing hemicellulosic sugars, depolymerized lignin, and other components [4].

The hydrolysis step produces a variety of sugars. Xylose, the most abundant five-carbon sugar in hemicellulose, cannot be fermented with the standard yeast used in the ethanol industry [14]. Ethanol production from these five-carbon sugars requires the use of specially selected or genetically modified micro-organisms. However, the glucose derived from cellulose is easily fermented into ethanol.

Lastly, the non-fermentable, lignin-rich fraction and other organic wastes from the process are use from Combined Heat & Power (CHP) production. The produced electricity and heat (steam) are used to a larger extent within the ethanol production process, whereas the surplus of electricity is fed to the public grid [14].

The ethanol processing of lignocellulosic biomass is illustrated in Figure 4[11].

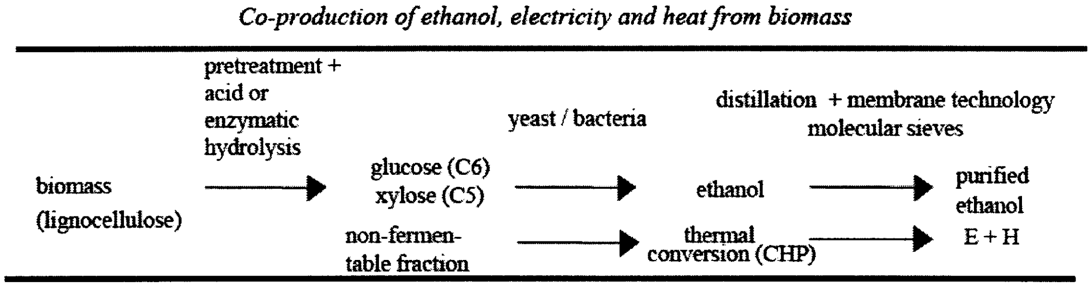

Figure 4: Outline of the lignocellulosic biomass to ethanol process [14].

Although considerable progress has been made in the past two decades, the lignocellulosic ethanol process is still economically unattractive. Major issues concern the development of a cost-effective pre-treatment/hydrolysis technology, fermentation of sugars derived from hemicellulose, and fuel formulation [14].

2.3.2 Energy Calculations

There is no net energy input for this section because the burning of biomass (lignin) and surplus organic wastes is anticipated to cover all energy requirements in the ethanol production process. NREL's design for a plant estimates a processing capacity of 700 kiloton wood and an ethanol output of 156 kiloton/year (approximately 500.4 GJ). The lignocellulosic process produces 95 MW (342 GJ) of thermal energy a year and 44 MW (158.4 GJ) of electric energy a year. All of the thermal energy is consumed in the production plant, while 11 MW (36 MJ) of electricity is available for export to the public grid [14]. However, in calculating the net energy output for the ethanol processing sector, co-products, such as the energy from the electricity generation, are not included.

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[11] Figure provided by Reith et al. First the biomass is pretreated and hydrolyzed to produce the free sugar polymers and non-fermentable components (lignin). Then both the five-carbon and six-carbon sugars are fermented into ethanol, while the lignin undergoes thermal conversion into electricity and heat.

2.3.3 Greenhouse Gas Emissions

No GHG emission is observed for the ethanol processing sector because all of the carbon dioxide released in the burning of the lignin was first absorbed by the hybrid poplar in the agriculture sector. Subsequently, the carbon dioxide intake was not taken into account during the cultivation of hybrid poplars.

2.3.4 Ethanol Yield

In section 2.3.1, the lignocellulosic ethanol process was explained. For this paper, the data from National Renewable Energy Laboratory (NREL) will be used in order to determine a low and high estimate of gallons of ethanol produced from one dry ton hybrid poplar.

The first step in evaluating the amount of ethanol produced from a dry ton of hybrid poplar is to ascertain the amount of cellulose and hemicellulose in poplars, since these are the two components that will be converted into ethanol.

Table 8 : Mass fractions particular to hybrid poplar

Biomass Composition [12] (Mass Fraction)	
Cellulose	43.4%
Hemicellulose	24.2%
Lignin	24.4%

Once the cellulose and hemicellulose contents are determined, a series of stochiometric fractions and efficiency factors are applied to calculate the final ethanol yield. Due to a range of efficiencies in the hydrolysis and fermentation steps, an optimistic and conservative yield was calculated.

