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Modeling the Feasibility of Corn Stover Combustion as a Heat Source at Corn Ethanol Plants

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MODELING THE FEASIBILITY OF CORN STOVER COMBUSTION AS A HEAT SOURCE AT CORN ETHANOL PLANTS

by

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ABSTRACT

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Alternative energy sources are of prime interest for most of the nations across the world. Rising fuel prices and depleting petroleum reserves are of serious national and global concern. Bio-fuels if proved feasible for larger scale implementation could become the ideal breakthrough in easing the extensive dependence on fossil fuels and retaining the current engine technology of fossil fuels. Current methods of producing bio-fuels rely heavily on the consumption of non-renewable energy in the production process. Therefore, it is desirable to find renewable alternatives to these non-renewable energy sources.

Although bio-mass based fuels have been tested and proven to be applicable in gasoline engines, the technology must be studied and extended for implementation at a larger scale.

This study models the feasibility of corn stover as a heat source at corn ethanol plants. It states the amount of corn stover required for the necessary heat requirement and the model also considers the harvesting techniques, transportation costs, storage costs and the implementation costs.

Six ethanol plant locations were considered and evaluated for the viability of installing a biomass fired system in addition to estimating the amount of raw material needed to run the plant. The biomass systems have a decent payback period but are not being realized due to the initial costs involved and the inclination towards cellulosic ethanol. But, that is a technology of the future and

there is an immediate need to sustain the biofuels industry and this can be done through using biomass as a heat source. This model can be used for different locations as a number of parameters can be changed making it very flexible. This model will aide in the development stages of the project and will need an advanced investigation if moved forward through with the project.

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LIST OF ABBREVIATIONS

AFDC	Alternative Fuels Data Center
AKI	Anti-Knock Index
ASABE	American Society of Agricultural and Biological Engineers
BTU	British Thermal Unit
CA	California
CO	Colorado
CS	Corn Stover
DOE	Department of Energy
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
ESP	Electrostatic Precipitator
EV	Electric Vehicle
EVI	Electric Vehicles Initiative
GHG	Greenhouse gases
I.C	Internal Combustion
IA	Iowa
IEA	International Energy Agency
IER	Institute for Energy Research
MGY	Million gallons per year

MLY	Million Liters per year
MMBTU	Million British Thermal Unit
MON	Motor Octane Number
MTBE	Methyl Tertiary Butyl Ether
NE	Nebraska
NG	Natural Gas
NHV	Net heating value
NY	New York
OECD	Organization for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PADD	Petroleum Administration for Defense Districts
PTO	Power Take-off
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
RON	Research Octane Number
TX	Texas
USDA	U.S. Department of Agriculture
VEETC	Volumetric Ethanol Excise Tax Credit
VM	Volatile Matter

LIST OF SYMBOLS

A_C	Amount of Corn
A_{CS}	Amount of Corn Stover
A_{CSA}	Amount of Corn Stover Available
A_{FC}	Annual fuel consumption
A_{NG}	Amount of Natural Gas
A_S	Amount of Soil Required
P_{pto}	Power of the equipment
Q_{Act}	Thermal Energy Available
Q_{avg}	Average fuel consumption
Q_E	Heating Energy Requirement
Q_{tot}	Total Heat Requirement
CC	Capital costs
D	Depreciation
FC	Fuel costs
L	Lubrication costs
LC	Labor costs
O&M	Operations and maintenance
P	Payback period
P	Payback period
PP	Purchase price
P_T	PTO equivalent power

Q_s	Specific fuel consumption
R&M	Repair and Maintenance
RF	Repair factor
SI	Simple annual interest
SP	Salvage price
TAC	Total annual costs
TC	Hourly cost of transportation
TS	Total savings

CHAPTER 1 : INTRODUCTION

Energy has been a necessity from time immemorial. As the world advanced, so did the different ways of producing and utilizing the energy. For over a century, fossil fuels and other non-renewable energy resources have been predominantly used in transportation, industrial, commercial and residential sectors. Although these resources are available abundantly and are sustainable for the years to come, their demand and consumption pattern is causing an imbalance in the environment with far-reaching implications. Renewable resources are more widely available which reduces the dependence on oil imports from politically-unstable regions. There is a tremendous interest, in particular, to search for an alternative fuel for transportation purposes as major production of these fuels is from petroleum. Concerns on the disturbances in the ecosystems and energy security have prompted the need to search for alternatives. Hence, there has been extensive research on biofuels as one method for sustainable development.

Ethanol, one among the biofuels, has a good market in the U.S for use in spark-ignition engines as a fuel additive and an oxygenate. Ethanol is regarded as a potential alternative fuel as it is made from corn that uses solar energy to grow, but the production process of ethanol requires large amounts of process heat which is obtained from natural gas. Hence, there is a need to increase the amount of renewable energy that is used during the production process so as to reduce the consumption of fossil fuels, reduce the greenhouse gas emission and improve the energy costs of the plant.

The renewable source that can be considered for the heat requirement is biomass combustion. Combustion is a technology that has been well-developed and biomass is a resource that can be made readily available. Ethanol is produced from corn, and the residue that is left-over in the field can be considered as a potential feedstock for biomass combustion.

The major purpose of this project is to create a model to evaluate the feasibility of using corn stover combustion for the necessary process heat at the ethanol plant. The model can be used with plant-specific information to accurately estimate the amount of corn stover that is required to replace natural gas as a heat source. The project takes into account the harvesting, storage and transportation costs to estimate the feasibility of using biomass as a potential heat source. It also takes into account the current natural gas prices to give a fair estimate of the pay-back period and cost-savings of the installation of a combustion plant. There are various factors to be considered for the economics of the stover combustion and it is not quite straightforward. There are different harvesting techniques and the choice of the technique depends on the certain location and the harvest window which is hard to determine because of the changing weather conditions.

This project is an extension of the work of Kumar (2009) where he created a model for the energy requirements of a dry mill ethanol plant and which was continued by Ehrke (2012) where she modelled the installation of wind and solar energy at ethanol plants. This work explores the possibility of using a different alternative energy source, biomass combustion, for replacing the process heat in ethanol production facilities.

The renewable energy sector continues to grow and has renewed interest in developing new technologies to improve the efficiency of vehicles, improve the process of producing biofuels, and decrease the equipment prices due to the environmental policies, and security concerns. The growth in market leads to a more economical process.

The following chapters discuss the global energy market and the trends in the U.S as to how ethanol production is expanding. Market projections for the energy sector is also been shown to indicate what the future of energy and the energy costs look like in the next couple of years. Prior to examining the feasibility of corn stover combustion, an extensive literature review of the

ethanol production process, the combustion processes of biomass and the harvesting methods of corn stover was conducted and this is presented in Chapter 2. Then a descriptive model is analyzed and the approach for building the model along with determining the costs is discussed. In the Conclusions and Recommendations, the effectiveness of the modeling and further improvements has been discussed.

Biofuels will play an important part in a country's economy and in the future of energy sector. Using biomass combustion as a heat source for ethanol plants significantly reduces the consumption of fossil fuels thereby, reducing overall energy costs.

CHAPTER 2 : BACKGROUND

2.1 Introduction

As the world energy demand increases, energy has become a major concern in both political and environmental world security. Fossil fuels dominate as a primary energy source in any economic sector. Although these fuels have at least a few decades before they are cost prohibitive, it is important that we search for alternative sources so as to avoid energy shortages later and also, there needs to be sufficient time to make such sources sustainable. The world economy is a major factor in determining energy trends and demand. Biofuels, wind, and solar are not only sustainable for the future generations but, they also provide a viable solution to the reduction of the consumption of fossil fuels.

The following sections give a brief background of the world's energy demand and consumption patterns, the transportation sector, ethanol properties and the use of biofuels in the U.S. market.

