Biofuels Supply Chain Characterization

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Abstract

Ethanol can be made from agricultural residues like wheat straw and from crops dedicated to energy use, like switchgrass. We study the logistics aspects of this transformation and determine the main characteristics of the supply chain making ethanol from cellulose. Important to the final acceptability of ethanol as a transportation fuel is both the economics as well as the environmental aspect of using ethanol. In this study we analyze the buildup of cost as biomass is transformed into fuel. We also look at all the steps involved and describe them from a supply chain perspective

We have found that the main cost components in the cellulosic ethanol production are biomass production, harvesting and ethanol refining. We have also found that the main factor in reducing the overall production cost is the biomass to ethanol conversion factor. The development of new technologies to convert biomass into ethanol becomes a critical issue to achieve the cost targets imposed in order to make ethanol more competitive with other sources of energy such as fossil fuels. An increase in the current conversion factor of 42% could potentially yield to a decrease of nearly 15% in the total production cost of cellulosic ethanol. Other factors such as increasing the refining plant size and biomass yield can also help to reduce the production cost but we found its impact to be lower than that of the conversion factor.

Finally, we also performed a strategic analysis of the entire supply chain to determine how is this industry likely to develop and who will have more bargaining power and therefore will realize most of the value and profits in the supply chain. Our analysis shows that in such a dynamic scenario as in the alternate energy industry, the best option is to build sustained advantage by strong alliances with different partners within the supply chain.

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Biographical Note

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Table of Contents

List of Tables

List of Figures

1 Introduction

The quest for alternate sources of energy is a high priority for many countries. The US government supports biofuels through the Department of Energy (DOE) and the Department of Agriculture. During 2007, the DOE has committed over $600 millions in alternative energy and efficiency projects, mainly to support bioethanol refineries. Furthermore, the 'Twenty in Ten' initiative pursues to reduce the gasoline consumption in the US by twenty percent in the next ten years. The idea is to achieve this goal by improving the fuel economy standards for cars and light trucks and by increasing the supply of renewable and alternative fuels. The objective is to increase the actual production from nearly 6 billion gallons in 2006 to 35 billion gallons of ethanol by 2017, which is roughly five times the current objective for 2012. Similarly, governments all over the world are passing legislation or funding research to develop alternative sources of energy. Yet the development of biofuels is not without significant challenges.

It is well understood now that logistics costs and inadequate logistics infrastructure pose difficult challenges to the biofuel industry. A study of the mechanics of the entire supply chain is a precursor to any efforts in optimizing the supply chain.

The nature of the supply chain in biofuels is different from the traditional hydrocarbon supply chain. The energy density of the raw materials (feedstock) as well the final product (ethanol) is less than those of crude and processed gasoline. Distributing ethanol has its own set of challenges since it absorbs water and is corrosive. New investments will be required to store and transport ethanol, and these investments will be best driven by an understanding of the supply chain dynamics involved.

We are confident that efficient operation of this supply chain will require new strategies and new models.

In the first section of this thesis we present an overview of the main aspects of ethanol production. In the second section, we discuss some of the key factors driving the supply and demand for biofuels and actual strategies used to cope with these issues. The third section presents a description of the supply chain for biofuels and its main components.

In the fourth section we introduce the model we have built to study the ethanol supply chain. We will describe the methodology and present the parameters we used to estimate the production costs for two types of biomass: wheat straw and switchgrass. In the following section we analyze some of the results and how they would be affected by changes in the main parameters being considered. We also discuss potential changes in the current scenario based on technological improvements. Finally in the sixth and last section we present the conclusions from our work.

1.1 Energy use

There has been an increasing interest in finding alternate sources of energy, triggered by increasing world energy demand, concerns about the effect of fossil fuels on global warming, and, for most countries, energy security. Globally this has been reflected in several initiatives such as the United Nations Convention on Climate Change and the Kyoto Protocol (UNFCCC, 1997), where targets have been set for the use of biofuels as a way to mitigate climate change. At the same time while demand for biofuels has increased over the last decade, not enough emphasis has been put to developing new technologies for producing and distributing biofuels and in designing the supply chain for them.

According to Allen *et al.* (1998) the biomass supply chain consists of a range of different activities. These activities include ground preparation, planting and harvesting, handling, storage, processing, transport and utilization as fuel. The most common way to transport biomass from the field is by road, given the short distances involved and the flexibility provided by road transport.

There are several options for supply chain configuration but these are tied to the technological processes used to convert biomass into ethanol and to the cost implications of such a configuration. In this thesis we will discuss some of the key decisions that must be made when designing the supply chain for the production of ethanol and the trade-offs between these decisions. For instance, some of the most important decisions include where to locate the ethanol refineries – closer to the supply or closer to the demand – and what is the most convenient stocking strategy.

Biofuels can be produced from several different resources such as dedicated crops, wood, forestry and agricultural residues, and organic wastes or residues. In this thesis we will focus our attention on two of these sources: wheat straw as an agricultural residue and switchgrass (*panicum virgatum*) as a dedicated crop.

Agricultural residues such as wheat straw are by-products of food production. Their main advantage is that as by-products, they are currently relatively cheap and extensively available. From a farmer's point of view most of the production cost is borne by the main crop, any income coming from this source will be beneficial. Their main disadvantage is that farming is optimized for the production of the main crop, in this case wheat. Consequently, the quality of the biomass obtained from residues may be inferior in terms of degradation, size or water content.

On the other hand, dedicated crops have higher energy yields which make them attractive for the production of ethanol. Although the cost of growing and producing the dedicated crop is often higher than the cost of agricultural residues, this cost difference can be offset by a smaller planting requirement of biomass to produce the same amount of ethanol. These also have several other advantages, such as less quantity of land required to grow the crop and therefore less transportation costs from the field to the plant. Additionally, dedicated crops tend to have a more consistent quality since they are grown specifically to be used as biomass.

There are mainly three drivers behind this increasing use of biomass as a source of energy for transportation. These drivers are:

- Increasing world energy demand: the energy consumption is expected to increase over time and since up until now most of the energy has been obtained from non-renewable sources such as fossil fuels, many countries are looking for alternate and renewable energy sources. According to Walsh *et al.* (2003) currently the US uses about $3.7 \cdot 10^{18}$ Joules of biomass energy, mainly in the form of ethanol, and while there is a potential to increase the use of biomass, in order to support future increases in the energy demand, the use of specialized bioenergy crops will be necessary. This is still a very small fraction of the entire world energy consumption. According to the Energy Information Administration (2006), the world energy consumption in 2005 reached nearly $500 \cdot 10^{18}$ Joules and by the year 2030 it is expected to increase to approximately $750 \cdot 10^{18}$ Joules.

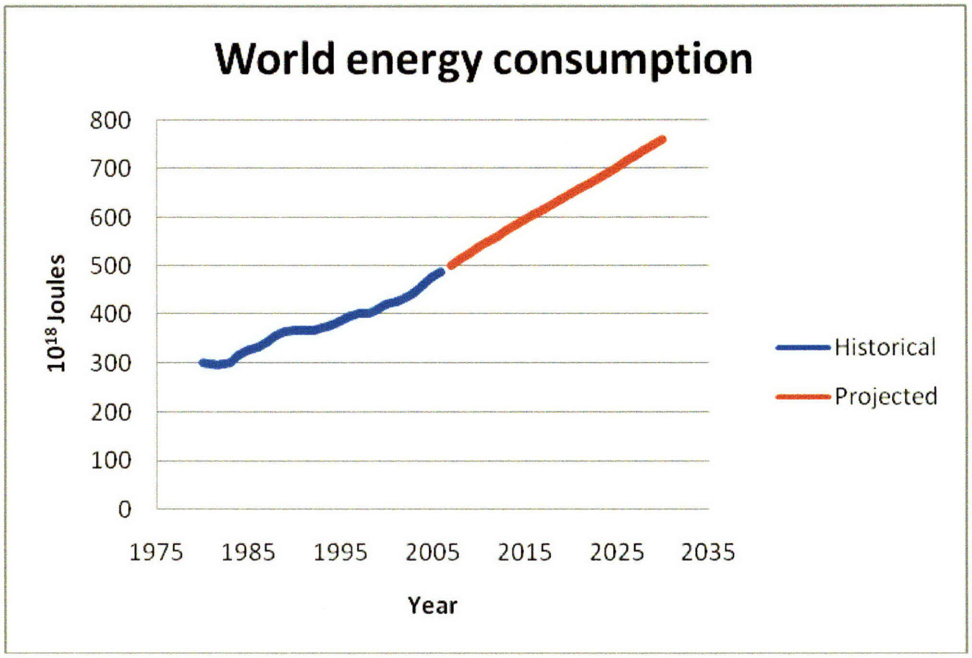


Figure 1: World energy consumption trend (Source: Energy Information Administration (2006)

- Global warming and climate change: greenhouse gas emissions have increased significantly in the last decades. This is believed to have had an impact on some of the climatic changes the world is experiencing such as an increase in the average temperature, in what has been called global warming. One of the main reasons behind the increase in greenhouse gases such as carbon dioxide (CO_2) is the increase in the use of fossil fuels. For this reason a group of nations have signed the Kyoto Protocol which is a legally binding international agreement which aims at reducing the green house gases emissions. In this agreement industrialized countries commit themselves to reduce the emissions of greenhouse gases by 5% by 2012. As of 2005, 153 nations have ratified the agreement, although the US withdrew support for the Kyoto Protocol in 2001. The use of biofuels has been considered as one of the best ways to contribute to the reduction of CO_2 emissions by replacing part of the energy demand for fossil fuels.

- Energy security and dependency on imported oil: due to geopolitical reasons the US is trying to limit the amount of fuels it is importing in order to decrease its dependency on imported oil mainly. Developing biofuels from biomass presents an opportunity to increase the amount of energy produced from both a local and renewable sources.

Brazil has been a pioneer and one of the leaders in the development and adoption of bioethanol from sugar cane. For decades, Brazilian cars have been able to run either on regular gas, ethanol or a mix of both fuels. On 2006, Brazil produced almost 4.5 billion gallons of ethanol equivalent to one third of the entire world production only behind the US with a production of almost 4.9 billion gallons (Renewable Fuels Association, 2006).

Kerstetter & Lyons (2001) performed a technical and economic assessment of the production of ethanol using wheat straw. This assessment was performed in the state of Washington and quantifies the availability of wheat straw, develops biomass supply curves, and calculates the cost of delivering biomass to a processing facility. This cost ranges from $32 to $54 per ton depending on the availability of wheat straw. Also, according a study performed by the National Renewable Energy Laboratory (Aden *et al.*, 2002) the cost of producing ethanol from biomass is still substantially higher than ethanol made from corn ($1.1 versus $1.7 per gallon) although this value is expected to decrease as processing technology is improved.

1.2 Ethanol

Ethanol, or ethyl alcohol, is a chemical compound produced by the fermentation of sugars with yeast. It is also commonly present in all alcoholic beverages. Ethanol's use as a fuel has increased steadily in the last 20 years as shown by the following graph.

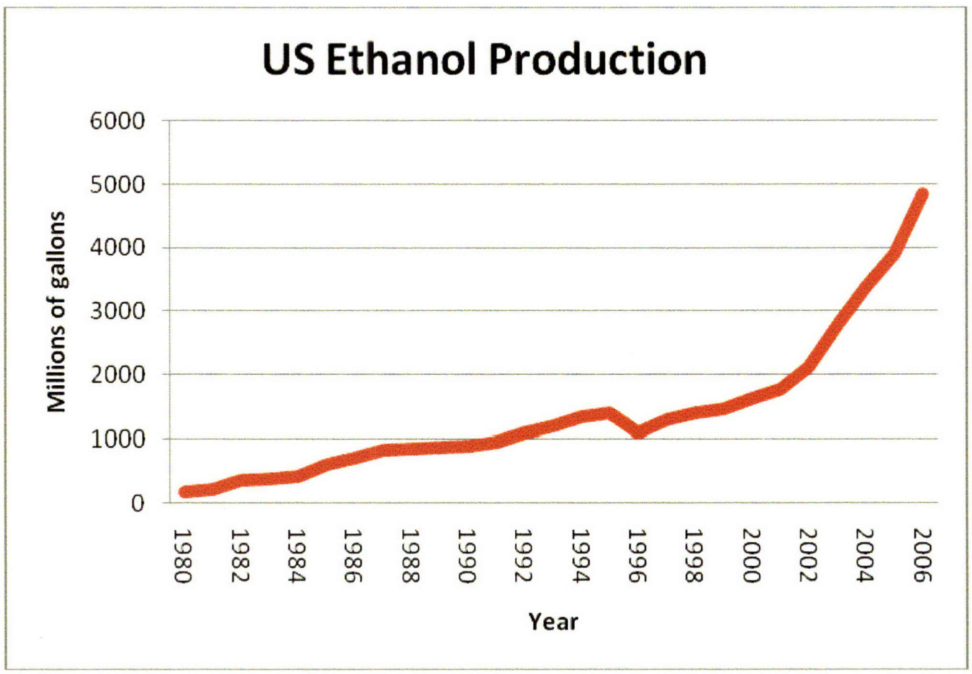


Figure 2: US Ethanol production between 1980 and 2006 (Source: Renewable Fuels Association)

Ethanol is produced from a number of biomass sources such as sugar cane, corn, wheat, and almost any other crop with minimum sugar or cellulose content. Biomass is composed of cellulose, hemicellulose, lignin, ash and extractives. Cellulose is difficult to convert into sugars while hemicellulose can be broken down into sugar relatively easy. Hemicellulose is composed of six-carbon sugars and five-carbon sugars. Lignin is used as a source of fuel to provide steam and power to run the ethanol plants. The content of sugars will depend on the biomass. For instance, wheat straw contains approximately 37% of six-carbon sugars (glucose), 21% of five-carbon sugars (xylose), and 12% of ash. Hardwoods on the other hand contain about 55% of six-carbon sugars, 19% five-carbon sugars and very low ash content (1%) (Kerstetter & Lyons, 2001). The composition of the biomass will determine the energy content of the biostock and how it will be transformed into biofuel.

The economic feasibility of producing ethanol has been a major subject of research over the last several decades. Kaylen *et al.* (2000) developed a mathematical programming model to determine the optimal refining plant size by comparing transportation costs versus capital expenditure. Allen *et al.* (1998) studied the logistics management of biomass for use as fuel for electricity generation. Their study focused on comparing different supply systems in terms of costs. One of the key results of this study is that they show that the use of bales reduces significantly the delivered costs of biomass. Also, the use of intermediate storage facilities between the field and plant increases the total cost by 10 to 20%.

Gigler *et al.* (2002) studied the optimization of the supply chain for agricultural products by dynamic programming. Their research focuses on the quality biomass and how that determines transportation and storage decisions. They identified three types of actions along the chain: handling, processing and transportation. Another technique that has been used to study the biomass supply chain is simulation. Mukunda *et al.* (2006) studied the logistics operations of corn stover supply for an ethanol plant. They identified unloading operations as the bottleneck and by using simulation they determined the optimal number of trucks required and average trip times. Kadam *et al.* (2000) studied the use of rice straw as biomass in California. They reviewed different harvesting techniques and determined a total delivered cost of about 20 $/ton using post harvesting baling and high density bales.