Table 9: Best and worst case ethanol yield for hybrid poplar

Ethanol Yield[13] (kg ethanol/dry ton poplar)	
Optimistic Yield	257.4
Conservative Yield	175.3

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[12] Appendix C, Table C-1

[13] Appendix C, Table C-2a and C-2b

2.4 Results from LCA

In the previous three sections, the total energy input was calculated for each sector. In order to determine the energy efficiency of the hybrid poplar biomass system, the total energy input must be compared to the total energy output, which is determined through the energy released from the ethanol yield.

2.4.1 Energy Assessment

While there are multiple methods to evaluate a system, this paper will utilize net energy ratios in order to determine the benefits and sustainability of poplar trees as a source for ethanol. This energy ratio is used to evaluate the relative effectiveness in converting input energy into useful output. [20]

Total energy input from the three sections:

Table 10: Total energy input from hybrid poplar system

Average Energy Input (MJ/dry ton)	
Agriculture	725.3
Transportation	170.7
Processing	0
Total	**896.0**

Next, the total energy output is calculated based on the previously calculated ethanol yield and ethanol properties. Due to the large range in efficiency for the ethanol processing sector, both the optimistic and conservative scenarios are used.

Table 11: Total energy output from hybrid poplar system

Energy Output (MJ/dry ton)	
Optimistic Output	7660.7
Conservative Output	5216.1

The net energy ratio (total output divided by total input) for the optimistic estimate was 8.55 and the conservative estimate was 5.82. This net ratio indicates that hybrid poplars generates somewhere between 5.82 and 8.55 times the amount of renewable energy (ethanol) than the amount of non-renewable energy (fossil fuels) it took to produce it.

Although a range was provided for the energy ratio, the ratio is still only a good estimate of the energy efficiency of hybrid poplars. The ethanol processing is still being developed so the numbers for ethanol yield is very likely to increase in the future. As for the energy input, only fossil fuels were considered, so other forms of energy such as human power and even solar power (for the photosynthesis required in growing biomass) are not taken into account. In addition, the fossil fuel input is sensitive to many factors. The largest energy input is from the fertilizer; consequently, the amount of fertilizer applied during cultivation deeply affects the overall net energy ratio. Also, the transportation sector was based off assumptions since there is no commercial lignocellulosic processing plant. Lastly, the ethanol processing produces co products, such as electricity that is not considered in the total energy output.

2.4.2 Greenhouse Gas Assessment

The breakdown and total GHG emission for the hybrid poplar to ethanol process:

Table 12: Total GHG emission for hybrid poplar system

GHG Emission ($g\ CO_2$/dry ton poplar)	
Agriculture	14,182.8
Transportation	4,327.3
Ethanol Processing	0
Total	**18,511**

The total (18,511 grams CO_2 per dry ton poplar) represents the total amount of CO_2 released from the burning of fossil fuels consumed to produce one dry ton of poplar. Subsequently, depending on the ethanol yield (optimistic or conservative) from that one dry ton of poplar, the overall carbon dioxide emission can be calculated in relation to renewable energy produced.

Table 13: GHG emission for hybrid poplar

GHG Emission ($g\ CO_2$/MJ ethanol)	
Optimistic Estimate	2.42
Conservative Estimate	3.55

Chapter 3: Comparison of Hybrid Poplar to Current Fuels

The purpose of this paper is to assess how energy efficient and environmentally beneficial hybrid poplars are as a biomass crop. However, the numbers collected have no implication if they are not compared to data from other forms of fuel. Thus, in this section, the energy and environmental impacts of producing hybrid poplars for cellulosic ethanol are evaluated against those of gasoline and ethanol from corn. Gasoline produced from petroleum is the most widespread form of transportation fuel, and corn ethanol is currently the most common form of biofuel.

3.1 Overview of Gasoline

The main steps in the energy consumption of the gasoline system boundary are: extracting crude oil from the ground, transporting crude oil to an oil refinery, and refining crude oil to gasoline. The energy input includes not only the consumption of crude oil during refining but also the consumption of natural gas, electric power, and other energy sources in crude production, transportation, refining, and distribution [15]. Using data from Weiss' report, On the Road in 2020 [15], the net energy ratio for gasoline was calculated to be 5.03[14] (MJ final fuel produced to MJ energy consumed in process) and the greenhouse gas emission to be 4.2 grams carbon dioxide per MJ gasoline.