2.2 Energy demand and consumption

For many centuries, a primary source of energy to heat houses and provide power to the world around us was wood. During the Industrial Revolution, coal and oil took over as the major energy sources. Since then, the world energy consumption has been doubling every 14 years. Studies indicate that coal and oil do not have the potential to be sustainable for the future generations. [1] [2]

According to EIA [3], global production of energy will be the same as the consumption of energy for the year 2016. This pattern may remain constant for a while but various studies indicate that it will become increasingly difficult to extract the resources in the required quantities. [2] [4]

There are primarily two kinds of energy sources, 1) Renewable Energy Sources and

2) Non-renewable Energy Sources. While the former refers to the sources that have the potential to be sustainable, the latter refers to the sources which are not environmentally sustainable for the future generations. Examples for renewable energy sources are 1) wind, 2) solar, 3) geothermal, 4) hydro-power and 5) biofuels. Examples of non-renewable sources are 1) coal, 2) oil, 3) natural gas and 4) nuclear fuel.

As can be seen in Figure 2.1, fossil fuels/non-renewable fuels account for about 91% (30% coal, 24% natural gas, 33% oil and 4% nuclear) of the world's energy consumption out of which 51% is accounted to the transportation sector and the remaining for the industrial, commercial and residential sectors. [5]

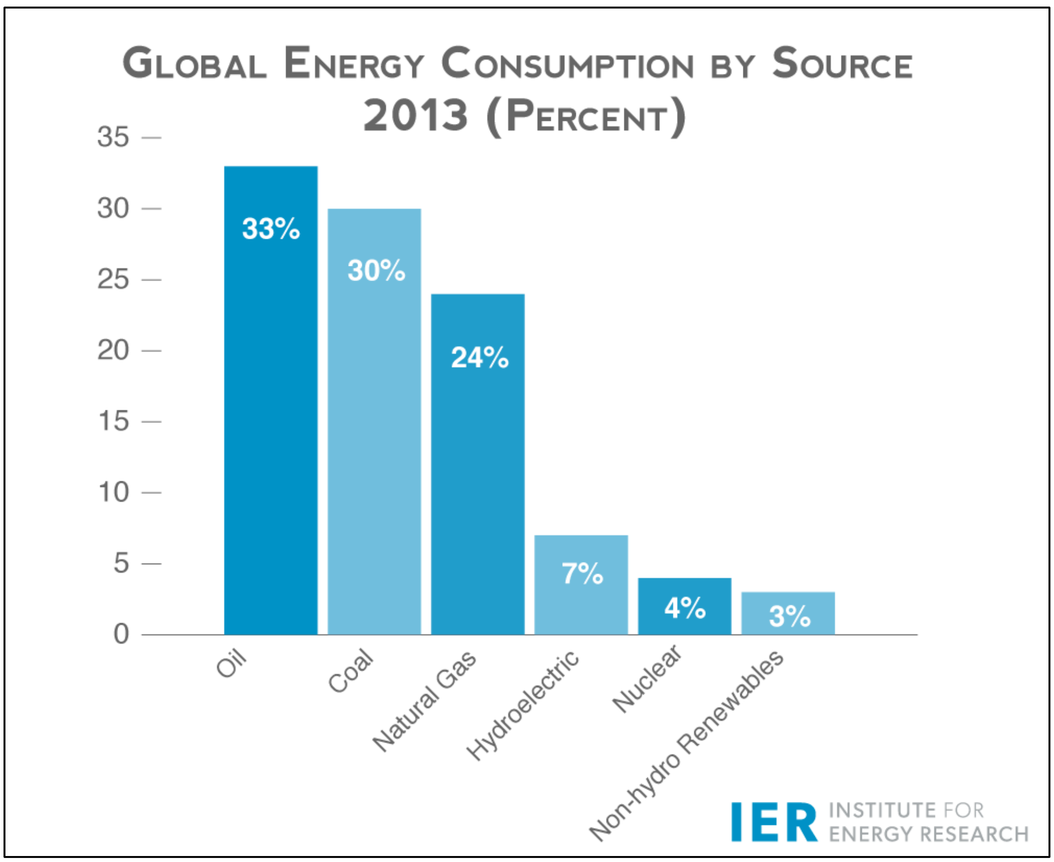

Figure 2.1: World Energy Consumption (Institute for Energy Research)

Studies estimate that based on expected reserves and consumption patterns, the time remaining before coal reserves are exhausted is 217 years, while natural gas has 65 years and oil has 42 years [2]. These are best estimates for the lifetime of the fossil fuels as they cannot be stated with certainty because of the unknown future changes in energy demand as well as uncertainty in finding additional reserves. Declining supplies will dramatically increase the cost of energy unless there is a shift toward unconventional/renewable sources. In addition, these non-renewable sources have an environmental impact with huge consequences.

Figure 2 contains an outline of the projected world energy demand as given by the US Energy Information Administration in their publication of the World Energy Outlook 2014. It can be seen that Asia is the growing dominance in energy trade and demand. It can also be noted that, China dominates Asian demand closely followed by India.

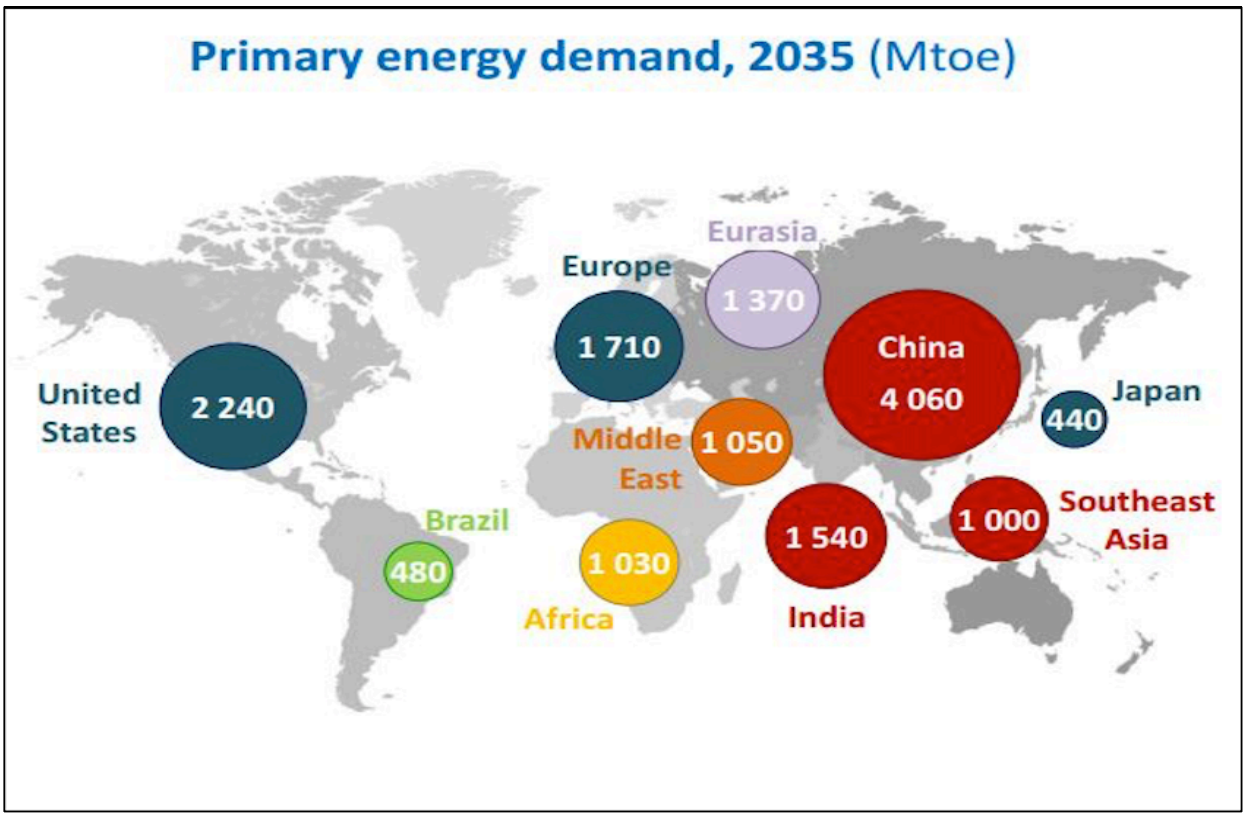

Figure 2.2: World Energy Demand, projected to 2035. (US-EIA, 2013)

As can be seen from Figure 2.2, the countries outside of the Organization for Economic Cooperation and Development (OECD) will account for a 60% increase in the demand for energy by 2035 as their economies continue to grow while that of the OECD countries have insignificant increase in energy demand. According to the EIA, the energy use per capita for the OECD countries will change very little from 190MMBTU in 2010-2040 while the non-OECD countries will see a rise from 50MMBTU to 73MMBTU by 2040.