Similarly, another focus for research has been dedicated to crops which can be used as biomass. Mani *et al.* (2004) described and characterized the grinding properties of several crops in terms of energy required for grinding. One of the key results of this research is that switchgrass presents the highest heating value (energy content) and lowest ash content of the reviewed crops. Lewandowski *et al.* (2003) studied four varieties of perennial grasses. This study showed that the high yields, low input requirements and multiple ecological benefits make perennial grasses a good source of biomass for the US and Europe. Switchgrass and miscanthus are the two species that show the best potential.

Sokhansanj *et al.* (2006) developed a model that simulates the different stages in the biomass supply chain to predict the costs per ton of biomass delivered at the refinery. Using EXTEND they obtained a value of 32.45 $/ton of corn stover. Another study that looks into the different stages in biomass supply chain is Hamelinck *et al.* (2005). In this study, the authors developed a modular structure model to compare different possible chains in terms of different types of biomass and several parameters such as distance, mode of transport, and energy conversion technology. This study highlights the importance of transportation costs and densification of the biomass prior to conversion into biofuel.

1.3 First generation of biofuels

The first generation of biofuels technology uses biostock such as sugarcane, beet, and corn. The main attraction of these crops is that their high sugar or starch content transforms easily into ethanol. The main first generation biofuels are biodiesel, bioethanol, pure oils or methyl esters and the two largest producers are the US and Brazil. Actually, Brazil is the second largest producer of ethanol in the world with 4.5 Billion gallons per year, produced mainly from sugar cane (RFA, 2006).

Two main characteristics of first generation biofuels are the following:

a. Taking advantage of higher contents of sugars in the biomass (sugarcane, beet, etc.) to obtain a simpler conversion into alcohols (ethanol).

b. Competition with food for the use of biomass, and its ethical implications. The major concern in this case is that as prices for biomass for the production of biofuels increase, a larger proportion of this biomass will be destined for the production of biofuels instead of using that to produce food. Between 1980 and 1998 the production of ethanol in the U.S. grew from 175 million gallons to 1.4 billion gallons, mainly produced from corn (DiPardo, 2002). The increasing use of corn to produce ethanol has caused an increase in the price of corn, which is one of the main sources of food. For instance, in Mexico this has caused a so called "Tortilla Crisis" where thousands of people have participated in protests against the government and accusing the president of wanting them to die of hunger (Boston Globe, January 31, 2007).

1.4 Second generation of biofuels

The second generation of biofuels is produced from lignocellulosic or woody sources. In this category we can consider some crop residues such as corn stover and wheat straw (Figure 3) and perennial grasses which have been widely used as fodder crops for centuries. According to

Lewandowski *et al.* (2003) the main characteristics that make perennial grasses attractive for biomass production are:

a. Use as energy crop does not compete with use for food. Lignocellulosic biofuels are produced using biomass that does not have an alternate use for food. In fact most of these biofuels are produced from either residues or crops without an alternate use other than to produce biofuels.

b. Higher energy content – high content of lignin and cellulose are desirable because they have higher carbon content which causes a higher heating value. Also, perennial grasses have lower water content than other annual crops. The benefit of this is that less biomass is required to achieve a certain production of ethanol, thus reducing the plantation and transportation requirements.

c. More energy efficient – some perennial grasses may be able to provide a higher amount of biomass yield per acre because of their more efficient photosynthetic pathway. Also some perennial grasses present a higher efficiency of water and nitrogen use.

d. Use of areas not under current cultivation – most of the perennial grasses can be grown in areas where there is no other use for the land and with little or no maintenance. This way, these crops do not compete for land with other uses such as the food industry.

Second generation biofuels can also be produced from agricultural and forest residues which are relatively inexpensive and that otherwise would need to be disposed of. Additionally this could represent an additional source of income for farmers.

English *et al.* (2004) studied the availability of switchgrass (Figure 4) and other residues at a US level as a function of the unit price per ton. Through a 10-year simulation they concluded that as the price increases, so does the availability of biomass reaching a total of 153 million tons at a price of $40/ton (53 million tons of switchgrass and 100 million tons of residues).

Figure 3: Wheat field

Figure 4: Switchgrass plants

McLaughlin *et al.* (1999) describes the main characteristics of switchgrass for use as a bioenergy crop. The average yield depends on whether it is harvested once or twice a year. In the first case the average yield ranges between 16 and 20 metric tons/hectare, while in the second case it ranges between 22 and 24 metric tons/hectare mainly in the southern states. This study also emphasizes the potential for use as biofuels reaching with an ethanol recovery of 280 liters per metric ton.

1.5 Technology

Several technologies have been developed to transform biomass into ethanol, but none of these have been successful enough in terms of costs and efficiencies to dominate the market.

The main process to produce Ethanol from lignocellulosic biomass has been developed by the National Renewable Energy Laboratory (NREL) based on corn stover (Aden *et al.*, 2002) and consists of four steps.

Figure 5: Four steps of ethanol production

1. Pretreatment: the biomass is reduced in size and chemically pre-treated. The chemical pretreatment may include dilute acid, alkaline, organic solvent, ammonia, sulfur dioxide or other chemicals. This process is used to release most of the hemicellulose sugars and acetic acid.

2. Hydrolysis: the feedstock is sent to an enzymatic or acid hydrolysis where cellulose and hemicellulose polymers are broken down into their basic sugars. According to Sun & Cheng (2002) the high cost and low yield of the current hydrolysis technologies are the main challenges to make ethanol more competitive as a biofuel. Major technologies used for hydrolysis are: dilute acid hydrolysis, strong acid hydrolysis and enzymatic hydrolysis. While dilute and strong acid hydrolysis are the most developed technologies, enzymatic hydrolysis is the technology that seems to have the better potential for achieving a cheaper and more efficient transformation.

3. Fermentation: sugars are fermented through the use of yeast into ethanol. Six-carbon sugars can be easily converted into ethanol by using yeast. However, this is more difficult for five-carbon sugars and accordingly the NREL and the University of Florida are working in developing yeasts that can convert both six-carbon and five-carbon sugars into ethanol (Kerstetter & Lyons, 2001).

4. Concentration: the final step in the process is the concentration of the ethanol. In this process ethanol is separated from the fermentation achieving a concentration of up to 95% ethanol. The yield for this process will depend on the biomass being used. For the corn stover the process has an estimated yield of 320 liters per metric ton.

The processing cost is very dependent on the type of biomass. For instance, for sugar cane the processing cost ranges between $0.21 and $0.25 per liter while for lignocellulosic biomass it ranges between $0.31 and $0.38 per liter (Huber *et al.*, 2006). These costs are still about twice of that for the equivalent fossil oil price which is why there is increasing pressures to reduce costs throughout the supply chain.

There have been some other attempts to find a more efficient process to convert biomass into ethanol although most of them are still in an experimental phase. One of these processes is Zeolite upgrading of sugars, which has been developed by researchers at Mobil (Huber *et al.*, 2006)

1.6 Trade offs

This study covers the entire process, from converting biomass on the fields to gasohol at the distribution terminals. As is common with any supply chain analysis, we will look at the important trade-offs inherent in the supply chain, and how to characterize them. While we will look at each of these decisions in more detail in later chapters, the following list provides a quick background that will help the reader structure the discussion later in this thesis.

a. Transportation vs. Economies of Scale. Biomass refining, like crude oil refining, has inherent scale economies that encourage the construction of larger refineries. Balancing this is the fact that larger refineries will need more feedstock, and hence a larger area from which the feedstock is grown. This will increase both the inbound cost of feedstock transportation, as well as the risk of feedstock supply instability.

b. Storage location. The two feedstocks we study – switchgrass and wheat straw – are harvested only twice a year. The resulting biomass needs to be stored for the rest of the year. This can be done in near the fields where the feedstock is harvested, or near the biomass refinery. Other options include building intermediate storage units along with storage units at the refinery locations. The cost of feedstock storage will be determined by the choice made.

c. Capital cost of inventories: one of the key decisions in the design of a supply chain for biofuels is where to hold inventories. Is it more convenient to store it as a raw material, when it's cheaper but more subject to degradation or as a finished product, when it's more expensive and requires higher infrastructure?

Capital cost of investments in facilities: the production of ethanol from biomass requires extensive investment on facilities to process and store biomass and the finished goods. The investment required to build a 100 million gallon/year refining plant is around $100 million (Kerstetter & Lyons, 2001). Larger facilities could benefit for larger economies of scale but also at a larger capital cost of the investment.

2 Matching Demand and Supply

In this chapter we take a look at the sources of aggregate demand and supply within the United States. We also look at possible distribution strategies for cellulosic ethanol. Almost all of the ethanol being produced today is corn based, and concentrated around the mid-western states. Cellulosic ethanol will be produced by other regions as well. These areas will need to use a combination of existing infrastructure and also new facilities built to support the expansion in ethanol use.

2.1 Aggregate Demand

Gasoline is reformulated with Methyl Tertiary Butyl Ether (MTBE) for two reasons. Firstly, it is used widely as an alternative to lead to enhance the octane number of gasoline. It is also used in higher concentrations in some areas to deal with smog and other air-pollution issues, as it imparts clean burning characteristics to gasoline. Due to recent concerns about the health impacts of MTBE, several states are replacing MTBE with ethanol to provide clean burning characteristics to gasoline. Aggregate demand is currently driven by the requirement of ethanol to serve as a replacement for MTBE. The popular versions are E10, which is 90% gasoline blended with 10% ethanol and E5.7 in which only 5.7% ethanol is used. E5.7 is used in California. 25 states have banned MTBE and more states are expected to follow suit. In this chapter, we estimate aggregate demand based on ethanol requirements as a replacement for MTBE.

Ethanol can also be used as a fuel in ethanol based vehicles. One such fuel is E85 which has 85% ethanol blended with 15% gasoline. This requires special infrastructure (car engines, gas terminals, etc.) as E85 is corrosive to current equipment. Most engines cannot handle such high concentrations of ethanol. The US has a small percentage of such vehicles. Brazil has a large proportion of vehicles that can use up to 100% ethanol as fuel. The growth of ethanol as a transport fuel beyond MTBE substitution will depend on the adoption of technologies that allow the use of more aggressive ethanol blends.

In the United States, two pieces of regulation are important in understanding the nature of ethanol demand. First is the Clean Air Act (CAA) of 1990 and second is the Energy Policy Act (EPA) of 2005. The CAA required the use of reformulated gasoline in urban areas with air pollution problems. The EPA, in turn, provides a mandate to triple the amount of ethanol that must be used in reformulated gasoline by 2012. Together, these two make for an explosive growth in the production and distribution of ethanol over the next decade or so. The following table shows the mandated use of ethanol according to the EPA (Scott D. Jensen, David C. Tamm, 2006).

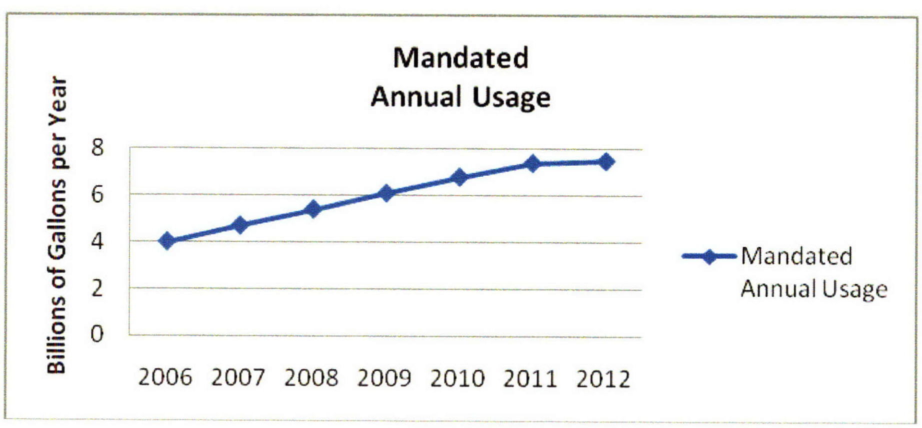


Figure 6: Growth in Mandated Usage

The CAA is being implemented in California, the East Coast, Dallas and Houston and some other areas. This is expected to grow as some other states implement CAA along with the MTBE ban. This map shows all states that have an active MTBE ban schedule in place.

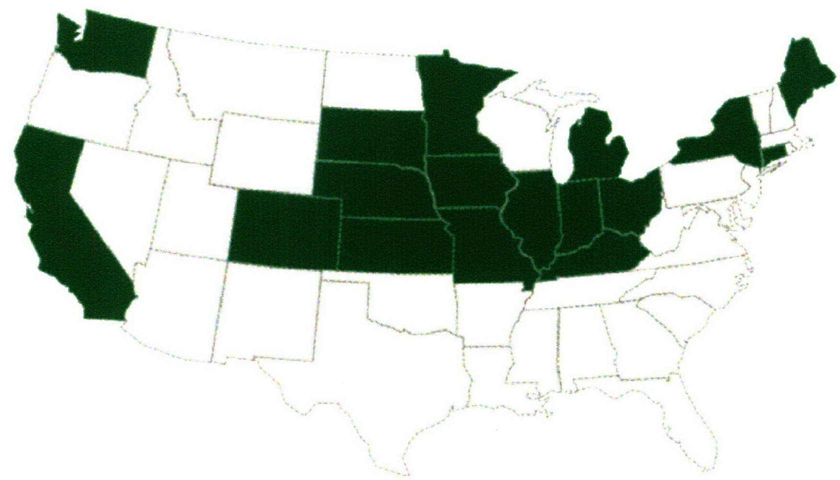


Figure 7: States with MTBE ban schedules (dark states)

These states cumulatively constitute over 44% of the current MTBE consumption in the United States (Energy Information Administration, 2003). Several states have enacted their own specific legislation that mandates the use of ethanol by a combination of using ethanol as an oxygenate for the CAA and a ban on MTBE.

Combining the two acts, it is possible to come up with scenarios about future ethanol use. Here is the base scenario from an NREL study (Steiner, 2003). This table provides a scenario for the growth of cellulosic ethanol and the related production costs. We will revisit the production costs when we study the supply chain in greater depth in Chapter 4.

YEAR	Cellulosic Ethanol (Billion Gallons)	Annual Growth Rate	Market Price ($/Gallon)	Incentive ($/Gallon)	Production Cost ($/Gallon)	Cumulative Production (Billion Gallons)
2010	1.5	-	-	-	$1.18	5.3
2020	9.2	8%	$0.69	$0.32	$1.01	56.7
2030	18.1	5%	$0.61	$0.19	$0.80	178.0
2040	32.6	2%	$0.61	$0.01	$0.62	434.5
2050	40.8	2%	$0.63	$0.00	$0.63	831.6

Figure 8: Ethanol Production (Volume and Cost). Source (Steiner, 2003)

The cost numbers here are just indicative, and have significant uncertainty built into them. We will do sensitivity analysis to understand the impact of this uncertainty later in chapter 4.