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[14] Weiss et al. (2000) The reported energy consumption included energy from distribution; however in order to equally compare with the hybrid poplar system boundaries, I did not include the energy from distribution.

3.2 Overview of Corn Ethanol

The types of energy input are very similar for corn ethanol and poplars because they are both biomass crops. Subsequently, the energy inputs from the corn system boundary are broken down into the same three sectors: agriculture, transportation, and ethanol processing.

Table 14: Shapouri's energy breakdown for corn ethanol[15]

Total Energy in Corn Ethanol System (MJ/ dry ton)	
Agriculture	2251.9
Transportation	118.7
Ethanol Processing	3997.0
Total	**6367.6**

Shapouri et al. (1995) [16] found the average ethanol yield for wet milling plants (the more common form of corn ethanol processing) to be 2.5 gallons of ethanol per bushel of corn. Using Shapouri's data, the net energy ratio of corn ethanol was calculated to be 1.25.

The greenhouse gas emissions for corn ethanol, provided by Groode, is estimated to be 90 g CO_2 per MJ corn ethanol produced. Thus, in order to find a breakdown of the carbon dioxide emission, a percentage (energy input per sector over total energy consumed) was used to calculate each sector's carbon dioxide emission.

Table 15: Carbon dioxide emission for corn ethanol

Total Emission in Corn Ethanol System ($g\ CO_2/MJ$)	
Agriculture	31.8
Transportation	1.7
Ethanol Processing	56.5
Total	**90.0**[16]

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[15] Shapouri et al. (1995)

[16] Groode

3.3 Comparison of Hybrid Poplar to Gasoline and Corn Ethanol

Below is a table to compare and contrast the energy ratio of fossil energy input to energy output and greenhouse gas emissions of the three different sources of fuel.

Table 16: Comparison of hybrid poplars to gasoline and corn ethanol

	Gasoline	Corn Ethanol	Hybrid Poplar (Optimistic)	Hybrid Poplar (Conservative)
Net Energy Ratio (Energy Output/ Energy Input)	5.03	1.25[17]	8.55	5.82
GHG Emission (g CO2/MJ output)	4.2	90	2.42	3.55

Looking at the table above, hybrid poplar at a conservative estimate is still more energy efficient and more environmentally safe than both gasoline and corn ethanol. Due to the fact that gasoline is produced in a much more different process than ethanol, it is difficult to compare the two on more comprehensive levels outside of the overall energy output and greenhouse gas emissions. However, hybrid poplars and corn have similar processes, and therefore can be discussed on a more detailed examination.

Table 17: LCA comparison of corn and poplar

	Corn Energy Input[18] (MJ/ dry ton)	Poplar Energy Input (MJ/ dry ton)
Agriculture	2251.86	725.29
Transportation	118.69	170.73
Ethanol Processing	3997.07	0
Total	**6367.62**	**896.02**

The numbers show that hybrid poplars need much less energy for farming operations and much less energy for the ethanol processing. The high agriculture input value is due mostly to the fact U.S. corn production uses more pesticides and nitrogen fertilizer than any crop produced [17]. From looking at the high density of energy that goes into producing fertilizer and pesticides, it is obvious that increasing the amount of chemicals to cultivate the crops will greatly affect the total energy. As for the ethanol processing sector, the plants producing ethanol from corn require fossil fuels as their

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[17] Shapouri et al. (1995) [16]

[18] Shapouri et al. (1995) [16]

source of energy because all of the extra non-starch are sold as co-products instead of fueling the plant.

However, many other issues arise from producing corn for ethanol production. Corn is a food product, so expanding corn cropland for ethanol production would mean competing for valuable cropland space from producing corn as food [17]. Also, on top of higher GHG emissions, U.S. corn production causes more soil erosion, uses more chemical applications than other biomass crops and consequently is a major contributor to soil and groundwater pollution [17]. Major air and water pollution problems also are associated with the production of corn ethanol in the chemical plant. For each liter of ethanol produced using corn, about 13 liter of wastewater are produced [17]. The soil erosion and pollution question corn ethanol's environmental sustainability.