This energy growth is mostly in the liquid oil consumption in the transportation sector and so there is a continued need for the increase and development of renewable sources in this sector. This will result in lowering the dependence of foreign oil in the United States as the consumption would lower quite significantly.

The global energy market is unstable and will result in conflicts as the demand for energy rises. Throughout the history of the energy market, there have been two oil crises in the United States, the first one in 1973 and the second, in 1979. This brought gas shortages, economic recessions and the need for energy conservation. As a result of the second crisis, in 1978, the United States government eliminated a federal fuel tax on gasoline blended with 10% ethanol. This still continues as a method of reducing gasoline consumption and as a result, increases the energy independence of the United States.

Petroleum, which includes crude oil, gasoline and diesel fuel, is by far the largest energy import and the most-consumed form of energy in the U.S. In 2014, according to EIA, the U.S imported about 9 million barrels per day (MMb/day) of petroleum from 75 countries and exported about 4 MMb/day resulting in net imports of 5 MMb/day. About 46% of the crude oil that was processed in the U.S refineries was imported [6]. This accounts for about 27% of the net import consumption, the lowest level seen since the year 1985.

As shown in Figure 2.3, the transportation sector accounts for about 80% of the petroleum consumption in the U.S. [7] Renewable fuels account for only about 7% of the consumption in this sector. This shows that petroleum imports and usage in the U.S market greatly influences the economy of the country and also, makes it dependent on foreign oil.

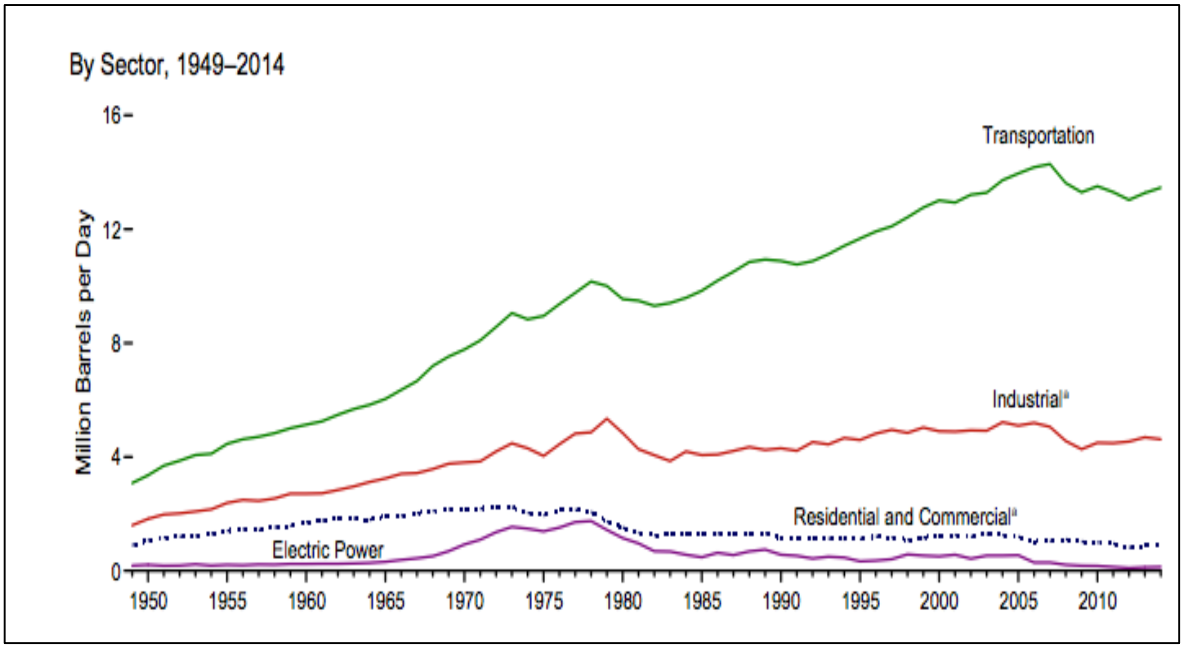

Figure 2.3: Petroleum Consumption by Sector in the U.S (US-EIA, 2015)

The increase in oil consumption and the decrease in the available sources has resulted in the development of gasoline alternatives. It should be noted that the price of oil depends on the discovery of new oil sites, the state of global economy, and global relations.

Figure 2.4 shows the world oil prices in three cases. The first is the reference case where the oil price decreases from 39% in 2014 to 37% in 2020 as a result of the U.S crude oil production and the decrease in world oil prices. It increases to 41% by 2040 in response to the demand in OECD countries. The second, is the Lower Oil price case where the oil prices increases slowly from 2015 to 2040 as a result of higher investment by OPEC and low demand by OECD countries. This case sees a rise from 38% in 2015 to 51% in 2040. The third, is the Higher Oil price case

where the oil prices increase as a result of significant reduction in the OPEC production coupled with high OECD countries demand. This case will see a decrease to 33% by 2025 and then an increase to 33% by 2040. [8]