2.2 Aggregate Supply

Currently, most of the supply is from corn based ethanol. The following map shows the 8 states most active in corn based ethanol manufacturing. These comprise of more than 96% of the total installed production capacity of ethanol today.

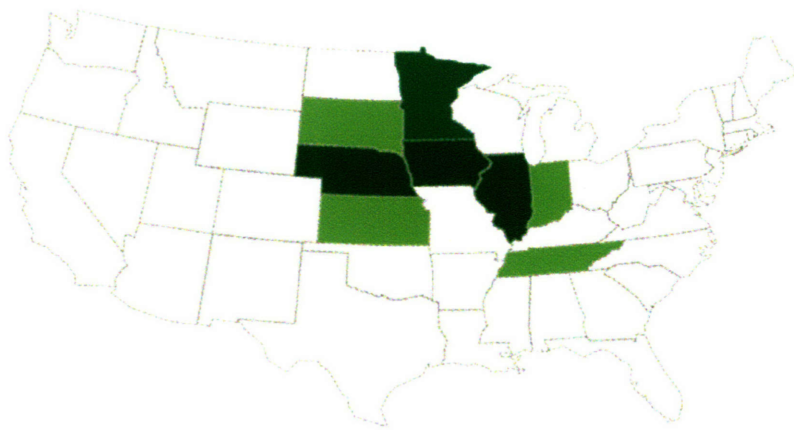
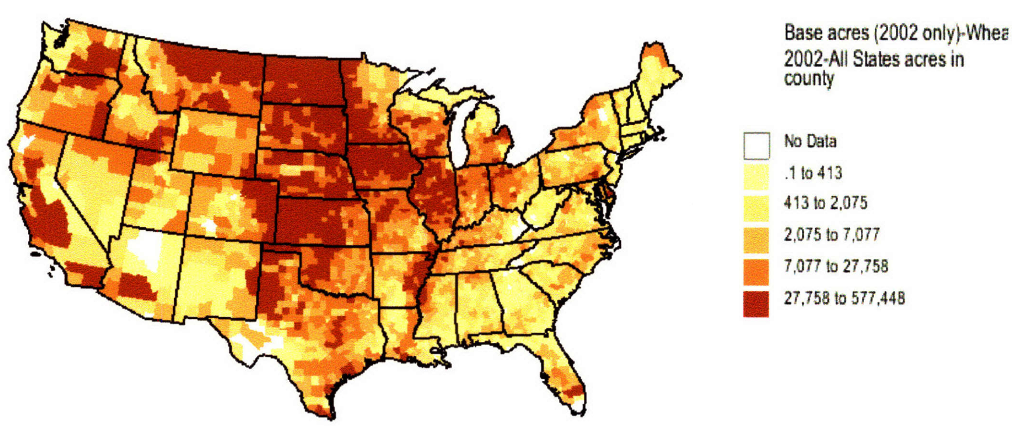


Figure 9: Current Ethanol Production (Darker shades mean more production)

Compare the current ethanol production picture to the figure below which shows the total area under wheat production by county.



Source: USDA/ERS

Figure 10: Wheat Production by county

We can observe that the northern Great Plains, in particular the states of North Dakota, South Dakota and Montana have significant potential biomass supply. The possible quantity of the annual supply of biomass can be estimated by several parameters including the yield and soil conservation status. Equally interesting is to understand how ethanol produced in these parts of the country can be moved to the coasts, where most of the demand is. It is to this question that we turn next.

2.3 Transportation Strategies for Ethanol

Ethanol processed from wheat straw in North Dakota will find markets in the cities of California, the east coast as well as Houston and Dallas. Typically, gasoline will be transported to the same places, but using different infrastructure. A lot of the infrastructure in place for transporting gasoline cannot be used for ethanol. We begin by first describing the transportation of gasoline.

2.3.1 Gasoline Transport

Gasoline is transported from the refineries to the continental US via pipeline, trucks and rail cars. There are 2 major stages in the transport. In the primary stage, ethanol is transported via pipeline, rail or truck to bulk storage terminals. Ethanol is shipped to the same bulk storage terminal. The blending of gasoline and ethanol happens at these bulk storage terminals, and requires specialized equipment to monitor the quality of the blends.

2.3.2 Ethanol Transport

Ethanol can be transported in most of the basic modes including truck, train, barges and ships. Some or most of the routes within the US will involve two or more modes. In addition, as the market expands, we may expect ethanol to be shipped to and from product exchanges to provide access to different markets for far flung producers. These modes are described below.

Ships are the cheapest mode of transport to move ethanol from the gulf coast to the northeast market as well as the California market. According to Downstream Alternatives Inc. (2002) , ethanol can be shipped in vessels containing gasoline. Typically, such a vessel would transport 10.5 M Gallons. Distance from New Orleans to San Diego via the Panama Canal is 4,222 miles(Downstream Alternatives Inc., 2002). This means an average transit time of about 18 days. The transit time to New York harbor from New Orleans is about 6 to 7 days. There are different regulations for denatured ethanol and pure ethanol. The economics make pure ethanol easier to transport, but this may not be feasible due to lack of handling capacity at the receiving port.

There are two types of barges – inland barges and ocean barges. Inland barges are used on the Mississippi river and the connected waterways. These are currently used widely for ethanol transport from the mid-western states. For North Dakota and Idaho, the ethanol needs to be sent by train to the Mississippi. They usually carry 25 barges of approximately 10,000 barrels of ethanol capacity each (Downstream Alternatives Inc., 2002). Ocean barges are double the size of river barges. They are used for gasoline on the west coast, but not currently in use for ethanol. For plants located in North Dakota and Idaho, using barges means extra delay and handling at the ports, which will inevitably increase costs. However, this mode may be of interest when ethanol exchanges are constructed around the hubs.

Rail cars are usually of 30,000 gallons in size. There are various forms of service offered by the railroad companies, including single cars, gather trains and unit trains. Unit trains are the cheapest, and usually involve 95 cars carrying ethanol. Not all receiving terminals can handle unit trains, but these are commonly in use for larger refineries (with more than 100 M gallons per year in capacity). Gather trains create a unit train from a number of smaller (2 to 3) refineries. The cost of putting together the gather train is borne by the refinery, and the rates for a gather train are higher per gallon of ethanol than a unit train. A single car of ethanol is usually only used for shorter distances and stop-gap measures rather than long distance bulk transport. There are 4 major railroad carriers in the United States, and atleast 2 of them, CSX and BNSF are increasing their capacity to transport ethanol from the mid-west and the norther great plains. It is interesting to note that the rail cars needed for ethanol transport are usually owned by the refinery and not by the railroad company. The refinery is responsible for loading the ethanol and the receiving terminal is responsible for unloading it.

A typical tanker carries around 8,000 gallons of ethanol. Trucks are usually used for transporting ethanol for short distances (200-300 miles) from source to loading terminals as well as to redistribute from a bulk receiving terminal to final retail locations or other smaller terminals.

The differing capacities of each of the modes gives rise to the following equivalence:

1 ship (10.5M Gallons) = 4 unit trains (11M Gallons) = 25 river barges.

Due to the corrosive nature of ethanol, as well as its affinity for water, it is unlikely that ethanol will be transported through existing pipelines. The increasing volume of ethanol transportation may cause these technical difficulties to be re-assessed. Another possibility is the emergence of biobutanol as a substitute for bioethanol. Biobutanol can be piped through existing pipelines with minimal retrofitting, and thus may make pipelines viable for biofuel transport.

2.3.3 Transportation Routes from North Dakota

Combining the above modes, we can think of a few possibilities for transporting ethanol from North Dakota. We will make detailed cost estimation for the most likely mode (train) in chapter 4, but in this chapter we list the possibilities and the lead time implications of each of these possibilities.

1. North Dakota to California

    a. Use a unit train or gather from one of the BNSF terminals. The turnaround time is 12 days, and each train will carry 2.85M gallons of ethanol.

    b. Send the ethanol from North Dakota to a port on the Mississippi. From there, the ethanol is loaded on to a barge and sent down to New Orleans. At New Orleans, there is another transfer to a large ocean barge or a ship. The total transportation time will depend on the delays at the transfer locations, but the time by ocean from the gulf coast to California via the Panama Canal is more than 2 weeks.

2. North Dakota to the North East

    a. Use a BNSF unit train to transport the ethanol to Chicago. From Chicago, the train is transported on CSX owned tracks.

    b. Use the combination of train-barge-ship that was used for California. For the east coast the transit times by ship are less than half of that of San Diego.

Figure 6 shows the possible routes graphically.

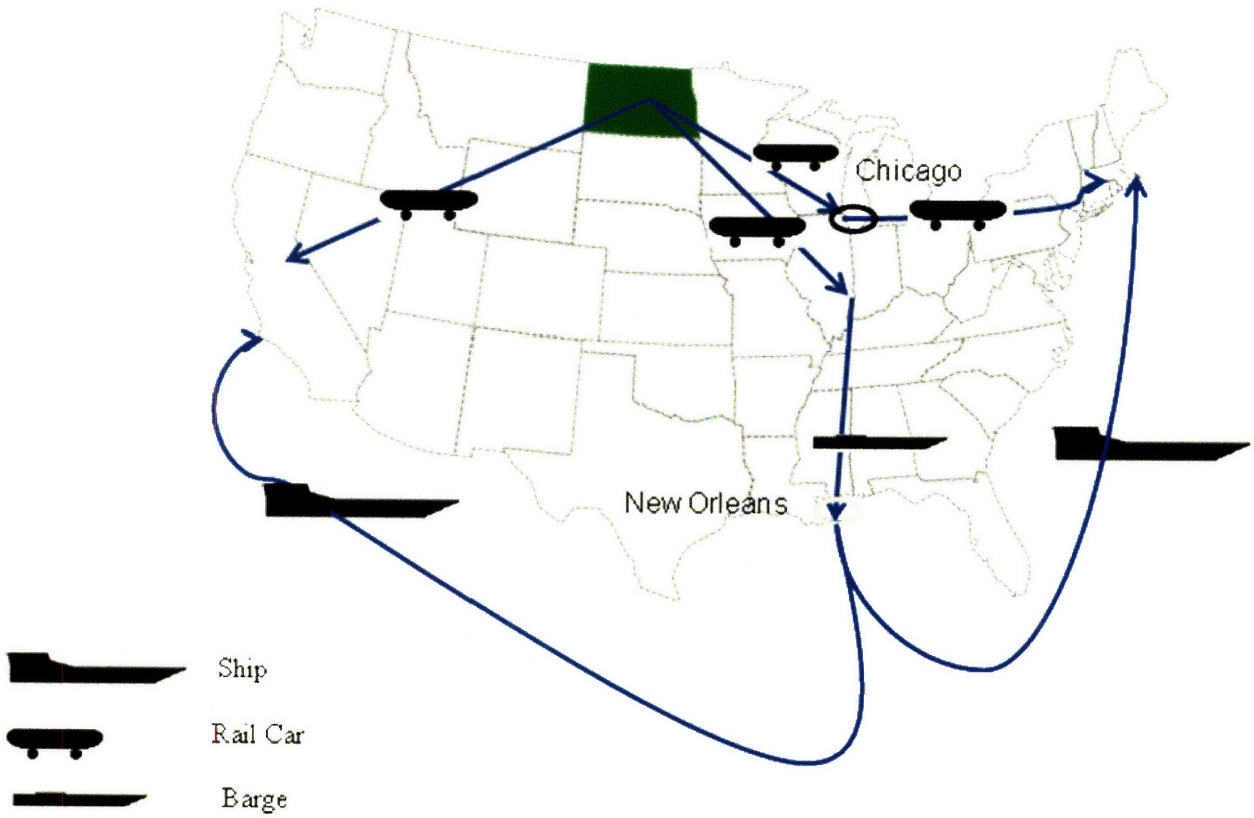


Figure 11: Ethanol transport from North Dakota

3 Description of the supply chain

The previous chapter described the aggregate characteristics of the ethanol industry in the US. In this chapter we will take a more detailed view of the supply chain by describing the various stages involved. The diagram below is a schematic showing these stages.

Figure 12: The biofuel supply chain

As shown in the diagram, the supply chain for agricultural residue and energy crop based ethanol starts with seeds and ends with the distribution of reformulated gasoline to retail stations. Today, all the different stages have different players. With the rising volume in ethanol production and consumption, these entities will compete among themselves to capture the value being created. These players are not equal in terms of their competitive and bargaining powers. We therefore present a strategic analysis of the industry to understand how profits will be distributed, and where the most profitable part of the supply chain is. This is especially of value to companies deciding in which part of the supply chain they wish to engage in.

3.1 Competitive Analysis

The bioethanol industry, in many ways, is similar to high technology industries. The dynamics of industry evolution in high technology products was studied and presented by Roberts, (2001). There are four stages of market evolution, and these stages are different from each other in the pace of technological innovation and the strategies followed by the key players in the market. The following graphic show these four phases.

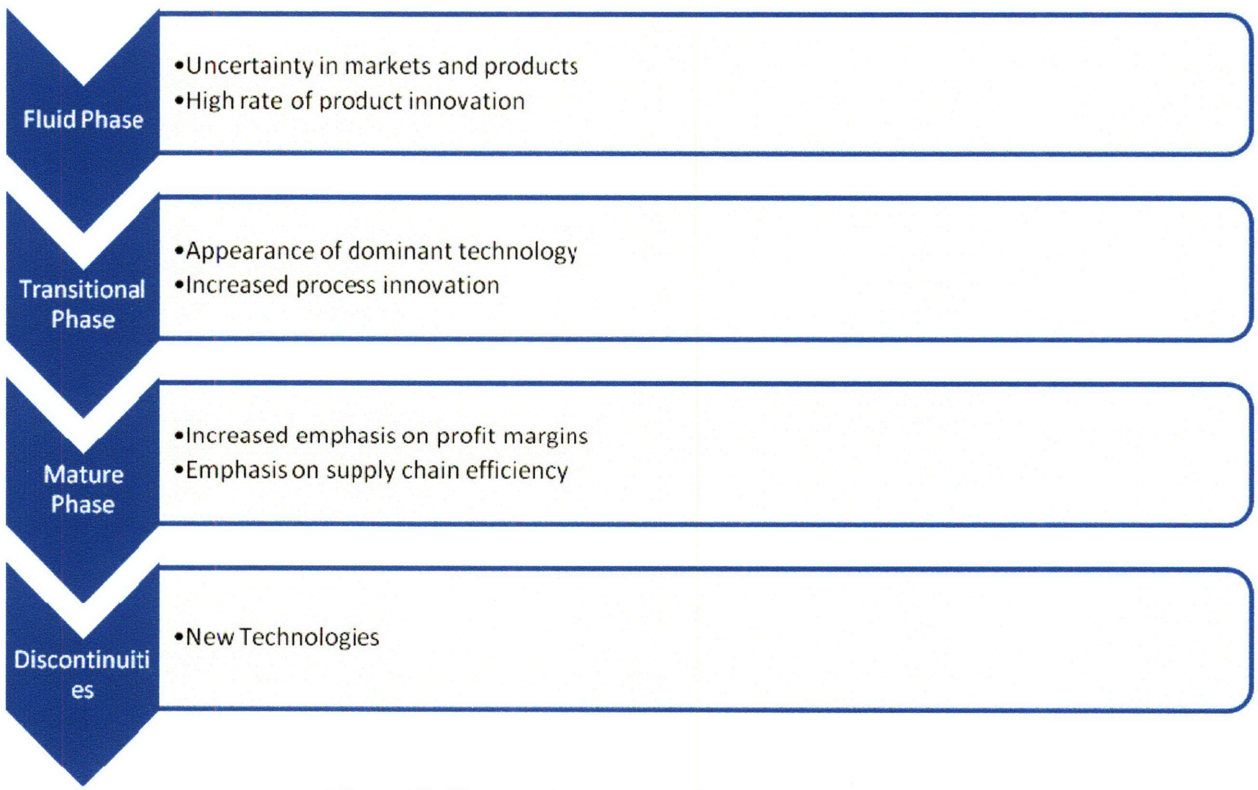


Figure 13: The Utterback model of technology lifecycle

3.1.1 Fluid Phase

Currently the cellulosic bioethanol industry is in the fluid stage. The state of the art in processing technology is being driven by small startup companies which are trying to improve the yield and reliability of the production process. These include companies working on plant genomics (to create better energy crops) to companies working on microbes that provide better yield of ethanol per ton of biomass produced. These companies are usually located near research universities and are different from the traditional oil and gas companies in many ways. To succeed, these companies need faster acceptance and an increased access to the end gasoline market. For this the innovators will often form marketing alliances with the key player in the supply chain, i.e. traditional energy firms. Over the next several years, some of these technologies will become available for commercial use, while many others will fail. One attractive alternative is to form an R&D alliance with the important startup companies and research universities. This may include minority equity investments. (Roberts, 2001). The key levers for advantage at this stage are an access to the thought leaders in the emerging technologies, as well as an understanding of the operational aspects of processing cellulosic feedstock that can be used to make later decisions in technology investments.