One must also take into account that LCAs are extremely sensitive to assumptions about the system boundaries. Nevertheless, comparing corn ethanol to even the low estimate for hybrid poplars reveal a large discrepancy for both GHG and energy values. In the future, the environmental impacts of ethanol production will become more important, and so analysis of fuel ethanol from different biomass systems should use standard system boundaries and energy metrics to have a more substantial and equal LCA comparison. [18]

Chapter 4: Comparison of Hybrid Poplar to Other Renewable Sources

To fully understand the advantages and disadvantages of a poplar biomass system, one must assess hybrid poplars in the context of not only other types of biomass, but other forms of renewable energy. Resources for renewable energy are developed from a variety of self-renewing sources such as sunlight, geothermal heat, wind, water, and biomass. These abundant resources can be used to produce heat and electricity, as well as fuel. The solar and wind energy are converted into electricity, while the hybrid poplars are converted to ethanol (biofuel). This difference makes this comparison more difficult, and so different energy ratios and GHG emission calculations need to be considered.

In this section, the hybrid poplar system is compared to both solar and wind systems in its ability to displace fossil fuels per acre land and its ability to displace GHG emission per acre land. All of the data collected for solar and wind is cited from Spitzley and Keoleian (2004) [20] and is for solar and wind energy conversion to electricity. This evaluation is not similar to the previous chapter's assessment of hybrid poplars to current fuels because the types of energy products being compared are different. The purpose of this chapter is to determine which renewable energy is the most energy efficient and environmentally safe per area of land.

4.1 Solar Energy

Worldwide, 100 times more energy is provided daily by the sun than is released by all fossil fuels consumed. [19] Solar energy can be used directly for heating and lighting buildings, for heating water systems, for producing electricity, and for multiple other industrial uses. For this section, the focus will be on solar power to produce electricity from a study by Lewis and Keoleian. [20]

This study considered the building integrated photovoltaic (BIPV) module system, a photovoltaic device that is a part of a building infrastructure, usually as the roof. Photovoltaic modules, in forms of cells, panels, or arrays, can produce electricity from sunlight through use of semiconductor materials such as silicon. They also require very little maintenance during their typical 20 year lifespan. At the National Center for Photovoltaics at NREL, researchers are working to lower production costs, develop more efficient semiconductor materials, and increase production capacity and rates. [19]

Lewis and Keoleian examined modules with a total area of 34 m^2. Since the BIPV system is contingent on the amount of solar radiation at the site, there is a range of electricity generation depending on geographic location. The net energy ration (energy output/input) ranged from 3.6 to 5.9 for 15 different cities across the U.S. For one specific site in Detroit, the energy ration was 3.9, net energy per acre (energy output less input) was 844,000 MJ/acre/year and GHG emission was 17.4 g CO_2/MJ. [20]

4.2 Wind Energy

Wind power currently supplies most of the renewable energy market. [19] Wind energy is produced through wind turbines, which convert naturally occurring wind flows into electricity. The U.S. DOE has been increasing efficiency and strength of turbine blades and developing taller towers to utilize the stronger winds found at higher altitudes. With the advancement of wind conversions technology over the years, now the costs of producing electricity from wind are near competitive with those of conventional power. [19]

In this paper, the wind power technology examined is provided by the Electric Power Research Institute (EPRI). EPRI considered two 25 MW wind farms in different locations (one on the plains of western U.S. and the other on a ridge in the western U.S.). Each wind farm used 500 kW wind turbine designs and had 50 turbines in a 10 row configuration with a total land requirement of 520 ha. [20]

The energy use and electricity production values result in a total life cycle net energy ratio of 47.4 for the plains site and 64.9 for the ridge site. EPRI cited results for annual net energy (energy output less input) per acre of between 235,000 MJ/acre and 323,000 MJ/acre, and annual GHG emission rate of .67 g CO_2/MJ and .44 g CO_2/MJ. [20]

4.3 Comparison of Hybrid Poplars to Solar and Wind

Table 18: Comparison of poplars to other renewable resources[19]

	Net Energy Produced (MJ/acre)	Carbon Dioxide Displaced[20] (g CO_2/acre)	Net Energy Ratio (MJ Output/MJ Input)
Hybrid Poplar (Optimistic)	36,600	73,930	3.55
Hybrid Poplar (Conservative)	23,400	18,380	5.82
Wind Energy (Ridge)	323,000	54,400,000	64.9
Wind Energy (Plains)	235,000	39,600,000	47.4
Solar Energy	844,000	12,800,000	3.9

The table above compares the net energy per acre, the carbon dioxide displaced per acre, and the net energy ratio for the three different renewable resources. The net energy number signifies the total amount of energy gained per acre of land when taking into account the amount of energy produced and the amount of energy consumed. The carbon dioxide displaced represents the amount of carbon dioxide that would have been released if conventional fossil fuels were used to produce that same amount of energy per acre.