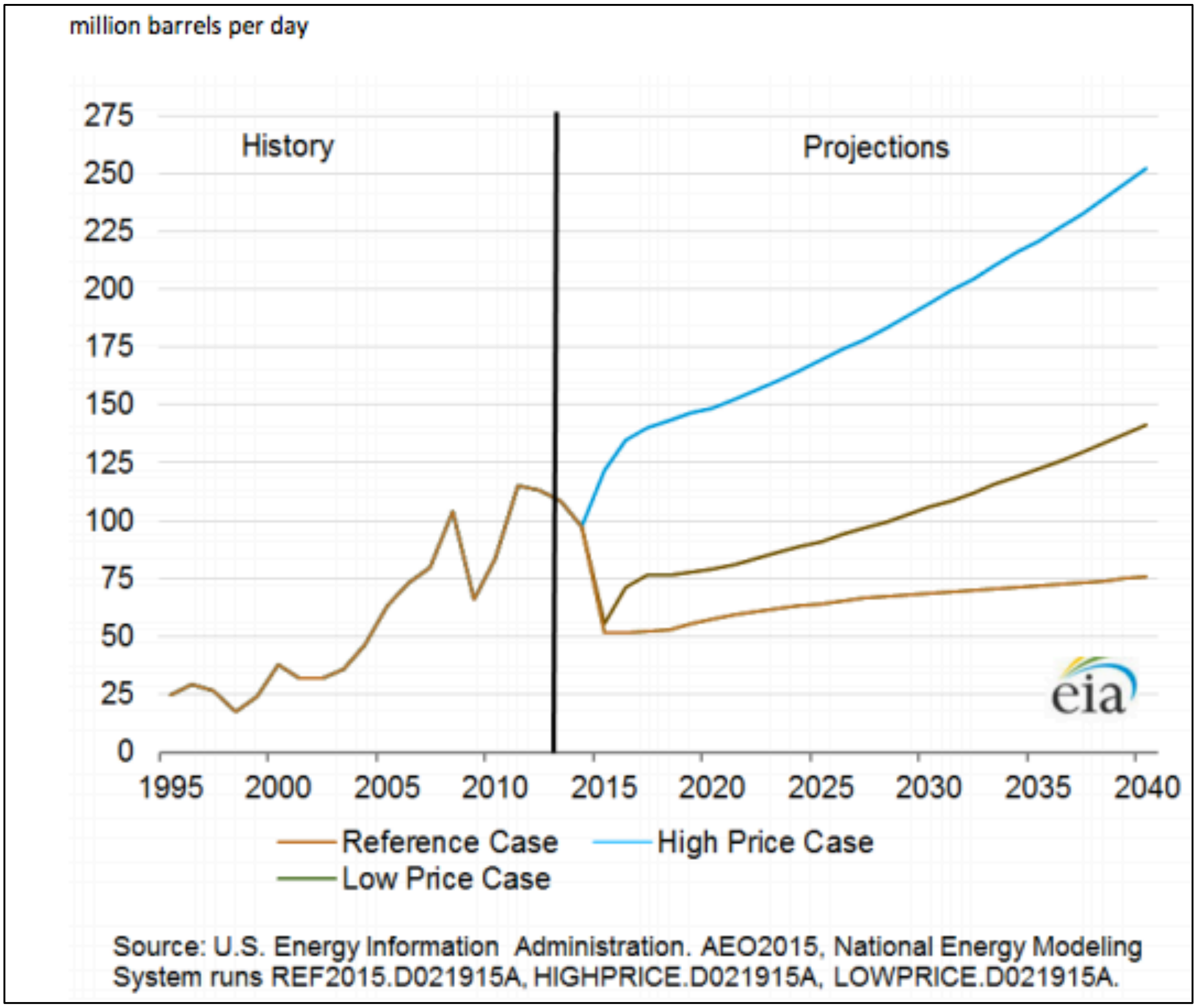

Figure 2.4: World Oil Prices in three cases, 1995-2040 (US-EIA, 2015)

There was a rise in oil prices in the early 1980s as a result of the two oil crises in the 1970s. It rose through the 2000s as well but, as a result of the economic downturn, it dropped in 2008. The world demand for oil in comparison to the oil supply determines the cost of oil and the oil prices are currently dropping. But, referring back to Figure 2.4, we notice that the oil prices are highly unpredictable and this is one of the many reasons to look for an alternative source.

The transportation sector can be made sustainable through the use of electric/hybrid vehicles and also, biofuels. Electric vehicles are those vehicles which run on an electric motor and a rechargeable pack of Lithium-ion batteries. These vehicles have the potential to remove the present internal-combustion engines entirely out of the equation resulting in lower petroleum consumption. Although there are advantages and advances in vehicle electrification, there are significant barriers that are unavoidable in the face of widespread adoption. These barriers could be in the form of technology, finance, market or policy challenges and hence, an electric vehicles initiative (EVI) has been launched by IEA in 2010 with over 16 member governments. This is dedicated to the acceleration of the introduction and adoption of electric vehicles. They aim at overcoming these barriers by investing in research, innovative policy and business solutions. [9]

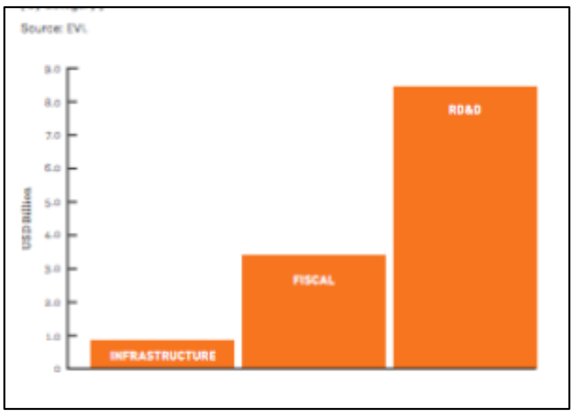

Figure 2.5: EV spending by category (2008-2012)

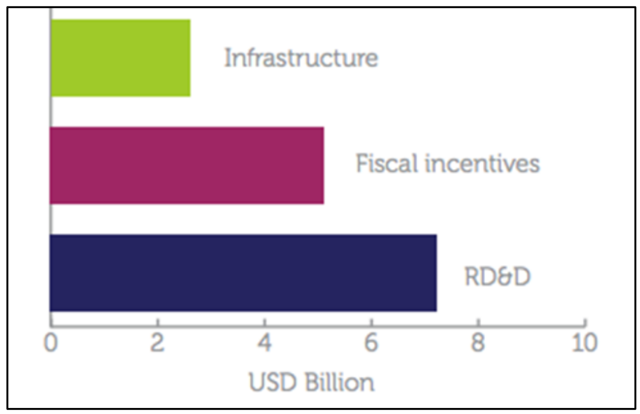

Figure 2.6: EV spending by category (2008-2014)

As shown in Figure 2.5 and 2.6, the Global EV Outlook published by the IEA for the year 2015 shows an increase in investments for infrastructure and fiscal initiatives from 2012-2014, resulting in a decrease of battery costs and an increase in sales of electric vehicles. [10] [11]

Although, there has been considerable growth in the electrification of the global vehicles, it still occupies only a 1% share in the global market. This suggests that the globalization of electric

vehicles is a long-term ambition. Hence, there is a need for a sustainable fuel for the present generation and for the near future.

2.3 Biofuels

Biofuels are fuels which are processed from biomass and bioenergy is the energy that is derived from these fuels. Biofuels are those fuels that are produced from plant matter and they are deemed as carbon-neutral sources as they absorb carbon-dioxide from the atmosphere for the process of photosynthesis. There are two types of biofuels:

1. First-generation biofuels-they are derived from biological sources such as starch, animal fats, sugar and vegetable oil. The processes to produce these fuels is developed and currently in practice throughout the world. Examples include ethanol, biodiesel and biogas.
2. Second-generation biofuels-they are considered to be advanced sustainable fuels and the production techniques are currently under research. These are derived from cellulosic materials like agricultural bi-products and are considered to be more sustainable. An example is cellulosic ethanol.

The U.S has taken a stance for developing renewable fuels by introducing tax incentives ethanol-blended gasoline in 1978 which continues even today to reduce the dependence on foreign oil. Kauffman et.al states the Energy Policy Act of 2005 which created the RFS program and was subsequently revised and expanded followed by the EISA of 2007 and is currently referred to as RFS2 [12]

The RFS program is a policy to reduce the GHG emissions along with increasing energy security for the U.S. The policy requires a certain volume of a renewable fuel to be mixed with petroleum-based transportation fuel. The expansion of the program requires increasing amounts of

renewable fuel to be added to the transportation fuel escalating by 2022 to about 36 billion gallons. [13]. Figure 2.7 shows the volume requirements that have been established based on the EISA-legislated standards by the EPA which administers the RFS program.