3.1.2 Transitional Phase

As the processing technologies for cellulosic ethanol reaches some standardization, the focus will move to leverage existing infrastructure to provide a reliable supply of ethanol. In the transitional phase, the main lever for advantage is to ensure product availability. This would mean that a distributor would have to potentially collaborate with a number of small refining companies, creating supply contracts and marketing agreements. The distributor could also signal its long term interests in specific geographic areas by making focused investments in processing and distribution capacity. Of course, the extent to which this strategy will make sense will depend on the existing infrastructure and position of the distributor in ethanol markets.

In this stage, there is also likely to be significant acquisition activities, and it is here that the partnerships built in the fluid stage come of use. There are some firms in the market today, like Delta-T (Delta-T, 2007), which are selling complete ethanol processing plants. This will significantly reduce the barriers to entry and make technology licensing the most viable option for the innovators. This phase is also likely to see competition between traditional corn based ethanol plants, being retrofitted to refine the cellulosic part of the feedstock, and new plants that are built to work on just cellulosic feedstock. The advantage in this market will belong to players that adapt to winning technologies early and build market share.

3.1.3 Mature Phase

One of the important insights from the relative diseconomies of inbound transportation of feedstock versus the economies of scale of refining is that most refineries will source feedstock from within 50 miles. This number is discussed later, in chapter 4, but for now this indicates that the ethanol refining industry has a high potential to develop in a distributed and possibly fragmented pattern. The mature phase will thus see the margins eroded from refiners, and most of the value being captured by the distributors. While this is likely due to the fragmented nature of the refining business, the biofuel business is also likely to be disrupted again and again over the coming decades.

3.1.4 Disruption Phase

There are significant opportunities to disrupt cellulosic ethanol technologies at any stage of its development. These include new products (like biobutanol), new processing technology, new feedstock sources (possibly genetically modified) and also new business models. In this respect, the biofuels market can look at the evolution of the high technology industry evolution over the greater part of the last century for strategies that succeeded.

Success in the longer term will require a strategy involving two key elements.

- Sustained innovation in biofuel related technologies. The strategy will involve creating stakes in promising current research activities.
- Stability of ethanol supply in the longer term.

The stability of supply will involve multiple sources of feedstock supplies as well as multiple ethanol refineries. In the US market it is unlikely that any player would want to integrate vertically, due to the vast disparity in the technologies and competencies in the different stages. Yet the most successful player will be able to build sustained relationships and stakes with the players in these different stages. Building these relationships will require some detailed understanding of the competitive position of each of the stages in the value chain.

3.2 Seed Production

Seed technologies for grain crops like wheat have been historically optimized towards higher production of grain. However, the yield of cellulosic biomass per unit harvested area is an important factor in the eventual cost of delivered ethanol. Hence there is an expectation that seed technology will deliver improvements in the yield of energy crops like switchgrass. The existing agri-businesses in seed production are large science based corporations like Syngenta and Monsanto. These companies are investing in next generation biofuel technologies, but there is an opportunity for someone to acquire intellectual property around energy crops by "shopping" for startups. There are many startups addressing all areas of yield improvement, like Ceres (Ceres Inc, 2006). Through acquisitions, other parties in the chain may get hold of these technologies. In such a case the position of the large seed companies could be weakened. There are other factors which may work to undermine the competitive advantage of large agri-businesses as well. One being the new generations of production and harvesting technology that promises to deliver yield improvements to regular seeds.

While entrepreneurial activity in the yield improvement area can undermine the bargaining position of large corporations, it is likely that these corporations will retain tremendous influence over the entire supply chain. Part of this is because that apart from intellectual property in the form of patents, large agri-businesses own the distribution channels. It will be difficult for smaller firms to sell to farmers without the reach or reputation of established firms. Besides, companies like DuPont are active in other areas of the supply chain like refining. DuPont is working with British Petroleum in and also developing alternatives to ethanol like biobutanol. (DuPont, 2007)

3.3 Farming and Harvesting.

Wheat in the US is classified by the time in which it is planted. The two varieties are winter and spring wheat. Winter wheat is harvested in the summer. Spring wheat, used more in the Northern Plains, is harvested in late summer or fall. Harvesting of wheat is highly mechanized, and the harvesting of straw is also a well studied area. There are two basic approaches to collecting wheat straw (Kadam, 2000):

1. Simultaneous collection of grain and residue, also known as the total harvest method.
2. Collection of residue after the harvest of the grain, also known as the post harvest method.

Figure 14: Combine Harvesting of Wheat

The most common practice is the post-harvest collection of straw. The grain harvest operations create "winrows" which are rows of straw in the field. These are then raked and baled. Baling creates bundles of straw. The size and density of these bales are discussed in chapter 4. These bales are then transported using trucks to the local refinery. The cost of the farming and harvesting operations are also discussed in chapter 4.

The farming of wheat is done for the value of the grain, and switchgrass is usually grown under conservation programs, aided by rent paid to not grow more intensive crops. The use of agricultural residues and energy crops creates new sources of revenue for the farmer. The value of the biomass will be determined by several factors, including its proximity to a refinery, its quality and availability. And most importantly, there will be an important dynamic between the seed producer, the refiner and the farmer to capture the value from the biomass being grown.

Traditionally governments and companies were able to buy or appropriate land if they needed to do so. It might be easier if the need is for energy and energy security. However, if we assume that the farmer is still the owner of the land in the 50-mile radius around the plant, then the position of the farmer becomes stronger. Most of the other parties in the chain will not be interested in buying and managing land. So even if in theory it is not hard to do, the other parties in the chain may lack the motivation to become landowners. Farmers have alternative uses for the land – food and animal feed. Hence we expect that farmers will probably hold more power in this chain than they do in the traditional food supply chain.

The bargaining power of farmers will be seriously undermined if they need to buy energy-crops protected by patents, in which case their share of the margin may be driven down by high seed prices. If the process at the local consuming refinery is specific to a single feed, and the facility has been designed in such way that it will rely on the 50-mile radius suppliers, then the threat from substitution for the farmer is lower. If the process is flexible and can accept different feed and logistics costs are such that using woodchip or other feed is economical, then the threat of substitution becomes higher, and in this case the farmer will face pricing pressure. One possibility is that farming co-operatives license refining technology and become players in a bigger part of the supply chain by setting up biorefineries. This would increase their bargaining power, and make for an interesting interplay between the owners of the intellectual property in biofuels (seeds and refining) with the manufacturers of biofuels.

3.4 Biomass Transport and Storage

Biomass transport is currently done by trucks. The costs for truck transportation of biomass are considered in detail in chapter IV. The following picture shows a trailer transporting bales.

Figure 15: Truck transportation of bales

Figure 16: Trailer transportation of bales

For storage, there can be two scenarios. In the first scenario, harvesting and baling operations are done by individual farms, and storage is mostly on farm, with bales stacked on top of each other. This is shown in the following picture.

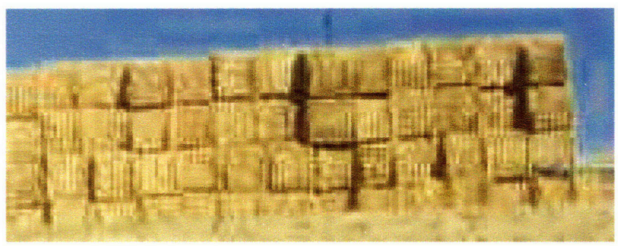


Figure 17: Field storage of bales of wheat straw

The second scenario would have a central refinery doing baling and storage of straw. In this case the storage locations will be near a refinery and will serve that refinery only. This would imply higher costs for storing the straw, but at the same time ensure better conditions and hence higher quality of feedstock for the refinery compared to open field storage.

We expect the straw transportation and storage stage to have similar characteristics as the farming stage. In this stage, the main value being added is the preservation of the biomass between harvesting and eventual consumption. There might be future technologies that pre-process the biomass at the storage centers to improve the inbound logistics cost to the refinery. These might be in terms of compaction (making pellets) or some chemical pre-processing. In either case, the value added will not be very significant. It is our view that this part of the supply chain will be owned by the weaker players in the supply chain.

3.5 Refining

For refineries, the location and ability of the refining process to handle different feeds without compromising quality of the final products will determine the strength of the refining step in the chain. The technology behind cellulosic ethanol is still evolving. It will be interesting to see if the technology is licensed out to manufacturers or used directly by the inventors of the technology. If it is the former, we would expect relatively lower barriers to entry and hence increased competition. In any case, we expect that capital requirements would present some barriers to entry, though not very significant in the longer run when conversion technologies are proven and well tested.

The buyers of ethanol are terminal operators and energy companies. In case of excess supply of ethanol or excess refining capacity, these players would have significant power to reduce the profitability of the refineries. It is our expectation that the refining industry will be fragmented, and hence there is a possibility of overinvestment and overcapacity in ethanol. Currently, ethanol is being pushed as a clean alternative to MTBE. However, ethanol has competition from other compounds for MTBE substitution as well as other forms of clean energy and even improved efficiency of gasoline use.

3.6 Ethanol Transport

Land locked states have to use railroads to transport ethanol to the main demand areas. This means that a majority of ethanol will be transported by rail in the foreseeable future. This gives the railroad companies some power to erode the profitability of refineries as well as energy companies. This is especially true for markets only reachable through one major railroad.

The substitutes for railroad are trucks, barges and pipelines. Trucks are more expensive, but provide an upper limit to the prices charged by railroad companies. Barges are useful only for certain routes (accessible by water). Pipeline is much cheaper, but will require significant investment to get started for bioethanol. There is another possibility, in which existing bio-ethanol plants are retrofitted to produce biobutanol, which can be transported using existing gasoline infrastructure, including pipelines.

3.7 Distribution

The distribution of ethanol will become one of the most important sectors in the supply chain. This is because current distributors have access to the markets and the infrastructure required. The demand for ethanol is being driven by government mandate. Gasoline distribution companies are in a significant position to capture a large part of the value from this supply chain.

3.8 Strategic Inference

The value chain for cellulosic ethanol is diverse. Several of the key components are still evolving rapidly, most important among which are processing technology, transportation capacity and bulk storage terminal capacity. The most important forces that will shape the strategic outcomes in this industry are:

1. The importance of process technology. The economics of cellulosic ethanol will be determined by process technology more than anything else.

2. Local advantages to processing. Favorable access to waterways or feedstock supply will determine the suitability of a region to biofuel refining. This also ties in with the fact that there are limited economies of scale in refining.

3. Growth in ethanol consumption will be shaped by environmental considerations and the various regulations. For the near future, most of the demand will be concentrated around major metropolis in California, New York and Texas.

In such a dynamic scenario, the best option is to build sustained advantage by strong alliances with different partners within the supply chain.

4 Methodology and Cost model

To determine the unit cost of producing Ethanol we determined several alternatives based on the available crops and the available technology. For simplicity and based on their characteristics and relative importance as a source of biomass, we have selected a residue, wheat straw, and a dedicated crop, switchgrass.

As mentioned earlier these two crops are very representative of the second generation of biomass. One crop, wheat straw, is relatively inexpensive as it can be considered a residue of the wheat production and therefore can be easily available in large quantities. The second crop, switchgrass, was selected because it is one of the perennial grasses with the better potential due to its high yields. Additionally, switchgrass has been one of the most researched energy crops by national programs.

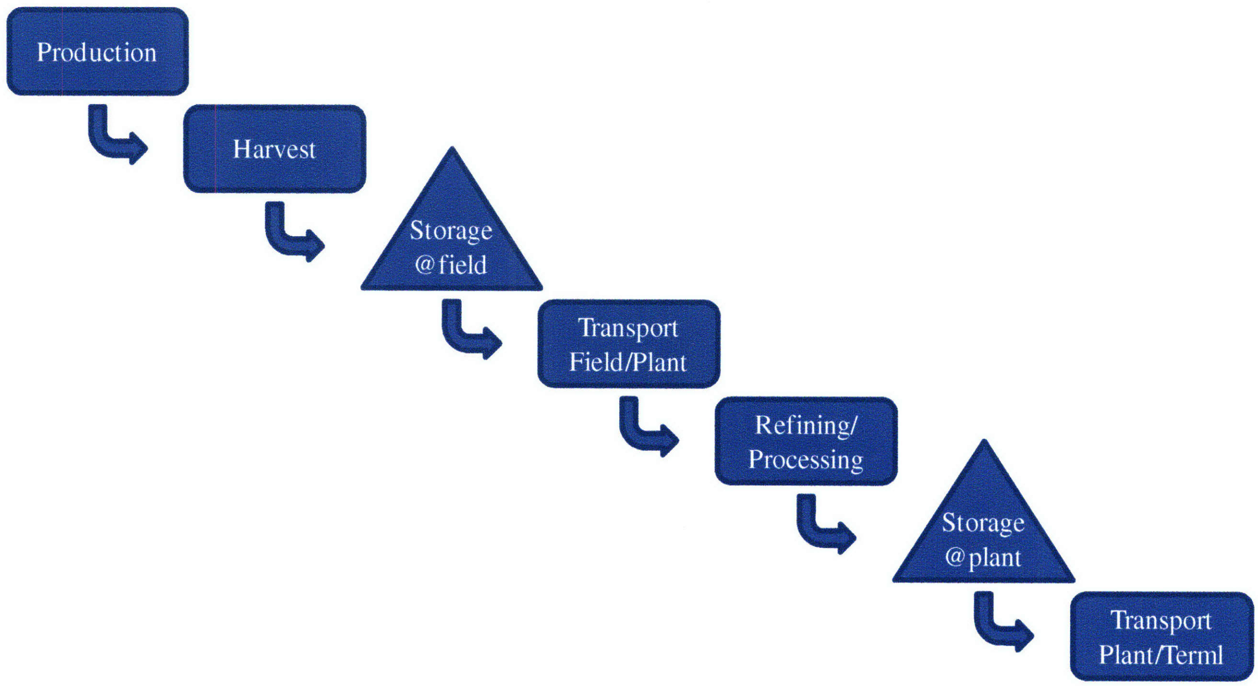


Figure 18: Ethanol Supply Chain

4.1 Wheat straw

To determine the costs of producing ethanol from wheat straw we based our calculation on parameters obtained for the state of Idaho. The main parameters our model uses are biomass yields, production costs, harvesting costs, transportation costs, biomass to ethanol conversion factors and distances from field to plant and from plant to terminal. Some of these are entered directly into our model and some others are calculated based on some of the previous parameters.