When compared to wind and solar, poplars are drastically less favorable. In looking at only these numbers, hybrid poplars come out to be the least appealing as it requires up to 40 times the amount of land to produce the same amount of energy as solar and up to 15 times the amount of land as wind. Hybrid poplar also displaces the lowest amount of carbon dioxide per acre. Solar energy, allows for the largest energy output per land area but has low energy efficiency (output/input), while wind energy, allows for much higher energy efficiency and releases much less carbon dioxide, but requires much more land to produce the same amount of energy. Although it seems if given an acre of land, solar power should be the obvious choice, one must remember that not only the amount of space, but location is extremely important. While for places closer to the equator solar energy may have more potential, on the coasts, wind energy may be the best option.

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[19] All data from Spitzley and Keoleian (2004) [20]

[20] Electricity emission factor taken from DOE/EPA (2000)

However, even though these numbers do demonstrate the dominance of wind and solar power over biomass, there are many other factors to keep in mind. First and foremost, one must realize that this comparison is of two completely different energy products. The conversion of hybrid poplars to ethanol is a much more difficult process than converting solar and wind power into electricity. Also, one must take into the account that the energy output for hybrid poplars does not include the energy co-products that are produced outside of ethanol. In addition, a key strength of biomass systems is the ability to be converted into multiple forms of energy. Similar to petroleum, biomass can be turned into fuels, chemicals, plastics, electricity, and heat. In particular, for the purposes of this study, biomass fuel is used as an alternative to standard transportation fuel. This important energy product is not achievable through solar or wind energy. The U.S. transportation sector consumes about two-thirds of the nation's oil demand, most of which is imported from foreign countries. Consequently, new sources of energy for transportation fuel are extremely important in moderating the problems of energy security and environmental sustainability. [19]

Economic and environmental feasibility must also be taken into consideration. In general, electricity and fuels from renewable energy are more costly than electricity and fuels from conventional fossil fuels; however, of the three renewable sources discussed, energy from wind is the closest to becoming competitive. [19] Furthermore, while solar and wind sources are endless and free of monetary costs, biomass sources depends on the availability and price of the crop. [19] Then again, solar and wind are intermittent sources of energy, thus making it rather difficult and costly to incorporate into the grid, whereas hybrid poplars and other biomass are better able to be stored and provide a constant supply of energy.

In the end, it is difficult to make judgments as to which form of renewable energy is more beneficial or has the most potential. There are many different factors to consider, and with the uncertainty of the future in respect to technological advances, energy security, and environmental sustainability, all forms of renewable resources are extremely important.

Chapter 5: Conclusions

The purpose of this thesis was to perform a life cycle assessment (LCA) to systematically evaluate the energy and environmental benefits and costs for growing hybrid poplar as a biomass crop for cellulosic ethanol in comparison to not only conventional fuels but other sources of renewable energy. In the end hybrid poplars were determined to be a better form of transportation fuel than gasoline and current corn ethanol. We also discovered that while hybrid poplars need much more land than other forms of renewable energy, they are still necessary and advantageous because of their multi-product industry and ability to be a constant energy supply.

In the LCA portion of the paper, hybrid poplars were calculated to produce somewhere between the range of 5.82 and 8.55 times more renewable energy than fossil fuel energy consumed. While there are multiple methods to evaluate a system, this paper utilized net energy ratios in order to evaluate the relative effectiveness in converting input energy into useful output. [20] These numbers were determined after thorough literature review of many past journals and reports. The LCA took into account the amount of fossil fuel used in the agriculture, transportation, and ethanol processing sector. However, the LCA did not include energy inputs from human labor or solar power, and did not include energy co-products in the energy output calculation.