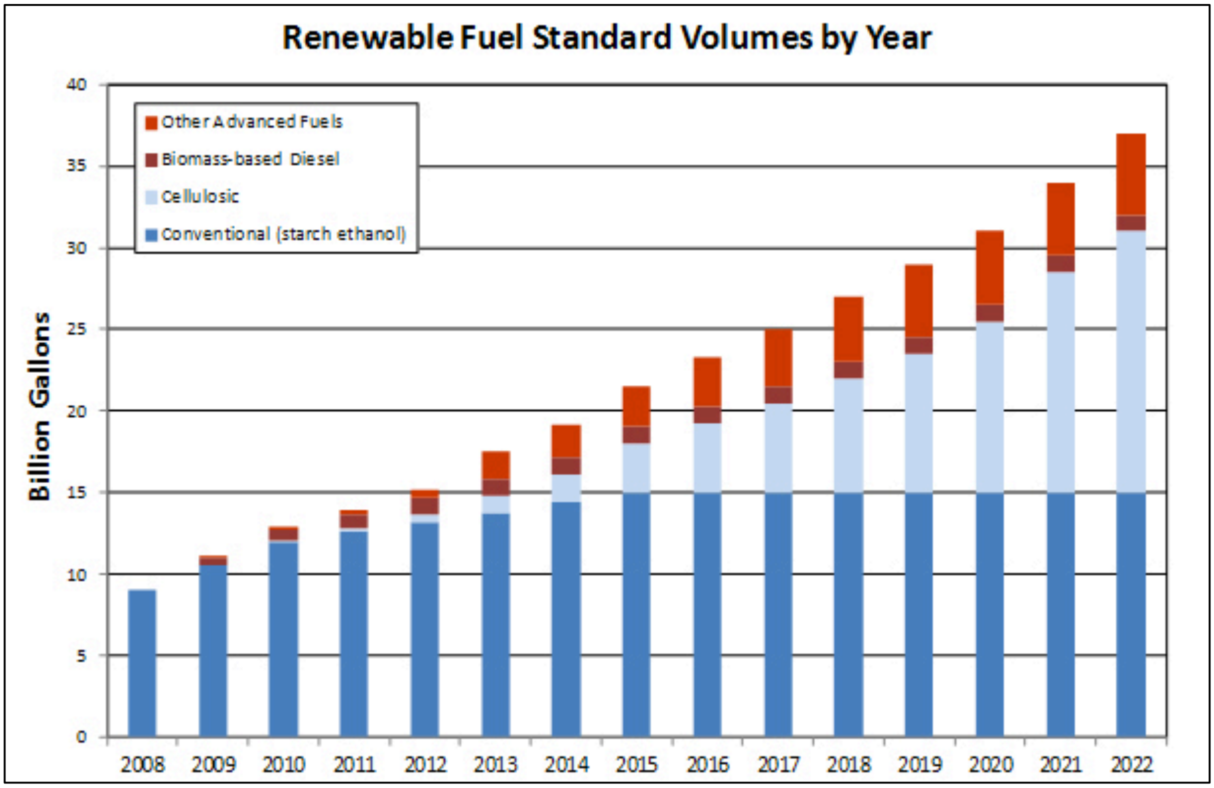

Figure 2.7: RFS Volumes by Year [14]

The four categories of biofuels which are included in RFS2 are as follows.

1. Total Renewable Fuels-These have to reduce the lifecycle of GHG emissions by at least 20% to qualify and the potential feedstock includes corn. The mandate grows to nearly 36 billion gallons by 2022.
2. Advanced Biofuels-They have to reduce the lifecycle of GHG emissions by 50% to qualify. The potential feedstock includes non-corn feedstocks like sorghum or wheat and cellulosic materials. The mandate grows to 21 billion gallons by 2022.

3. Biomass-based Biodiesel-They have to reduce the lifecycle of GHG emissions by 50%. The potential feedstock would be the one which can be processed to diesel fuel.
4. Cellulosic Biofuels-These have to reduce the lifecycle of GHG emissions by 60%. The potential feedstocks are cellulosic materials.

From Figure 2.7, it can be seen that the regulations established shows impressive increase in the use of biofuels, increasing the production of these fuels. It can be seen that the production of conventional biofuels is constant while there is a moderate growth in cellulosic biofuels and the advanced biofuels.

The realization of the RFS mandates is delayed as there has not been much progress in the production of cellulosic ethanol. However, there are three cellulosic ethanol plants that have been recently opened and are expected to offer production of cellulosic ethanol at a meaningful scale. [15]

Source: Republished with permission from POET-DSM

Figure 2.8: Aerial view of POET-DSM cellulosic ethanol plant (US-EIA, 2014)

The RFS mandates help reduce the gasoline consumption which in turn reduces oil imports which improves the U.S energy independence. The biofuels can also reduce GHG emissions at a significant level.

2.4 Ethanol

2.4.1 Introduction

Ethanol has been in use for many years as a fuel additive to reduce pollution, improve the octane rating of the fuel and to reduce gasoline consumption. Ethanol, otherwise known as ethyl alcohol is an alternative fuel that is an oxygenate and an octane enhancer *[16]*. It is hydroscopic, corrosive to common metals that are used in fuel systems and has less energy than gasoline, but the heating value is significantly lower. As can be seen from Table 2.1, the octane rating and heat of vaporization are higher for ethanol as compared to gasoline. *[17] [18]*

Table 2.1: Fuel grade properties of Gasoline and Ethanol

Property	Gasoline	Ethanol
Research Octane Number	91-93	109
Motor Octane Number	81-84	90
Anti-knock Index	87-88	99
Density(kg/L)	0.75(0.72-0.78)	0.79
Heat of vaporization(kJ/kg)	349	921
Reid Vapor Pressure at 37.8°C (mmHg)	414-776	119
Net Heating Value(NHV) MJ/kgfuel	44	27

The octane rating is a measure of the fuel's ability to resist auto-ignition and knock in spark ignition engines. The anti-knock tendency of fuels is determined by two tests: the research octane number (RON) and the motor octane number (MON). The anti-knock index (AKI) is an average of RON and MON and has been used as an octane rating for gasoline in the U.S. The modern engines performance is now better correlated with RON than AKI. Ethanol-gasoline blends have improved octane ratings and the RON increase is essentially linear when evaluated using molar ethanol content. [19] [17]

2.4.2 Ethanol Use

Ethanol blends of E5-E25 are typically used in more than 20 countries in the world. The list of ethanol blends used around the world are shown in Table 2.2 [17]

E100 is a good fuel for I.C Engines because of the properties mentioned earlier but, has poor cold-start properties. On the other hand, E85 has similar cold-start properties as that of 87 octane gasoline. Ethanol addition to gasoline has its own challenges, including increasing (or decreasing) the Reid vapor pressure (RVP) and preventing the transportation through existing pipeline systems due to risk of contamination by water. In the U.S, 90% of the gasoline blends are transported by train or truck. (Kutz, 2008)

Table 2.2: Ethanol Blends in various countries

Country	Ethanol Blends	Legal Use
USA	E10/E15/E85	Mandated only in certain states
Brazil	E20-E25	Mandated
Canada	E5	Mandated
China	E10	Nine provinces
India	E5	Mandated
Netherlands	E5/E10/E15	Optional
Mexico	E6	Mandated
Thailand	E10/E20	Mandated
Austria	E10	Optional
Denmark	E5	Optional
Finland	E5/E10	Mandated
Germany	E5/E10	Optional
Ireland	E4	Mandated
Romania	E4	Mandated
Sweden	E5	Mandated

2.4.3 U.S. Ethanol Market

The U.S and Europe use E85 in flexible-fuel vehicles and Brazil uses blends of E20-E25. It is primarily processed from corn in the U.S and sugarcane in Brazil. Ethanol can be processed from agricultural wastes/bi-products and has shown promising advantages over corn ethanol, but this is still in the development phase.

As of January 1, 2015 EIA reported that there are 195 ethanol plants with a total nameplate capacity of 14,757(MMgal/year). The majority of ethanol production capacity of 13,151 MMgal/year comes from PADD 2 district which is the mid-west area. [21]. This is because the plants are located in closer proximity to the corn-producing farms thereby reducing the transportation costs and ensures adequate supply. Figure 2.9 shows the location of ethanol plants in the United States as of the year 2013 and also, includes the corn production by county.