4.1.1 Production

To determine the production costs for the wheat straw, we used different scenarios based on a range of parameters. We started by defining a base size for a refining plant. Based on this size, we determined the required acreage and average distance from the field to the plant, based on productivity parameters such as wheat yield, conversion factor of wheat to straw, conversion factor of biomass into ethanol and percentage of the land dedicated to production of the crops.

This way we defined a pessimistic scenario based on more conservative values for yields, costs and productivities; and optimistic scenario, based on more aggressive values; and finally an average scenario which considers the values more commonly used for the above mentioned parameters.

For these three scenarios, we first calculated the production of wheat in Idaho and later based on this number we obtained the amount of wheat straw available as a residue of the wheat production. To determine the production of wheat for the three scenarios we used the information from the US Department of Agriculture for the state of Idaho corresponding to the year 2004. For the pessimistic scenario we used the average yield of the Bear Lake County. For the optimistic scenario we used the yield of the Twin Falls County. Finally to calculate the wheat production for the average scenario we used the average yield for the whole state of Idaho.

Table 1: Wheat yields by scenario

Scenario	Yield [lb/acre]	([ton/acre])
Pessimistic scenario	1,830	(0.915)
Average scenario	5,130	(2.565)
Optimistic scenario	7,452	(3.726)

Other parameters we considered are the percentage of land that is unusable and percentage of the land that corresponds to usable crops. We considered that about 4% of the land is unusable since it will correspond to houses, roads, ponds, etc. and that the usable land that can be harvested is 40% (USDA). This allows to calculate the amount of wheat obtained for a given acreage.

With this information we calculated the production costs based on a costs study performed by the USDA (2004). The costs are broken down into several categories including: fertilizers, chemicals, operations, fuel, irrigation, taxes and general overhead. These costs are expressed as a function of the planted acreage for each of the scenarios. Below is a table with the costs being considered.

Table 2: Wheat straw production costs

Item	Cost	Unit
Seed	0.18	$/acre
Fertilizer2/	0.46	$/acre
Chemicals	0.30	$/acre
Custom operations	0.14	$/acre
Fuel, lube, and electricity	0.18	$/acre
Repairs	0.21	$/acre
Purchased irrigation water and straw baling	0.00	$/acre
Interest on operating inputs	0.03	$/acre
Hired labor	0.04	$/acre
Opportunity cost of unpaid labor	0.30	$/acre
Capital recovery of machinery and equipment	0.94	$/acre
Opportunity cost of land (rental rate)	0.77	$/acre
Taxes and insurance	0.14	$/acre
General farm overhead	0.20	$/acre
TOTAL	**3.88**	**$/acre**

Now, once we determine the production of wheat, we used the parameters defined by Kerstetter & Lyons (2001) to determine the amount of straw available. This study defined a correlation to determine the amount of wheat straw generated by acre based on historical data. The parameters they obtained are 1,067.7 [lb/acre] as a fixed amount of straw and 69.76 [lb/bushel]. Therefore the formula to obtain the total amount of wheat straw generated per acre is:

$$\text{Production}_{straw}[lb/acre] = 1{,}067.7[lb/acre] + 69.76[lb/bushel]\cdot yield_{wheat}[bushel/acre]$$

Using the yields shown above, we obtained the following wheat straw generated per acre:

Table 3: Wheat straw generation

Scenario	**Wheat straw generation** **[lb/acre]**	**([ton/acre])**
Pessimistic scenario	3,195	(1.598)
Average scenario	7,032	(3.516)
Optimistic scenario	9,732	(4.866)

Using these values and the required acreage we determine the total production of wheat straw which is the main input for the following stages.

4.1.2 Harvest

The main inputs to calculate the harvesting costs are the wheat straw production obtained in the previous section and the harvesting unit cost. For this case we used the values obtained by Thorsell *et al.* (2004) calculated harvesting unit costs as a function of the biomass yield assuming some operational parameters such as machinery capacity, windrow width and speed of the harvesting equipment. Based on the values obtained in the previous stage we calculated the harvesting costs. The values obtained are shown in the table below.

Table 4: Wheat straw harvesting costs

Scenario	Harvesting unit cost [$/acre]
Pessimistic scenario	14.0
Average scenario	23.0
Optimistic scenario	27.0

Using these costs and the total required acreage we determine the total harvesting cost for each scenario.

4.1.3 Inventory at the field

Most production, processing or refining facilities will have only limited storage capacity. Therefore, the need to store the wheat straw is important in order to cope with variability in the supply of biomass, since it's harvested once or twice a year, and also to prevent the degradation of the biomass.

To determine the storage cost associated to each of the alternatives we assumed an annual inventory holding cost of 20%. The next step was to determine the average storage time. If we consider that wheat is harvested twice a year, this means that the processing plant needs to store enough material to operate without interruption until the next harvest. In this case, the average storage time would be three months. If the biomass is harvested once a year, the average storage time will be 6 months. Finally, we determined the accumulated unit cost up to this stage and using this value we obtained the total storage cost. This is represented by the following equation:

$$\text{TIHC}[\$] = \text{h}[\%/\text{month}] \times c[\$/ton] \times S[month] \times Q[tons]$$

Where:

TIHC[$]: Total Inventory Holding Cost

h: Inventory Holding Cost

c: Accumulated Unit Cost

S: Average Storage Time

Q: Biomass Production

4.1.4 Transportation

The role of transportation for commodity products plays an important role in the economics of commodity markets.

To determine the transportation cost, we estimate the required number of trucks. We do this by assuming a loading capacity of 35 tons/truck. The other critical parameters to calculate the transportation costs are the transportation rates and the distance to the processing plant.

To determine the average distance from the field to the plant we assumed that the planted area has a circular shape with the plant located in the center. To determine the area of this circumference we started with assumed that the size of the processing plant is given and based on the wheat straw to ethanol conversion factor, wheat to wheat straw factor, wheat yield and percentage of crop available. The formula to calculate this is the following:

$$Area = \frac{PlantCpcty[gallons/year] \cdot Concentration[\%]}{Conv_{Ethl-straw}[gallon/ton] \cdot \Pr oduction_{Straw}[lb/acre]} \cdot UsflCropland[\%] \cdot (1 - UnusableLand[\%])$$

We then calculated the average distance to the center which in this case corresponds to two thirds of the radius of the circumference, assuming that all planting is done in the area adjacent to the biorefinery.

$$\bar{d} = \frac{2}{3} \cdot \sqrt{\frac{Area}{\pi}}$$

This shows that the average distance from field to plant is increasing with respect to the planted area which is directly related to the plant refining capacity.

Using Sokhansanj *et al.* (2006) we obtained a transportation rate based on a fixed cost per truck for loading, and unloading, of 16.33 $/ton and 0.21 $/mile/ton.

$$RateperTruck[\$/truck] = 35[ton/truck] \cdot \left(16.33[\$/ton] + 0.21[\$/mile/ton] \cdot \bar{d}[miles]\right)$$

As the distance from the field to the farm increases, the transportation cost also increases almost linearly. Since we found a large variability of this parameter in the existing literature, in section 5.3 we present a sensitivity analysis for this parameter.

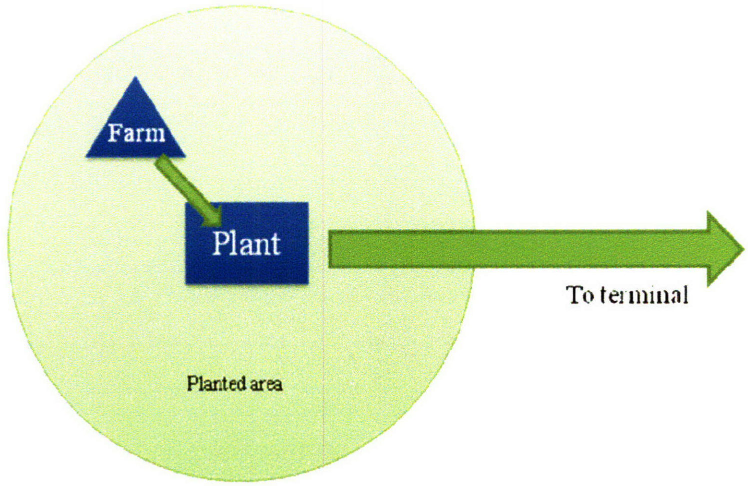


Figure 19: Biofuel transportation diagram

4.1.5 Refining/processing

The refining or processing costs will depend on two main parameters. The first one is the conversion factor from straw into ethanol. This factor will obviously depend on the different configurations and technology being used by the processing plant. As described above, there are many different technologies through which the biomass can be processed to obtain ethanol.

In this case again we identified three possible scenarios based on the conversion factors obtained from Kerstetter & Lyons (2001). The table below presents the conversion factors for the three scenarios.

Table 5: Conversion factor from wheat straw into ethanol

Scenario	Ethanol/Straw Conversion factor [gallons/ton]
Pessimistic scenario	62.75
Average scenario	68.00
Optimistic scenario	72.00

We have assumed that the costs for the biorefinery can be decomposed into fixed and variable costs. The fixed cost is assumed to be a function of the total biomass processed by the biorefinery and an economies of scale factor α. The fixed cost factor C_1 is estimated at 337.32 $/ton of biomass and α = 0.765. The fixed refining cost can be calculated as follows:

$$FixedRefiningCost = C_1 \cdot (TotalBiomassProcessed)^{\alpha} = 337.32 \cdot (TotalBiomassProcessed)^{0.765}$$

The variable refining costs are obtained from Kerstetter & Lyons (2001) and are shown in the table below.

Table 6: Variable refining costs

Item	**Cost ($/gallon)**
Enzymes	0.16
Other raw materials	0.10
Waste disposal	0.03
Electricity	-0.06
Capital depreciation	0.23
Income tax	0.17
Return on investment	0.40
TOTAL	1.02

Additionally, based on [reference] we have considered a concentration of 99.5% Ethanol for the final product.

Since the size of the plant in terms of its production capacity is one of the starting parameters of the models, there is no need to calculate again the production. Instead, the parameters shown above have been used to determine all the other flows preceding this stage.

4.2 Switchgrass

To determine the cost of producing ethanol from switch grass we followed the same approach as for the wheat straw section. The main differences are the parameters being used, which in most cases are specific for each crop, as we tried to keep the same structure as much as possible.

4.2.1 Production

In this case we defined three scenarios based on the yield obtained from Lewandowski *et al.* (2003). The yields are presented in the table below.

Table 7: Switchgrass yield by scenario

Scenario	Yield [metric ton/hectare]	Yield ([lb/acre])
Pessimistic scenario	5.0	(4,460.9)
Average scenario	10.0	(8,921.8)
Optimistic scenario	16.0	(14,274.9)

Similarly to the wheat straw cost calculation presented in section 4.1 we also estimated the percentage of land that is unusable and percentage of the land that corresponds to usable crops using the same values as in section 4.1.

For the production unit costs we again considered three scenarios since there no conclusive data about the production costs. For instance, McLaughlin *et al.* (1999) considered a value of 24.4 ($/ton), while other studies have estimated this cost as 60.0 $/ton (Brummer *et al.*, 2000). We considered the first value to correspond to the optimistic scenario and the latter to the pessimistic scenario. The cost for the intermediate scenario was estimated at 41.7 $/ton.

4.2.2 Harvest

Thorsell *et al.* (2004) developed a model to calculate the harvesting cost of biomass based on several parameters such as biomass yield, capital cost of machinery and other operational parameters. They estimated that the harvesting cost ranges from $58 to $152 per hectare depending mainly on the crop yield. The higher the yield, the higher the unit harvesting cost per acre. However, since higher yield means also a higher production of switchgrass, in the end, the unit harvesting cost per ton of switchgrass decreases as the yield increases.

The following table shows the harvesting cost for each of the three scenarios.

Table 8: Switchgrass harvesting costs

Scenario	Harvesting unit cost	
	[$/hectare]	([$/acre])
Pessimistic scenario	58.0	(23.5)
Average scenario	114.0	(46.1)
Optimistic scenario	153.0	(61.9)

4.2.3 Inventory at the field

Inventory cost is calculated similar to section 4.1.3.

4.2.4 Transportation

Transportation cost is calculated similar to section 4.1.4. For this case we also determined the total acreage required to achieve the nominal processing capacity of the refining plant and based on this number determine the average distance from the field to the plant.

With these two parameters and the same truck rates as calculated in 4.1.4, we estimate the total transportation cost.

4.2.5 Refining/processing

Refining and processing cost is calculated similar to section 4.1.5.

4.3 Distribution of Ethanol

To calculate the distribution cost for the ethanol we considered that the only alternative to transport the biofuel is by railroad. To do this we considered a tank car size of 29,400 gallons and a train size of 95 cars. The transport rates were obtained from the Burlington North Santa Fe railroad company, Ethanol Services Division, and depend mainly on the total number of cars being shipped and the distance. For our analysis we considered three destinations: California, Texas and Illinois.

Similarly to the previous stages, we defined three scenarios for each one of the destinations being considered. The rates for each scenario will depend on whether the plant is shipping a full train or just a few cars. The pessimistic scenario considers shipping less than 34 cars; the intermediate scenario considers shipping between 35 and 94 cars; and the optimistic scenario considers shipping a full train (95 cars). The table below presents the rates for each destination and scenario, both for wheat straw (shipping from Idaho) and Switchgrass (shipping from North Dakota).

Table 9: Plant to terminal transportation rates

Rates ($/car)		Destination								
		CA			TX			IL		
		Lo	Med	Hi	Lo	Med	Hi	Lo	Med	Hi
Origin	ID	6,600	5,600	5,100	5,650	5,100	5,100	4,000	3,600	3,200
	ND	6,225	5,425	4,925	5,275	4,175	4,175	3,675	3,275	2,875

The lead times for each one of the destinations are shown below.