Although a conservative and optimistic energy ratio was given, due to the many confounding factors, the range is still only an educated estimate. The ethanol processing is still being developed so the ethanol yield is very likely to increase in the future. Similarly, hybrid poplars are being genetically improved to enhance their ease of growth and resistance to climate and pests. As a result, the actual dry ton yield per acre of poplar is also likely to increase. Furthermore, since there is no commercial lignocellulosic processing plant, the transportation sector was based off data from articles on other biomass systems. In addition, the fossil fuel input is sensitive to many factors. The largest energy input is from the fertilizer; consequently, the amount of fertilizer applied during cultivation deeply affects the overall net energy ratio. However, the fertilizer application rate is highly dependent on the location of the farm.

As for the total amount of GHG released, the emission is completely contingent upon the amount of fossil fuels consumed during cultivation. In this paper the only GHG considered was carbon dioxide, so the calculated emission was 18,511 grams CO_2 per dry ton poplar. Subsequently, depending on the ethanol yield from that one dry ton of poplar, the overall carbon dioxide emission can also be calculated in relation to renewable energy produced.

As a biomass crop, hybrid poplars are attractive for many reasons: fast growth rate, ease of breeding, and ability to resprout after multiple harvests. [9] Hybrid poplars are also able to be grown throughout most of the continental U.S, and have been bred to become very pest resistant. Compared to other biomass crops, hybrid poplars require less farming maintenance and produce higher yields. Subsequently, when poplars were compared to corn, the most common biomass crop used for ethanol, poplars had a much higher energy efficiency rate (Table 16) and a much lower GHG emission rate. Hybrid poplars do not consume any fossil fuels for the ethanol processing sector and requires less farming operations. Still, the largest energy input value difference is due to the fact U.S. corn production uses more pesticides and nitrogen fertilizer than any crop produced. [17] From looking at the high density of energy that goes into producing fertilizer and pesticides (Table 5), it is obvious that increasing the chemicals application rate will greatly affect the total energy. As for the ethanol processing sector, the plants producing ethanol from corn require fossil fuels as their source of energy since all of the extra non-starch are sold as co-products.

Many other issues arise from producing corn for ethanol production. Foremost is the issue of corn's competition as a food product. Expanding corn cropland for ethanol production would mean competing against corn food producers for valuable cropland space. [17] Also, on top of higher GHG emissions, U.S. corn production causes more soil erosion, uses more chemical applications, and is a major contributor to soil and groundwater pollution. [17] All of these concerns question corn ethanol's environmental sustainability.

In comparison to gasoline, hybrid poplars were also determined to be more energy efficient and much less environmentally harmful. For gasoline the largest energy input is the energy it takes to retrieve the fossil fuel. This input will only become larger in the future as fossil fuels become more and more difficult to attain. Petroleum, from which gasoline is made, is found deep inside the earth's surface. So, in order to find more petroleum, oil companies must continue to dig deeper and deeper and consequently spend more time and energy into retrieving the fossil fuel.

Yet, while hybrid poplars had a clear advantage over current gasoline and corn ethanol, when evaluated against other renewable sources, wind and solar, the numbers for hybrid poplars were less favorable. The method of comparison for the three different resources were less focused on energy efficiency and GHG emission rate, but concentrated on the best way to utilize a piece of land. Thus, in fourth chapter, the amount of energy produced per acre of land was calculated for poplars, wind, and photovoltaics. Hybrid poplars were determined to produce approximately 30 to 40 times less energy than photovoltaics and 7 to 15 times less energy than wind. As for a comparison of GHG emission, the amount carbon dioxide displaced per piece of land was calculated. The number represented the amount of carbon dioxide that would have been released if conventional fossil fuels were used to produce that same amount of energy per acre.

However, even though these numbers do demonstrate the dominance of wind and solar power over biomass, there are many other factors to keep in mind. Most importantly, one must realize that this comparison is of two completely different energy products. The conversion of hybrid poplars to ethanol is a much more difficult process than converting solar and wind power into electricity. Moreover, the energy output for hybrid poplars does not include the energy co-products, usually in the form of electricity, which are produced outside of ethanol.