The U.S consumes about 130-145 billion gallons of gasoline blends a year. These blends only consisted about 10% ethanol. The U.S has recently opened market to E15 and vehicles have not reported any cases of engine damage. Today, E15 is approved for all vehicles built in 2001 or later and is being sold in 12 states, primarily in the mid-west regions. In addition, sales of FFV's have escalated in response to the RFS requirements and favorable economics. [22]

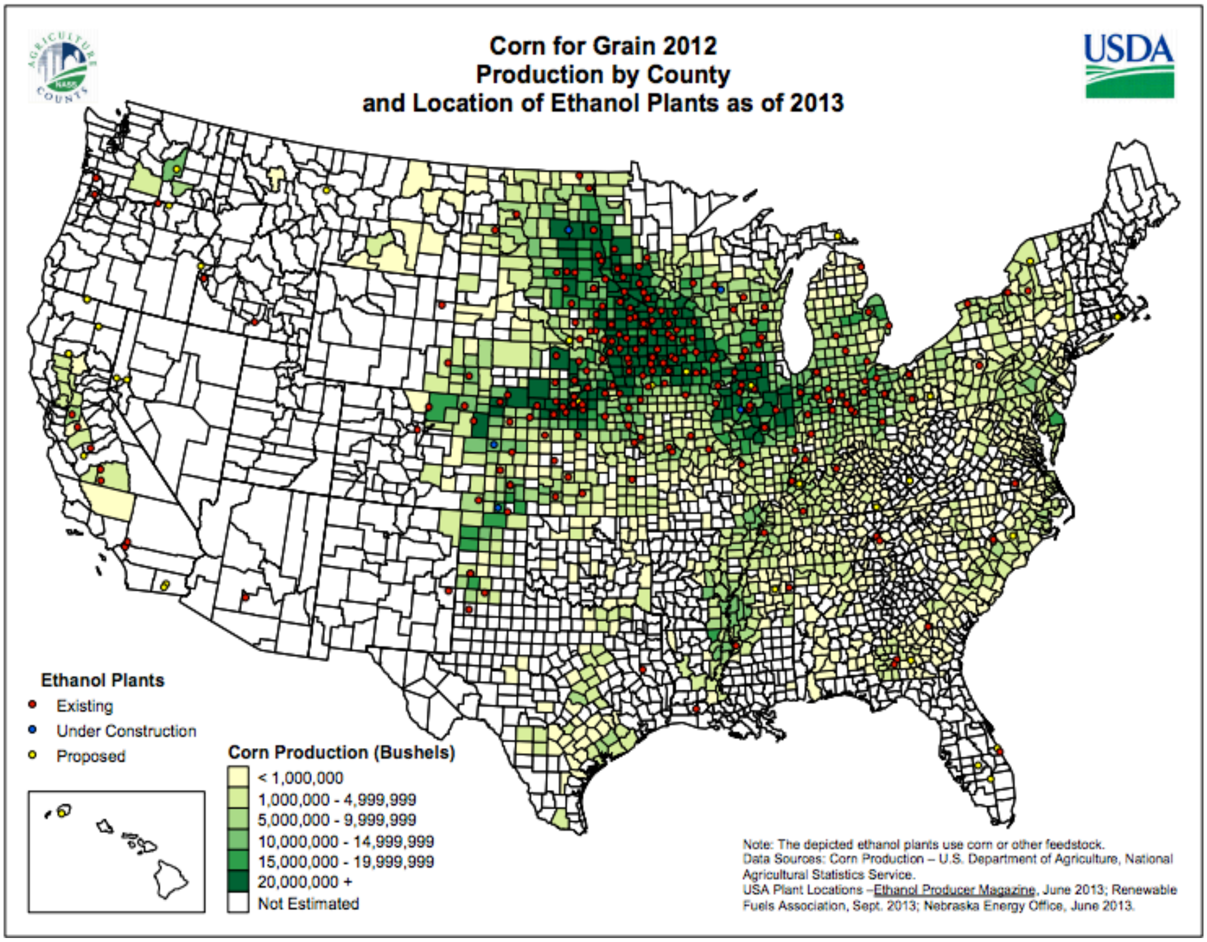

Figure 2.9: Corn Production by County and Location of Ethanol Plants [23]

Advances in technology, improved productivity in corn farming and ethanol conversion together with biofuel policies have contributed significantly for the growth of this industry in the past 20 years [24]. For ethanol to be competitive in today's market, government subsidies are required. In the U.S, the Volumetric Ethanol Excise Tax Credit (VEETC) is a policy to subsidize the production of ethanol. The tax breaks include "a 45-cent a gallon tax credit for gasoline blenders, a 54-cent a gallon tariff on imports, a $1.01 a gallon credit to cellulosic ethanol producers, and a 10-cent a gallon small-producer tax credit for ethanol." [25] This credit has been extended until the year 2016. Although there is a lot of criticism surrounding these subsidies, they return more revenue to the U.S Treasury than they cost [20]. This returns to the consumer in the form of

lower pump-prices. According to Consumer Federation of America, consumers could be saving $0.08 per gallon when purchasing gasoline with 10 percent ethanol as compared As a result, the U.S continues to have a secure energy supply and it has established itself as a major exporter of ethanol.

2.4.4 Food versus Fuel Debate

As the world progresses towards sustaining the development of biofuels, there are concerns that these fuels are competing with food production. In other words, there is a risk of diverting farm lands for the production of crops that may reduce the potential food supply. This is a more pronounced dilemma in the U.S as ethanol is produced from corn which is one of the largest sources of food in the nation. However, a number of studies and reports contradict these claims [26].

According to USDA, the corn crop that has been harvested in the year 2014/15 has a 5% decrease from the previous year. But the yield per acre has increased by 7.5% for the year 2014/15 from the previous year. [27] Figure 2.11 shows the production of corn in the U.S along with corn actually used for ethanol production. This shows that although the production rates are high for corn and the yield is increasing by every year as the farming techniques continue to improve, the corn that is used for ethanol production is only about 26%. [22]

The DOE continues to stress the importance of biofuels in the fuel market despite these debates in order to deviate the market from the volatile foreign energy markets. The USDA and DOE have conducted an assessment survey and concluded that the forest and agricultural resources have the potential to sustain the supply of 1/3rd of the nation's current petroleum consumption, without compromising on the food supply [28]. This shows that the nation has very high hopes for the future of cellulosic ethanol and the advanced biofuels.

This debate leads to the claims that ethanol has a negative energy balance, lowers the fuel economy and increases GHG emissions. The DOE reports a negative energy balance for gasoline which means that it takes more energy to produce than what is delivered [29]. There are claims that this is the same case with ethanol but, others disagree on the basis that the co-products in the process have not been adequately accounted for [30].

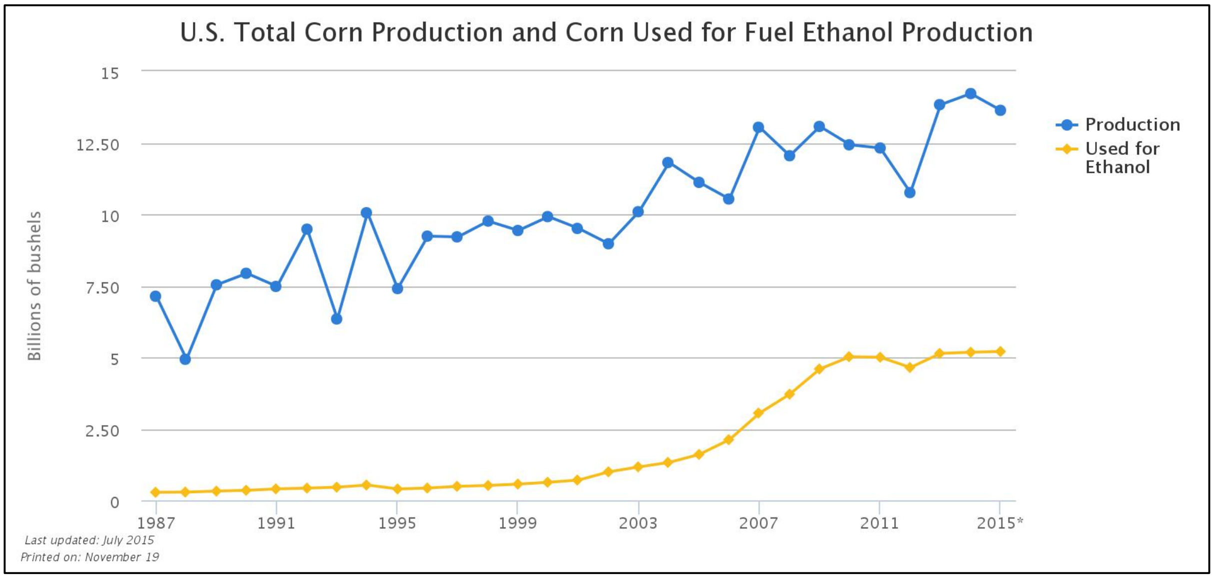

Figure 2.10: Corn Production and Corn Used for Fuel Ethanol Production [31]

Corn ethanol net energy balance is about 0.73 BTU energy in to deliver 1BTU while the cellulosic ethanol net energy balance is about 0.1 BTU. [32] The co-products can be used as animal feed and the energy required to produce them can be replaced and hence, have to be considered for the energy balance. Advances in technology and better farming techniques have considerably increased the efficiency of this industry.