Table 10: Plant to terminal transportation lead times

Destination	Lead time [days]
California	4
Texas	3
Illinois	2

Finally we calculate the pipeline inventory. To do this we determine the amount of trains required to ship the entire yearly production. With this we can determine the frequency of shipments and the shipping period. That is, every how many days there is a shipment. Also, taking into consideration the lead time for each of the scenarios we determine the pipeline using the following formula:

$$PipelineInventory = TotalTrainCapacity[gallons / train] \cdot \frac{LeadTime[days]}{ShippingPeriod[days]}$$

We now calculate the total pipeline cost similarly to the calculation of inventory costs at previous stages.

With these model and parameters we can estimate the cost of producing ethanol from either wheat straw or switchgrass. The diagram below illustrates the overall conversion process.

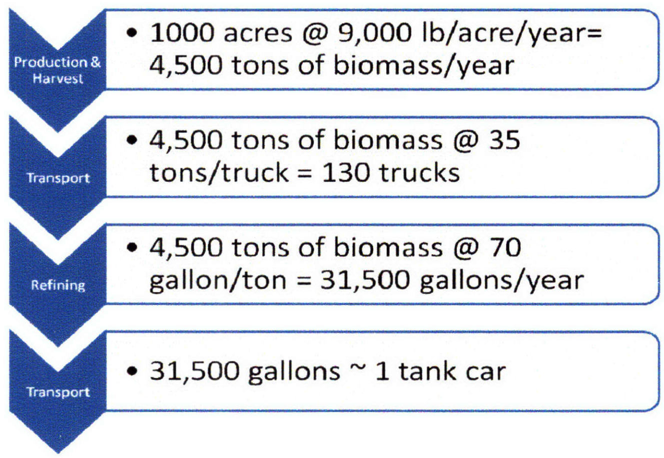


Figure 20: Ethanol conversion process

5 Analysis

In this chapter we extend the discussion from chapter 4 and take a closer look at the various parameters to find which of these are more important to supply chain performance than others. We first present a couple of simple analytical models that provide some insight into the tradeoff between logistics cost and economies of scale in refining. Next, we do some sensitivity analysis on the cost model presented in chapter 4.

5.1 A Couple of Analytical Models

To design a supply chain network, the most important decisions are to determine the nature and size of the facilities that need to be built and operating parameters for these facilities. The most accepted methodology involves the construction of mixed integer optimization models. These models are powerful and flexible, being able to model and solve a wide variety of network design problems.

5.1.1 The Facility Size Model

The first model is the simplest, and captures the trade-off between the economies of scale of production and the corresponding increased transportation costs.

Consider a circular area of radius $\boldsymbol{r}$ miles that provides biomass to a central facility, assumed to be located at the center of the circle. The supply of biomass, for this model, is assumed to be a constant ρ tons/mile^2. Note that this factor takes into account the proportion of land typically under cultivation as well as the harvestable straw per ton of straw produced. There are two kinds of cost associated with running this facility:

1. Facility costs, which again can be divided into fixed and variable costs. The variable costs depend linearly on the amount of biomass processed by the facility. Fixed costs, representing amortization and other overheads can vary with the scale of the facility. Together, we can model the facility costs as – $C_1W^{\alpha} + C_2W$, where W is the total amount of bio-mass

   processed. The factor α determines to what extent the fixed cost depends on the scale of the facility and lies between 0 and 1.

2. Transportation costs for moving the biomass from the field to the refinery. For this model we assume that the transportation costs are equal to t ($/ton-mile).

The area of the supplying area = $A = \pi r^2$

Hence, the total mass of biomass being supplied = $W = \pi r^2 \rho$

Total cost (TC) = $\frac{2}{3}\pi r^3 \rho t + C_1W^{\alpha} + C_2W$

TC per unit of supply (UTC) = $\frac{2}{3} r t + C_1W^{\alpha-1} + C_2 = C_1W^{\alpha-1} + \frac{2}{3} t\sqrt{\frac{W}{\pi\rho}} + C_2$

To find the optimal size of the facility W, we let $\frac{d(UTC)}{dW} = 0$. Then we can write

$$W^* = [3C_1(1 \quad \alpha)]\left[\frac{\sqrt{\pi\rho}}{t}\right]^{\frac{2}{(5-3\alpha)}}$$

The advantage of this expression is that we need to estimate only 3 parameters, namely the economies-of-scale parameters C_1 and α and the transportation cost per mile ***t***.

If we measure W in tons, then we have the following estimates –

	ρ	Alpha	C_1	T
Estimate	224.0 (tons/mile^2)	0.7655327	337.3226	\$0.15 (\$/ton/mile)
Reference	(Johnson, 2006)			

Note that the values of C1and α imply the following:

1. An initial capital expenditure of \$59,723,000 for a 25 million gallon refinery, \$101,529,000 for a 50 million gallon refinery and \$172,599,000 for a 100 million gallon refinery (Johnson, 2006).

2. The initial capital expenditure is amortized over a period of 15 years.

3. On an average, only 20% of the land in the circle is under wheat cultivation, and also only 50% of available straw is harvestable.

W^* = 36,000,000 gal/year and an optimal radius of 25 miles. This is an important insight, showing that this simple model points to the fact that refining will be relatively small scale effort, due to diseconomies of inbound transportation. To understand the influence of α, we plot the W* (in gallons of ethanol per year) against different values of α.

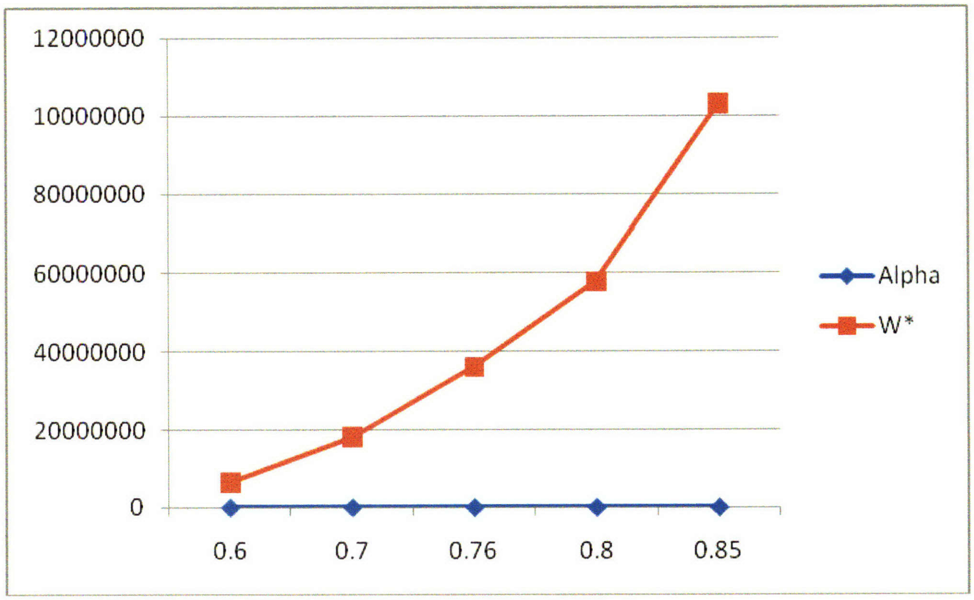


Figure 21: Optimal Facility size by scale parameter

Even when α = 0.85 and the facility refines more than 100 million gallons per year, the radius of the feedstock supply area is 42 miles. Hence, we believe that most refineries will take their supply from an area of within 50 miles in radius from the location of the refinery.

5.1.2 Facility Size Model (Including Ethanol Prices)

We can extend this model to calculate the facility size for a given market price of ethanol. To model the revenue in this case, consider the following new parameters

Let **μ** be the yield of ethanol per ton of biomass (assumed to be 100 gallons here) and let **P** be the price of ethanol that is paid at the refinery. We assume P = \$2.6 /gallon. Of course these numbers are preliminary guesses, and we hope to understand the sensitivity of the size of the facility to these numbers by using these models.

In this case, we have W* given by the following equation –

$$\alpha C_1 W^{\alpha-1} + t\sqrt{\frac{W}{\pi\rho}} = \mu P - C_2$$

From the spreadsheet, we assume C_2 = \$1.19 / gallon. Using this expression and the Excel solver, we can find the optimal W* = 45,600,000 gallons. At P = \$2, W* = 26M gallons and at P = \$3, W* = 61M gallons.

5.2 Results

Using the model and parameters shown in the previous chapter we were able to calculate the unit production costs for all scenarios. As a base case, we used a plant size of 100 million gallon/year and we determined the unit cost for each stage of the process for all three scenarios and for the combinations of origin and destination. For the wheat straw, we considered Idaho as the origin, whereas for switchgrass we considered North Dakota to be the origin. In both cases, the destinations being considered were California, Texas and Illinois.

The estimated costs include all costs up to the terminal at the destination and do not consider the distribution of the biofuel once it has been mixed with gasoline.

The results obtained are shown in the tables below.

Table 11: Unit cost per gallon of ethanol produced from wheat straw

Biomass/Origin	Wheat Straw/Idaho								
Destination	California			Houston			Illinois		
$/gallon	Pess.	Interm.	Opt.	Pess.	Interm.	Opt.	Pess.	Interm.	Opt.
Production	0.04	0.02	0.01	0.04	0.02	0.01	0.04	0.02	0.01
Harvesting	0.36	0.25	0.20	0.36	0.25	0.20	0.36	0.25	0.20
Inventory @ field	0.03	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02
Transportation Field-Plant	0.34	0.26	0.24	0.34	0.26	0.24	0.34	0.26	0.24
Processing	1.21	1.20	1.19	1.21	1.20	1.19	1.21	1.20	1.19
Inventory @ plant	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
Transportation Plant-Terminal	0.22	0.19	0.17	0.19	0.17	0.17	0.14	0.12	0.11
Pipeline inventory	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
TOTAL	2.22	1.95	1.84	2.18	1.93	1.84	2.13	1.88	1.78

Table 12: Unit cost per gallon of ethanol produced from switchgrass

Biomass/Origin	Switchgrass/North Dakota								
Destination	California			Houston			Illinois		
$/gallon	Pess.	Interm.	Opt.	Pess.	Interm.	Opt.	Pess.	Interm.	Opt.
Production	0.89	0.58	0.32	0.89	0.58	0.32	0.89	0.58	0.32
Harvesting	0.41	0.37	0.29	0.41	0.28	0.22	0.41	0.28	0.22
Inventory @ field	0.19	0.14	0.09	0.19	0.13	0.08	0.19	0.13	0.08
Transportation Field-Plant	0.28	0.25	0.23	0.28	0.25	0.23	0.28	0.25	0.23
Processing	1.20	1.19	1.18	1.20	1.19	1.18	1.20	1.19	1.18
Inventory @ plant	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Transportation Plant-Terminal	0.21	0.18	0.17	0.18	0.14	0.14	0.13	0.11	0.10
Pipeline inventory	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	3.21	2.74	2.30	3.18	2.59	2.19	3.12	2.56	2.15

From these results we can observe that ethanol produced from wheat straw has a cost advantage over switch grass in terms of the production costs. Switchgrass average production cost is $0.59/gallon while the same for wheat straw is only $0.02/gallon. Since wheat straw is a residue from the production of wheat, its production cost is almost negligible. On the other hand, the higher yields of biomass per hectare of switchgrass over wheat straw give a cost advantage on transportation from field to plant to switchgrass. The average transportation cost from field to farm for switchgrass is about $0.25/gallon compared to $0.28/gallon for wheat straw. This is 10% lower.

We also calculated the unit production cost in terms of the energy content. According to the Oak Ridge National Laboratory, the energy content per gallon of ethanol is 89 MJ/gallon. Using this value we converted the results shown in the previous tables in to dollars per energy unit. The results using this conversion can be seen in the tables that follow.

Table 13: Unit cost per GJ of ethanol produced from wheat straw

Biomass/Origin	Wheat Straw/Idaho								
Destination	California			Houston			Illinois		
$/GJ	Pess.	Interm.	Opt.	Pess.	Interm.	Opt.	Pess.	Interm.	Opt.
Production	0.43	0.18	0.12	0.43	0.18	0.12	0.43	0.18	0.12
Harvesting	4.07	2.80	2.24	4.07	2.80	2.24	4.07	2.80	2.24
Inventory @ field	0.34	0.22	0.18	0.34	0.22	0.18	0.34	0.22	0.18
Transportation Field-Plant	3.81	2.92	2.68	3.81	2.92	2.68	3.81	2.92	2.68
Processing	13.61	13.48	13.40	13.61	13.48	13.40	13.61	13.48	13.40
Inventory @ plant	0.06	0.05	0.05	0.06	0.05	0.05	0.06	0.05	0.05
Transportation Plant-Terminal	2.52	2.14	1.95	2.16	1.95	1.95	1.61	1.38	1.22
Pipeline inventory	0.06	0.05	0.05	0.06	0.05	0.05	0.06	0.05	0.05
TOTAL	24.90	21.86	20.68	24.54	21.67	20.68	23.98	21.09	19.95

Table 14: Unit cost per GJ of ethanol produced from switchgrass

Biomass/Origin	Switchgrass/North Dakota								
Destination	California			Houston			Illinois		
$/GJ	Pess.	Interm.	Opt.	Pess.	Interm.	Opt.	Pess.	Interm.	Opt.
Production	9.99	6.49	3.56	9.99	6.49	3.56	9.99	6.49	3.56
Harvesting	4.57	4.19	3.29	4.57	3.12	2.45	4.57	3.12	2.45
Inventory @ field	2.18	1.60	1.03	2.18	1.44	0.90	2.18	1.44	0.90
Transportation Field-Plant	3.15	2.81	2.58	3.15	2.81	2.58	3.15	2.81	2.58
Processing	13.50	13.40	13.31	13.50	13.40	13.31	13.50	13.40	13.31
Inventory @ plant	0.28	0.24	0.20	0.28	0.23	0.19	0.28	0.23	0.19
Transportation Plant-Terminal	2.38	2.07	1.88	2.02	1.60	1.60	1.40	1.25	1.10
Pipeline inventory	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
TOTAL	36.07	30.83	25.87	35.71	29.11	24.61	35.10	28.77	24.11

From these results, we can observe that of the total unit cost in both cases – wheat straw and switchgrass – Production, Harvesting and Processing represent the largest portion ranging between 73% and 80%. Transportation from the field to the plant and from the plant to the terminal rages between 13% and 25% and finally inventory cost at the field, at the plant or in the pipeline only accounts for 1% to 7% of the total costs.

The general cost structure for ethanol production from wheat straw and switchgrass can be better seen in the following graphs.