A major strength not demonstrated by the numbers is biomass system's ability to be converted into multiple forms of energy. Biomass can be turned into fuels, chemicals, plastics, electricity, and heat. Wind and solar power cannot be transformed into any of the physical energy products, such as chemicals and fuels. The U.S. transportation sector consumes about two-thirds of the nation's oil demand, most of which is imported from foreign countries. As a result, alternatives forms of transportation fuel are extremely important in helping solve the problems of energy security and environmental sustainability. [19]

Economic and environmental feasibility must also be taken into consideration. In general, electricity and fuels from renewable energy are more costly than electricity and fuels from conventional fossil fuels. [19] Furthermore, while solar and wind sources are endless and free of monetary costs, biomass sources depends on the availability and price of the crop. [19] On the contrary, solar and wind are intermittent sources of energy, whereas hybrid poplars and other biomass are better able to be stored and provide a constant supply of energy.

Ultimately, there are many different factors to consider in deciding how to best employ the world's current resources to create more sustainable energy systems. However, in evaluating hybrid poplars, much of the data is still tentative due to the ongoing improvement in breeding, cultivation, and processing. Expanding hybrid poplars and other biomass to a level capable of impacting energy security and GHG emissions will require vast progress in the growth of feedstock and efficiency of conversion. New knowledge of the genetics and biological conversion processes will make growing hybrid poplars for cellulosic ethanol more energy efficient and economically feasible.

Evaluating the many different renewable resources is an extremely challenging but vital task. It is clear that with the current trends in demand for energy, all forms of renewable resources will one day be useful in overcoming the energy security crisis. In the end, hybrid poplars do have the potential to make a significant contribution to a more sustainable future, and currently is a more environmentally safe and energy efficient alternative to corn ethanol. Nonetheless, advances will be required to overcome the high costs of pretreatment procedures and low conversion rates before poplars can be used commercially.

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Appendices

Appendix A: Agriculture Supporting Data

A-1: Hybrid Poplar Yield

The annual hybrid poplar yield was calculated through averaging three nation-wide studies of hybrid poplars.

Table A-1: Sources for calculating hybrid poplar yield (dry ton/acre/year)

	Walsh (1999)	Walsh (1996)	Verwijst (1999)
USA-unspecified		5	6.1
Oregon	6.03	N/A	N/A
Washington	5.9	N/A	N/A
Illiinois	5	N/A	N/A
Indiana	5	N/A	N/A
Iowa	4.9	N/A	N/A
Missouri	4.78	N/A	N/A
Ohio	4.87	N/A	N/A
Minnesota	4.74	N/A	N/A
Total	5.15	5	6.1

A-2: Fertilizer

For the data collected on fertilizer, minor calculations for unit conversions were made for some sources.

Table A-2a: Sources for annual nitrogen, phosphorous, and potassium fertilizer spread

Fertilizer Spread			
	Welke (2006)[21]	Perlack (1992)[22]	Rose (1980)
Nitrogen (lbs/acre/yr)	53.56	45	100
Phosphorous (lbs/acre/yr)	13.39	13.3	N/A
Potassium (lbs/acre/yr)	13.39	13.3	N/A

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[21] Original data in kg/hectare/year

[22] Original data in kg/acre/year

Table A-2b: Sources for energy consumed from production, packaging and transportation of fertilizer

Fertilizer Energy Production			
	Helikson (1991)[23]	Shapouri (1995)[24]	Helsel (1992)[25]
Nitrogen - Urea (MJ/lb)	40.18	23.38	35.49
Phosphorous (MJ/lb)	12.69	4.40	7.94
Potassium (MJ/lb)	4.23	1.31	2.90

A-3: Herbicide:

For the data collected on herbicides, minor calculations for unit conversions were made for some sources.

Table A-3a: Sources for total annual herbicide spread

Herbicide Spread				
	Perlack (1992)	Wang (1999)	Rafaschieri (1999)[26]	Average Herbicide
Herbicide (lbs/acre/yr)	0.23	0.31	0.24	0.23

Table A-3b: Sources for total energy in production, packaging, and transportation of herbicides

Herbicide Energy Production			
	Rose (1980)[27]	Helsel (1992)[28]	Lorenz (1995)[29]
Herbicide (MJ/lb)	46.03	136.44	114.12

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[23] Original data in btu/kg.

[24] Original data in btu/lb.

[25] Oirginal data in btu/lb.

[26] Original data in kg/ha over whole life cycle so the total was divided by 10 to get annual result.

[27] Original data in kcal.

[28] First averaged different types of herbicide, then converted btus to MJ.

[29] First averaged different types of herbicide, then converted btus to MJ.

A-4: Diesel Consumption in Farming:

For the data collected on diesel consumption, minor calculations for unit conversions were made for some sources.