The DOE has reported that biofuels burn cleaner than gasoline and are completely bio-degradable. The GHG emissions vary by feedstock and corn ethanol has the potential to reduce the emissions by 52% while cellulosic ethanol has the potential to reduce it by 86% [29]. Unlike

MTBE that was used as a fuel additive, ethanol is a clean burning additive. Even though there have been some disparities regarding the reduction of the lifecycle of GHG, ethanol still displaces about 500 million barrels of petroleum thus ensuring energy security.

The production of ethanol along with the government subsidies for biofuels enable the U.S to be independent of energy imports upto a significant level. It also makes the nation a world leader in the exporter of ethanol. Hence, there is a need to sustain this industry by relying on renewable fuels in the production process.

2.4.5 Production Process of Ethanol

The production method of ethanol depends on the feedstock used. For starch or sugar-based feedstocks, the process is short as compared with that of cellulosic feedstocks. Most of the ethanol in the U.S is produced from starch-based crops and 80% of the plants use the process of dry-milling as it is economical [14]. This is a production process where the corn is ground to a flour and fermented to ethanol with co-products of carbon-dioxide and distillers grains.

Typically, this process consists of grain handling and milling, cooking, liquefaction and saccharification, fermentation, distillation, dehydration and co-product recovery. Grain handling and cooking includes the corn that is brought to the facility and is ground to produce starch. Liquefaction and saccharification is the process where starch is converted to glucose and is fermented with yeast to produce beer. Distillation is the process of beer-to-ethanol conversion and is dehydrated to obtain pure ethanol. Co-product recovery is the process where the co-products are made market-ready. The main co-product, distillers grains, is sold as an additive to livestock feed. This is another reason for the location of ethanol plant close to farms as it significantly reduces the energy for transportation of the co-products. As of 2013/14, the U.S ethanol industry produced

about 39.2 million metric tons (mmt) of feed, making the renewable fuels sector one of the largest feed producing sectors. [33]

A typical ethanol plant requires 34695 BTU of process heat and 1.09 kWh of electricity to produce about 1 gallon of ethanol [34]. A survey that was conducted has shown that there has been a decrease in the amount of process heat and the amount of corn required to produce the same gallon of ethanol [35]. About 70% of the total process heat in an ethanol plant is required for the cooking and fermenting process. One of the major reasons corn ethanol is not considered completely renewable is the high amounts of heat requirement for the cooking and fermenting process. Over 90% of the facilities use natural gas for process heat and reducing this usage will make the production process of ethanol more sustainable.

2.5 Summary

From the study of the production process of ethanol, it can be seen that the process required high amounts of energy and has to be made sustainable to align with U.S goals of increasing the use of biofuels and reduce the pollution. Most importantly, this increases the energy security of the nation and helps it reach its energy goals.

CHAPTER 3 : LITERATURE REVIEW

3.1 Report on Previously-Published Literature

The main focus is to provide a thorough literature review on biomass combustion and its use as a heat source at Ethanol plants. This also discusses the harvest techniques and storage solutions for corn stover. As to how these are being incorporated in the project as been summarized at the end of this chapter.

3.2 Biomass Combustion

3.2.1 Types of Biomass

Biomass encompasses the living matter on Earth. It is a non-fossil and complex organic-inorganic source that is obtained from several natural or man-made processes [36], [37], [38], and [39]. Biofuels are fuels obtained from the processing of biomass and the bioenergy is the energy that is obtained from these fuels [36], and [39]. Biomass can be obtained from various sources depending on their origin [36], [37], (Vassilev S B. D., 2013). These sources are as follows.

1. Woody biomass- coniferous, stems, branches, bark, lumps and various other species.
2. Herbaceous and agricultural biomass-grasses and flowers, straws and their residues
3. Aquatic biomass-Algae, seaweed, marine or freshwater and others.
4. Animal and human wastes- meat-bone meal, manures, sponges, others.
5. Contaminated and industrial biomass wastes- municipal solid waste, wood pallets and boxes, waste papers and others.
6. Biomass mixtures.

The types of biomass that are the focus in this literature review are the first two types, woody biomass and herbaceous biomass, as they are gaining importance in the past few years as they have the potential to trap solar energy in the most efficient manner. Reasons that they are a

good reliable source of renewable energy are as follows [36], [37], (Vassilev S B. D., 2013), [38], [39] and [41].

1. They are a carbon neutral resource as the amount of carbon that is released into the atmosphere is recaptured in the process of photosynthesis.
2. They are not a contributor to greenhouse effect.
3. They have sufficiently low amounts of carbon and sulfur and the amount of sulfur dioxide that is produced is about 92% less than that of the solid fossil fuels.
4. Due to lower amount of sulfur, there is a lower possibility of acid rain.
5. They have a very good ignition stability as they consist of high volatile matter.
6. During combustion, they help capture some of the hazardous components by the ash formed.
7. Biomass sources help reduce the problem of waste disposal as they contain mostly waste matter.

3.2.2 Composition of Biomass

In order to understand the various aspects of biomass, one needs to look at the composition of biomass. This can be a daunting task as there are various sources from which biomass can be obtained, and the composition is based on the following factors [36]

1. The species of biomass.
2. The age of the species.
3. The conditions under which the species grew or is growing.
4. The process of growth.
5. The chemicals used for the species to grow.
6. The location of the species from polluted areas.

In general, biomass comprises of organic matter, namely cellulose, hemicellulose, lignin, proteins, sugars, starch and lipids [37], [38], [39], [41] and [42]. Of these, the first three are the main components in biomass that act like lithotypes in coal [37]; that is, these components help define the types in biomass. Lithotype is a stage one petrographic analysis and gives information about the properties of the coal type.

Cellulose is defined as a polysaccharide, an organic compound, that has various linear glucose chains [37], [38] and [42]. These chains have tendencies to form a structure that has crystalline and amorphous domains [42]. Biomass consists of two different phases of crystalline polymorph. Cellulose content is relatively low for woody biomass as compared to paper, cotton, and stalks [37]. Hemicellulose is a class of mixed heteroglycans that is amorphous in nature with little strength and accompanies cellulose in plant cell walls [37] and [42]. This is seen mostly in woody biomass [37]. Lignin is a polyphenolic polymer that is amorphous in nature, and is irregular in shape, acts as a binder in plants and accounts for $1/4^{th}$ of plant biomass [42]. These three components are highly variable and cellulose values decline in the following order: contaminated biomass, agricultural biomass, woody biomass and animal biomass. Hemicellulose values decline in the following order: woody biomass, agricultural biomass, animal biomass and contaminated biomass. Lignin values decline in the following order: softwoods, hardwoods, agricultural biomass [37].

The inorganic components of biomass include mineral matter such as silicates, oxides, phosphates, carbonates among others, along with poorly crystallized mineraloids and inorganic amorphous phases from natural or derived sources [37]. The occurrence and distribution of these components in both the biomass and solid fossil fuels play a critical role in the conditions of processing and applications relative to these fuels. There is a possibility of high variation of these

components from plant-to-plant due to the genetic, environmental, and morphological diversities. This inorganic matter is much less when compared to that of fossil fuels possibly because of the considerable differences in the occurrence and formation of these fuels as compared to biomass.