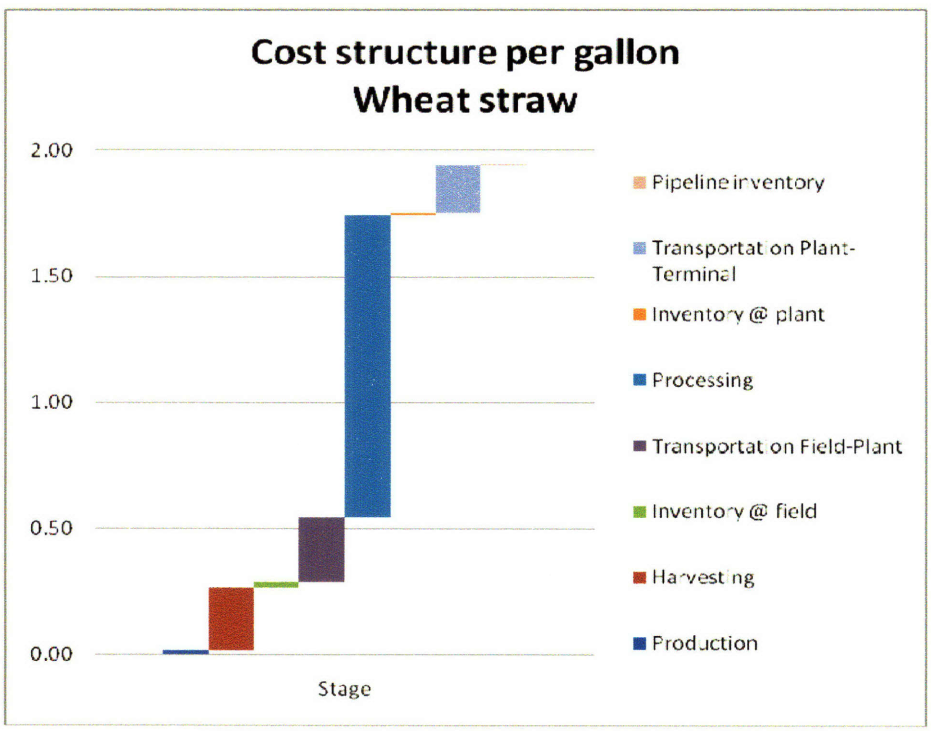


Figure 22: Cost structure per gallon of ethanol produced from wheat straw (intermediate scenario)

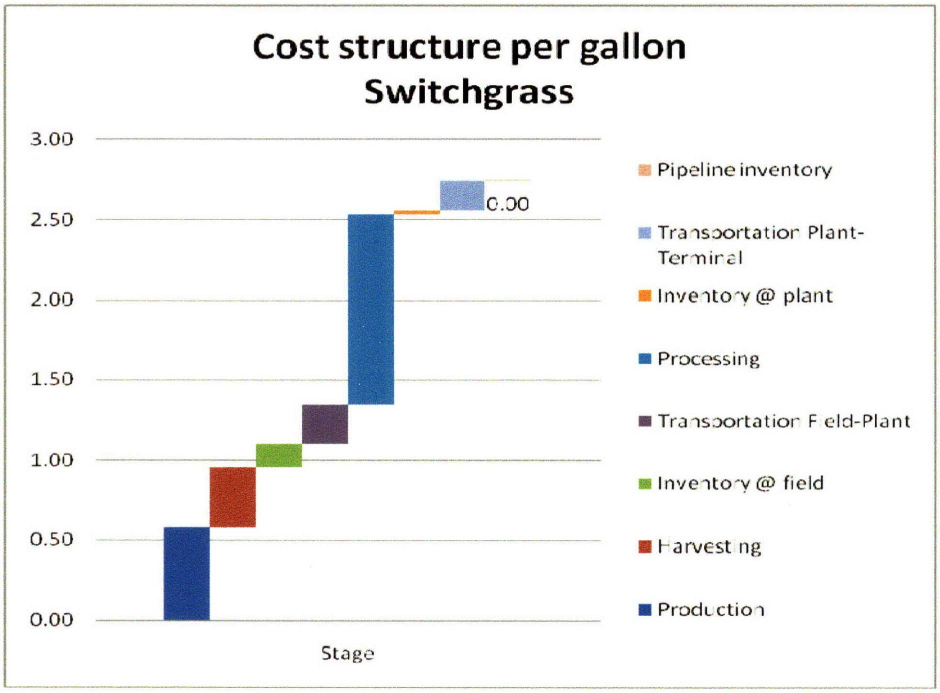


Figure 23: Cost structure per gallon of ethanol produced from switchgrass (intermediate scenario)

As mentioned above, the largest part of the total unit cost in both cases corresponds to the processing or refining stage.

The costs obtained for each biomass, scenario and origin-destination combination are shown in the graphs that follow.

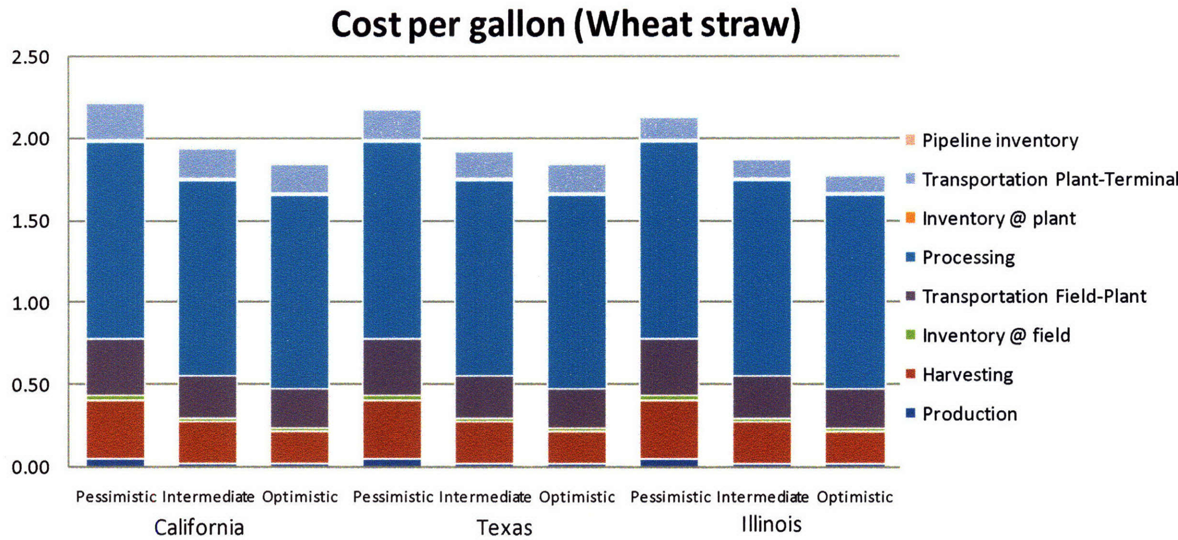


Figure 24: Cost per gallon of ethanol produced from wheat straw

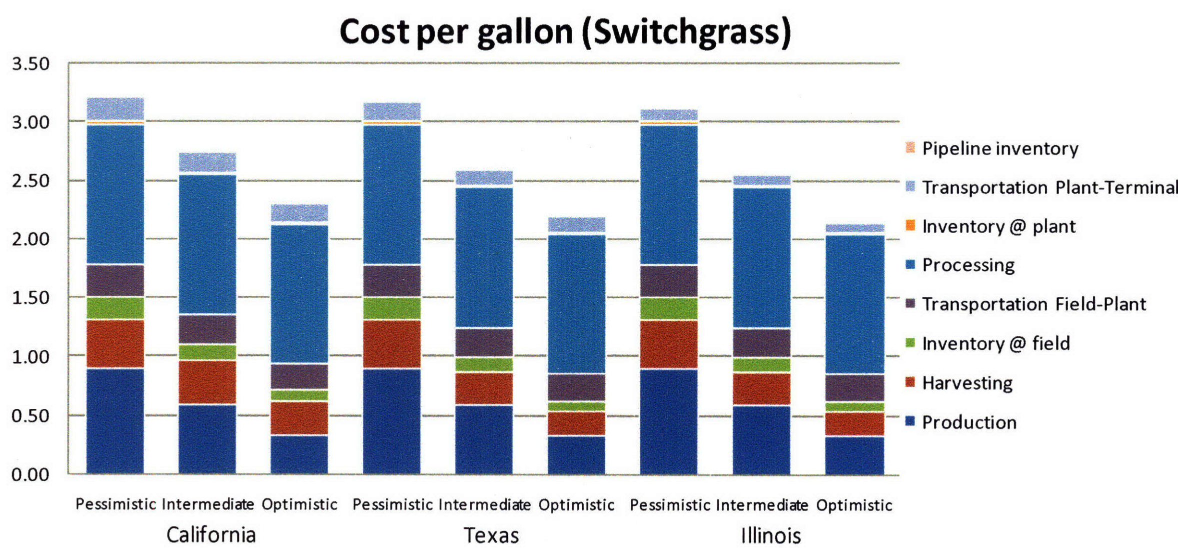


Figure 25: Cost per gallon of ethanol produced from switchgrass

5.3 Sensitivity on parameter assumptions

One of the main assumptions of our cost estimation model is the size of the processing plant. As explained in section 3, the size of the plant determines the scale of operation for all other stages. In particular, it will determine the total area that needs to be planted and harvested in order to ensure a reliable and constant input for the plant. This in turn determines the average distance from the field to the plant and therefore impacts the transportation cost. The cost structure for the refining stage will also be affected as the plant size will determine the amount of biomass required and therefore the fixed cost.

In our base case, we considered a plant size of 100 million gallon/year, which led to a total cost of $2.63/gallon. If we consider a plant size of 30 million gallon/year the total cost is $2.67 per gallon. On the other extreme, if we consider a plant size of 180 million gallon/year, the total cost is reduced to $2.62 per gallon, therefore the impact of the plant size on the total cost is minimal. The transportation cost advantage of a smaller plant size is offset by a larger refining cost and similarly the economies of scale in the refining phase are partially offset by a higher transportation cost for larger plant sizes. This can also be seen in the graph below.

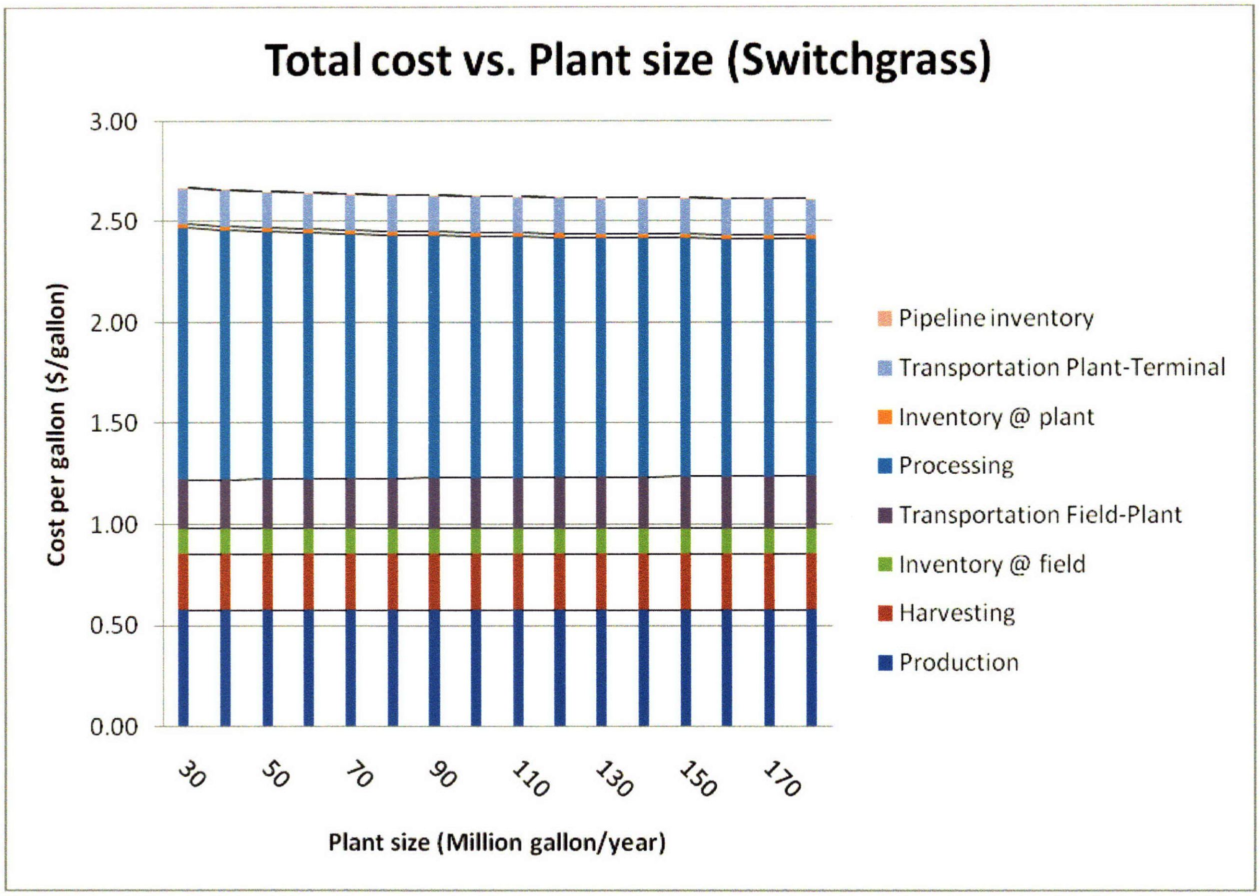


Figure 26: Sensitivity analysis of total cost per gallon of ethanol vs. plant size

Similarly, we also analyzed the impact of the average distance from the farms to the plant. In our cost model, this [parameter was tied to the size of the plant and the land required to feed the selected plant size based on the biomass yield. For the base case plant size of 100 million gallon/year, the average distance was 8.3 miles. However, this number differs from other values found on part of the existing literature (Kerstetter & Lyon, 2001; English et al., 2004). For this reason, we determined the impact of a change in the average distance between 5 and 180 miles in the total unit production cost. As mentioned in section 4.1.4, the transportation cost from field to plant changes almost linearly with the average distance from field to plant. For a distance of 5 miles, the transportation cost is $0.26 per gallon and the total cost is $2.63 per gallon. For a distance of 100 miles, the transportation increases to $0.2 per gallon for a total cost of $2.90 per gallon.

The results can be seen in the graph below.