Table A-4: Sources for annual consumption of diesel in farming operations

Diesel Consumed in Farming			
	Cook (1996)	Wang (1999)[30]	Heller (2002)[31]
Total Energy (MJ/dry ton)	480.00	247.68	147.13

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[30] Original data in btu.

[31] Data based on willow trees; however, willows and poplar are assumed to have similar farming operations.

Appendix B: Transportation

Table B-1: Sources for transportation data (carrying harvested poplar to ethanol plant)

Transportation Data			
	Kozak (2003) [32]	Rose (1980)	Shapouri (1995)
Type of Vehicle	Diesel Truck	40-feet van	Diesel Truck
Load		12 dry tons	
Distance[33]	100 mile round trip	100 mile round trip	100 mile round trip
Gal/dry ton		0.75	
Btu/dry ton/mile (Loaded)	1465		2000
Btu/dry ton/mile (Unloaded)	1465		1000
Btu/dry ton	146,500	189,000	150000
MJ/dry ton	154.56	199.40	158.25

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[32] The data for Kozak (2003) was collected for paper transportation, similar modes of transportation for the paper industry and biomass were assumed. Also, Kozak did not distinguish loaded and unloaded mileage, but only provided an overall mileage.

[33] Due to the fact no large-scale lignocellulosic ethanol plant exists, the distance was estimated to be 100 mile round trip for all three sources.

Appendix C: Ethanol Processing

C-1: Biomass Composition

Table C-1: Sources for Biomass Composition

Biomass Composition			
	DOE	GCEP (2005)	Dinus (2000)
Cellulose	39.23%	41%	50%
Hemicellulose	16.66%	33%	23%
Lignin	25.18%	26%	22%

C-2: Ethanol Yield

Due to the lack of experimental data for poplar to ethanol conversion efficiencies, the data was estimated through corn stover numbers. Hemicellulose was assumed to be composed only of xylan. The percentages below reflect the range of efficiency (fraction of product) for the chemical reactions.

Table C-2a: Percentage of product formed during pretreatment/hydrolysis reaction

Pretreatment/Hydrolysis Conversion Efficiency			
	Corn Stover		Poplar
	Sheehan (2004)	Aden (2002)	Pan (2006)
Xylan -> Xylose	67.5% - 90%	90%	72%
Cellulose -> Glucose	63.5% - 90%	90%	85%
Xylose -> Ethanol	80%-85%	N/A	N/A
Glucose -> Ethanol	90%-95%	N/A	N/A

Reactions Used for Stochiometric Yield of Ethanol	
Step #1	Step #2
Xylan + Water → Xylose $C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$	3 Xylose → 5 Ethanol + 5 Carbon Dioxide $3\ C_5H_{10}O_5 \rightarrow 5\ C_2H_5O + 5\ CO_2$
Glucan + Water → Glucose $C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$	Glucose → 2 Ethanol + 2 Carbon Dioxide $C_6H_{12}O_6 \rightarrow 2\ C_2H_5O + 2\ CO_2$

Table C-2b: Calculation of ethanol yield from glucose and xylose

Ethanol Yield from Glucose		
	Best Case	Worst Case
Dry Stover (kg)	907	907
Cellulose Content[34] (mass fraction)	0.4341	0.4341
Cellulose Conversion and Recovery Efficiency[35]	0.9	0.635
Ethanol Stochiometric Yield[36]	0.51	0.51
Glucose Fermentation Efficiency[37]	0.95	0.9
Ethanol Yield from Glucose (kg)	171.69	114.76

Ethanol Yield from Xylose		
	Best Case	Worst Case
Dry Stover (kg)	907	907
Hemicellulose Content (mass fraction)	0.2422	0.2422
Hemicellulose Conversion and Recovery Efficiency	0.9	0.675
Ethanol Stochiometric Yield	0.51	0.51
Xylose Fermentation Efficiency	0.85	0.8
Ethanol Yield from Xylose (kg)	85.71	60.50

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[34] Table C-1

[35] Table C-2a (Cellulose to Glucose and Xylan to Xylose).

[36] This fraction refers to the amount of product made from the reactant after all of the ethanol chemical reactions. Refer to Reactions Used for Stochiometric Yield of Ethanol on previous page.

[37] Table C-2a (Glucose to Ethanol and Xylose to Ethanol).