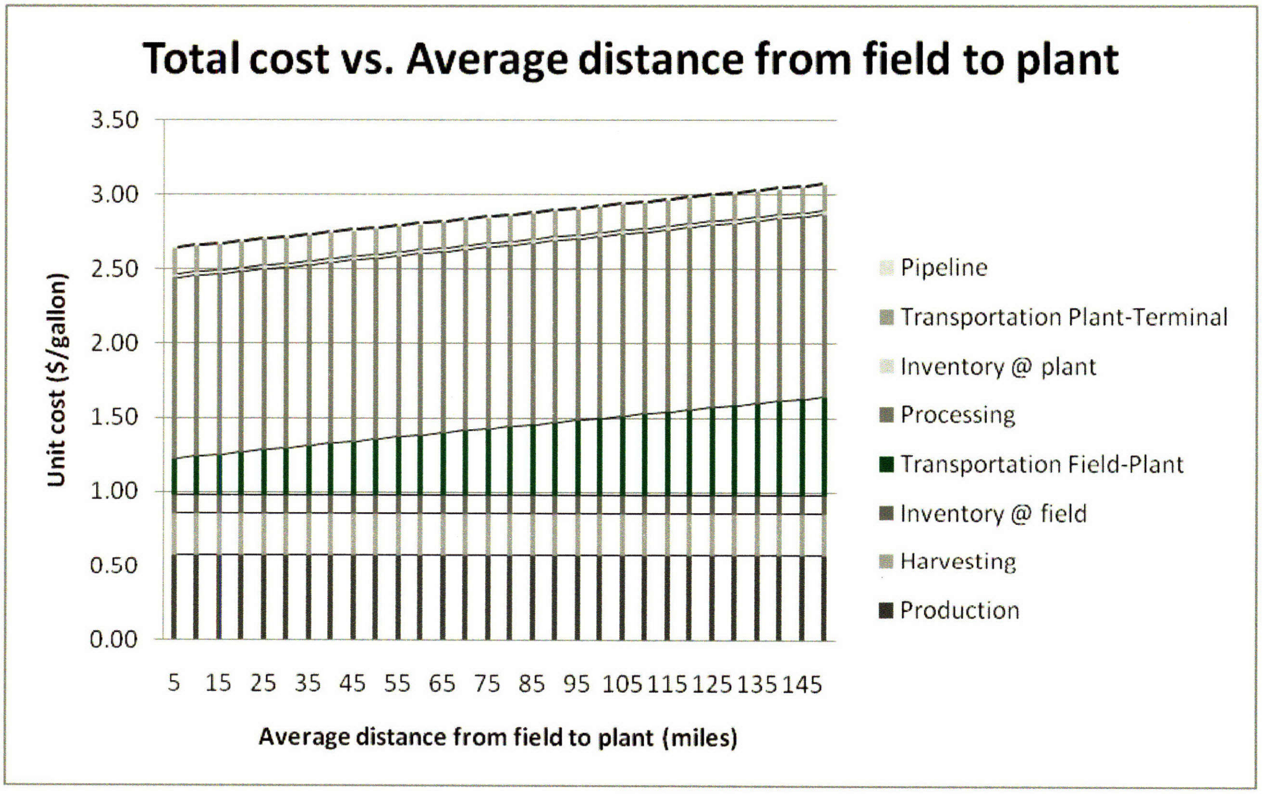


Figure 27: Sensitivity analysis of total cost per gallon vs. average distance from field to plant.

5.4 Scenarios for different technologies

As explained above, one of the key factors in the cost estimation is the yield of biomass per unit of land. This yield determines the required amount of land to plant and harvest in order to ensure a steady supply for the processing plant. As the biomass yield increases, less land is required. Therefore the harvesting cost and the transportation cost from field to plant should decrease, under our model assumptions. This situation is supported by the evidence from our model. This can be seen in the following graph.

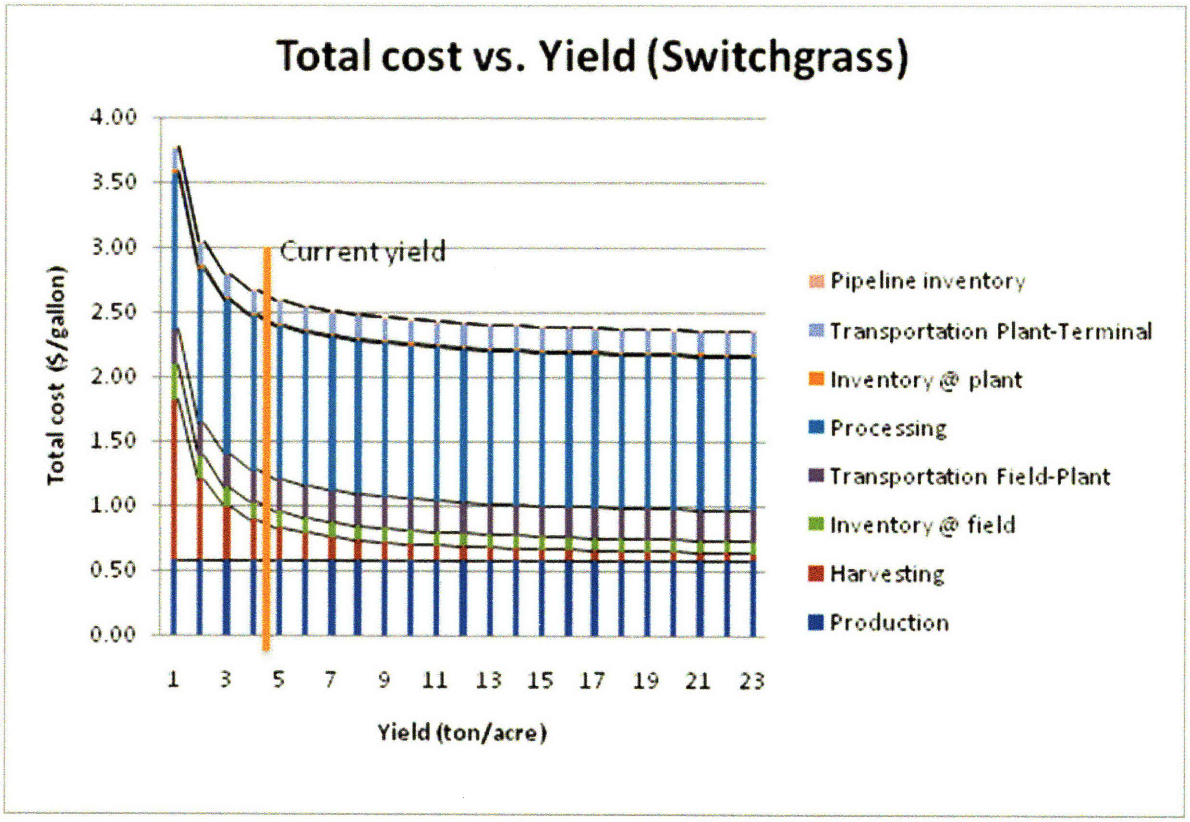


Figure 28: Sensitivity analysis of total cost per gallon of ethanol vs. biomass yield

In this case, an increase in the average yield has a great impact in decreasing the total unit cost. However, this impact does not seem enough to decrease the unit cost below $2 per gallon. Furthermore, the sensitivity analysis was performed for the intermediate scenario of ethanol produced from switchgrass, and delivered from North Dakota to California. In the original estimate, we calculated a cost of $2.63 per gallon considering a yield of 4.5 ton/acre (10 metric tons/ hectare) and when the yield increases up to 23 tons/acre, that is more than five times, the calculated cost only goes down to $2.36 per gallon. This is a reduction of 11% in the total cost. This seems to be substantial but it is clearly not enough to achieve costs below $2 per gallon.

Another parameter that may have a great impact on the total ethanol production cost is the biomass to ethanol conversion factor. This conversion factor will have an impact on all the activities performed prior to the refining of the biomass since it will determine the amount of biomass required to achieve a certain ethanol production. At the same time, this will have an impact on the average distance from the field to the plant. The other impact will be on the fixed cost of the processing plant. In our cost model, the fixed cost depends on the processing capacity of the plant in terms of tons of biomass.

In this case, we used a biomass to ethanol conversion factor of 71.90 gallon/ton in our base case. In the graph below we present the results obtained for conversion factors between 50 and 100 gallon/ton. In the right end of the graph we can observe that by improving this factor from 70 to 100 gallon/ton, or by 42%, the total cost goes from $2.63/gallon to $2.24/gallon. This represents a decrease of nearly 15%. This seems like a most effective way to reduce the production cost of ethanol.

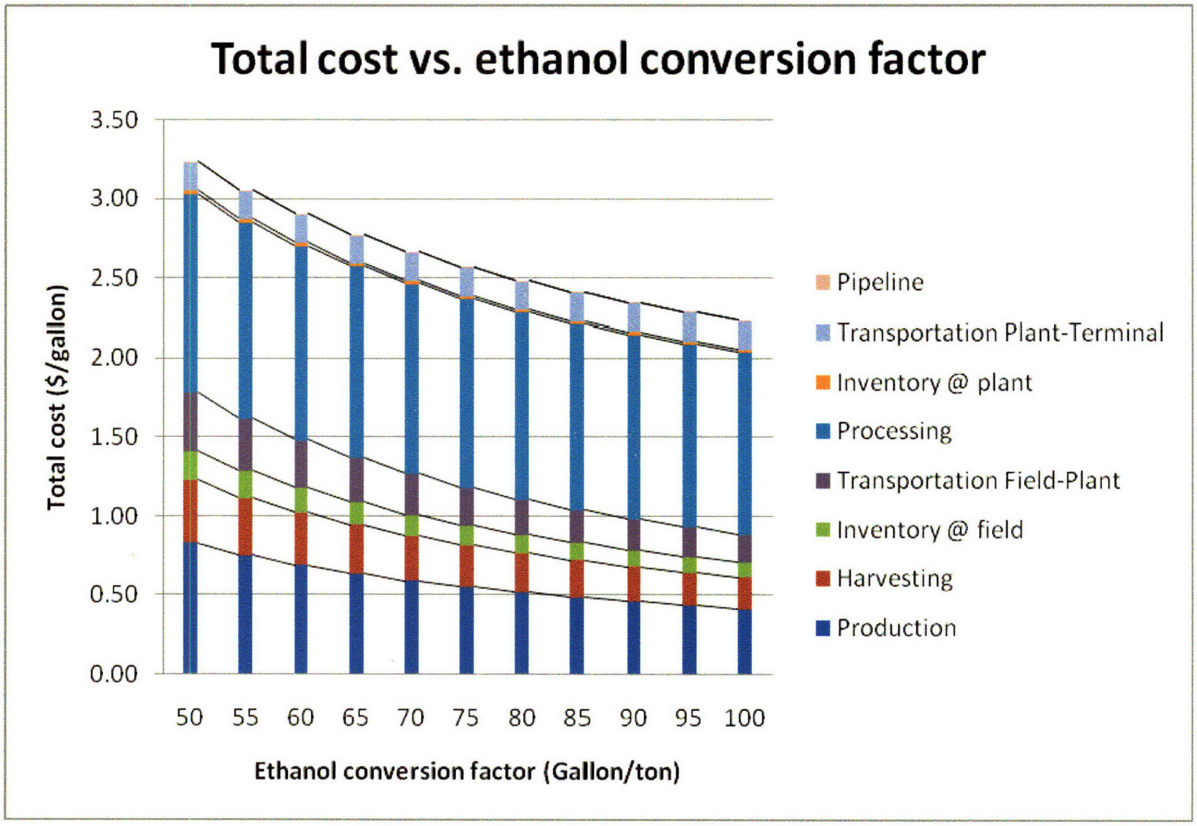


Figure 29: Sensitivity analysis of total cost per gallon of ethanol vs. ethanol conversion factor

In summary, we have determined a cost for producing ethanol ranging between $1.78 and $2.22 per gallon for wheat straw based ethanol and between $2.15 and $3.21 per gallon for switchgrass ethanol. The cost differences can be mainly explained by differences in biomass yield, biomass to ethanol conversion factor and distances between the farms and the plant and between the plant and the terminal location.

The main cost components are production and harvesting of biomass and ethanol refining which amount between 73% and 80% of the total cost. Transportation both from farms to the plant and from the plant to the terminal amount between 13% and 25% and finally inventory costs account for 1% to 7% of the total cost.

We have also determined that the parameter that shows the greater potential to decrease the overall production cost is the biomass to ethanol conversion factor. In fact an increase in the conversion factor of 42% can lead to a decrease in the total production cost of 15%.

6 Conclusions

Our model provides a tool for identifying the overall cost structure of this industry and also provides some insight on where the effort should be put in order to achieve the overall cost and production targets.

The main cost components for the production and distribution of ethanol correspond to the production and harvesting of the crop and its conversion into ethanol, which amount between 73 and 80% of the total cost. Transportation both from the field to the plant and from the plant to the terminal plays only a minor role in the overall total cost. Therefore in order to achieve the objective that cellulosic ethanol can be cost competitive with gasoline by 2012 (Davies, 2007), the emphasis should be put on finding ways to reduce the production and conversion costs.

Although not all parameters could be precisely determined, we performed sensitivity analyses for those parameters that we believe could have a greater impact in the final result. The sensitivity analysis provides some insight regarding the areas to focus attention on. We have found that the most effective way to reduce the overall ethanol production cost is to increase the biomass to ethanol conversion factor. This requires the development of new technologies that achieve a more efficient and cost effective transformation of biomass into ethanol. This will become a critical factor in the success of the ethanol industry.

On the other hand, transportation costs account for between 13 and 25% of the total ethanol production costs. The size of the plant, biomass yield, and average distance from the farms to the processing plant can determine the transportation cost from the field to the plant.

Larger plants will require a larger volume of biomass, increasing the planted and harvested area thus increasing the distances that inbound trucks need to cover. However, we found that this increased cost is compensated by economies of scale in the refining stage, although the overall effect is minimal. An increase in the plant size from 100 to 180 million gallon per year only causes a decrease in the overall production cost of $0.01 gallon. Similarly, higher biomass yields will reduce the requirements in terms of planted and harvested area, thus causing a reduction in the inbound transportation costs. An increase in the biomass yield for switch grass from 4.5 ton/acre to 23 ton/acre is likely to cause a decrease in the overall production cost of nearly 11%. This is one of the reasons why the development of dedicated crops has become more important in recent years.

Another important factor to analyze is the decision of where to locate the plants. We observed that the inbound transportation is more expensive than the outbound transportation in terms of dollars per gallon per mile. Ethanol is more dense than biomass and can take advantage of more efficient means of transport such as unit trains, barges or pipelines eventually, because the origin and destinations are somewhat fixed and con thus be more easily optimized. Biomass on the other hand is dispersed across the planted area so the way it is transported from the farms to the plant is usually by trucks. Therefore, it makes more sense to locate the refining plants closer to the biomass source than to the end customers. This seems to be the case in the few existing refining plants.

One of the drawbacks of our model is that it has a rather simplistic approach to determine the costs to produce ethanol. In our model, we considered only to types of biomass for simplicity and focus on two specific locations as sources of the biomass. It could be useful to extend this model to other locations and other types of biomass to understand the advantages and disadvantages of other supply chains. Similarly, a next step for this model would be to look into more detail at the cost structure of each particular stage in the supply chain. This would allow for a deeper level of understanding of the cost drivers and how some other factors that were not taken into account in our research, such as water content, ash content and biomass degradation, might impact the total production cost.

As mentioned above, future research in this area should be concentrated in study each stage in the supply chain in more detail, incorporating other factors such as the impact of cellulosic ethanol production on CO_2 emissions reduction and the disposal of byproducts and residues. These issues will impact the development of the cellulosic ethanol production industry.

Similarly, other areas of further research are network design and strategic analysis of the various players in the supply chain. Our work could be used as a first approach towards a more comprehensive strategic analysis of the cellulosic ethanol supply chain

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