In addition to these components, biomass also consists of liquid matter, bulk extracts and organic minerals [37]. Liquid matter is a solution of complex origin with free ions and non-charged species. The common mobile elements are Cl, K, Mg, N, P, S and at times, Na and Ca. Bulk extracts, most commonly consist of water, ethanol, toluene, benzene and the corresponding mixtures extracted from biomass and hence, do not form a fundamental part of the structure of biomass. These values are variable and decrease as follows: agricultural biomass, woody biomass. It is generally high in content for corn grains, straws, grass and others. Organic minerals are oxalates which are end-products of plant metabolism. During water treatment, these are partially soluble in acidic-to-neutral conditions.

The above-mentioned composition was organic and inorganic phase compositions given by Vassilev et.al [37] while the Table 3.1 gives the chemical composition of biomass by Vassilev et.al. [36].

Table 3.1: Characteristic enrichment and depletion trends for the chemical characteristics (mean values) among the biomass groups and sub-groups specified.

Biomass group and subgroup	**Enriched in**	**Depleted in**
Wood and woody biomass	CaO, M, MgO, Mn, VM	A, Cl, N, P_2O_5, S, SiO_2, SO_3
Herbaceous and agricultural biomass	FC, K_2O, O, VM	C, H, CaO
Grasses	K_2O, O, SiO_2, VM	Al_2O_3, C, CaO, H, Na_2O
Straws	Cl, K_2O, O, SiO_2	C, H, Na_2O
Other residues	FC, K_2O, MgO, P_2O_5	Cl
Animal biomass	A, C, CaO, Cl, H, N, Na_2O, P_2O_5, S, SO_3	Al_2O_3, Fe_2O_3, M, MgO, Mn, O, SiO_2, TiO_2, VM
Contaminated biomass	A, Al_2O_3, C, Cl, Fe_2O_3, H, N, S, TiO_2	FC, K_2O, P_2O_5

The elements in biomass are given by major elements constituting C, O, H, N, Ca and K, and the minor elements constitute Si, Mg, S, Fe, P, Cl, Al and Na while Mn and Ti are the trace elements, which have high variations owing to the genetic variations and physiological conditions of biomass [36]. This composition of chemical elements is more complex for solid fossil fuels as compared to that of the system of biomass.

3.2.3 Conversion process to Bioenergy

Once the composition of biomass is understood, we can look at the various conversion processes of biomass to bioenergy. This can be done in two ways: Thermo-chemical and Biological processes [38], [39], [43], [41], [44], [45], and [46]. The processes have been put forward by Caputo et.al. as shown in Table 3.2.

The choice of these processes, generally depends on the type, properties and applications of biomass [43] and [44]. Fermentation and anaerobic digestion are the main conversion choices for biochemical processes [45] and these processes are conventionally not implemented as they require more reaction time which results in lower efficiencies when compared to thermo-chemical processes [39].

Table 3.2: Conversion processes of biomass

Conversion process	**Solutions**	**End Products**
Thermo-chemical process	Combustion	Steam Process heat Electric energy
	Gasification	Steam Process heat Electric energy Fuel gas methane
	Pyrolysis	Charcoal Bio-coal Fuel gas
Biochemical Process	Fermentation anaerobic digestion	Ethanol Water for irrigation Compost Biogas

Thermo-chemical processes as can be seen are classified into combustion, gasification and pyrolysis. Of these, combustion is in the developed stage while the other two are still in the developing stage [43]. The thermo-chemical processes have two methods of conversion depending on the type, properties and application of the waste biomass:

1. Converting the biomass into hydrocarbons after gasification,
2. Liquefy biomass through pyrolysis, liquefaction and others [41].

Pyrolysis is the process of converting biomass to carbonaceous charcoal, liquid and gases in the absence of oxygen [39], [43], and [41]. The first step is pre-pyrolysis where some bonds are broken but it is in the second step where the actual thermal degradation takes place [39]. There are two types of pyrolysis [39], [41]: (1) slow pyrolysis that takes place at slow heating rates and produces more char, (2) fast pyrolysis that takes place at higher heating rates and results, in favorable yields of liquid products. These products can be used in a variety of applications. Char can be used to produce activated carbon while pyrolysis gas can be used for power generation [43].

Gasification is a process of converting biomass to syngas—a combustible form of bioenergy--which contains H_2, CO_2, CH_4, and CO in the presence of an oxidizing agent which can be 35% oxygen or air [39], [43], and [46]. If air is used then the nitrogen present in air reduces the heating value of the produced syngas, but employing pure oxygen is more expensive. Using steam as an oxidizing agent increases the heating values. Employing carbon dioxide as an oxidizing agent is an advantage as syngas consists of CO_2. When employing pure steam or CO_2, an external heat source is required for the gasification process [46]. The first step in this process is pyrolysis, which is followed by series of oxidation reactions which are exothermic and provide enough heat for the next few steps. This is followed by the water-gas reactions and a methanation reaction to produce syngas [39].

L. Zhang et.al showed that syngas can be classified into four groups based on the heating values [39] as listed in Table 3.3

Table 3.3: Heating values and typical applications for different grades of syngas

Type of syngas	Heating values (MJ/m^3)	Applications
Low heating value gas	3.5-10	Gas turbine fuel, Boiler fuel, fuel for smelting
Medium heating value gas	10-20	Gas turbine fuel, hydrogen production, fuel cell feed, chemical and fuel synthesis
High heating value gas	20-35	Gas turbine fuel, SNG and hydrogen production, fuel cell feed, chemical and fuel synthesis
Substitute natural gas (SNG)	>35	Substitute for natural gas, hydrogen and chemical production, fuel cell feed.

Gasification reactions occur in reactors called as gasifiers [39], and [43] and the main process zones are (1) the drying zone, (2) the pyrolysis zone, (3) the combustion zone, and (4) the reduction zone. There are fixed bed, fluidized bed and entrained flow gasifiers [39], [43] and [46]. Fixed bed gasifiers are classified as updraft and downdraft gasifiers. As the name suggests the different zones are fixed and in the former, biomass and air move in opposite directions and produce syngas along with a lot of tar-like residues while in the latter they move in the same direction and reduce the amount of tar. Entrained flow gasifiers are gasifiers where the biomass

and air move concurrently producing syngas but reducing the overall thermal efficiency. For a fluidized gasifier, there is uniform temperature distribution resulting in syngas with a higher heating value. In this, air is introduced into the gasifier while the biomass is mixed with the circulating bed.

Combustion refers to the complete oxidation of fuel and this is the most widely used and developed process [39] [43], [41], [44], [45] and [46]. The three stages in the process of combustion are (1) drying, (2) pyrolysis, (3) reduction and combustion of volatile matter [39]. Almost 70% of the heat is generated from the combustion of volatile matter and this can be used as direct heating in small-scale applications, heating purposes in a boiler that is used to generate electricity [39], and [44]. At times, a pre-treatment process such as pelletizing or torrefaction is required to upgrade the biomass [43] and [44]. The slow heating of biomass isothermally is called "torrefaction" [47]. For small-scale space heating, the appliances used are wood fires, fireplaces, pellet stoves, central heating furnaces, over-fire boilers. If the burner-boilers are well-designed, efficiencies of over 90% are achieved [44]. Two of the main combustion systems that are employed in large-scale industries are fixed-bed combustors and fluidized-bed combustors [39], [43], and [44].

Fixed bed combustion is the simplest technology and, hence is widely used. In this, air passes through a fixed bed where the three stages occur and then using secondary air, combustion occurs in another chamber. The operating temperatures are between 800-1400°C The types of systems are grate furnaces and underfeed stokers. The different grate furnace technologies are fixed, moving, travelling, and rotating grates. These are primarily used for biomass with a high moisture and ash content. Depending on how the air and biomass are mixed, there are three operating systems: (i) counter-current flow, (ii) co-current flow, and (iii) cross-flow. Underfeed

stokers are used for biomass with low ash content and they provide a safe technology for small and medium scale applications. There are two chambers, one being the primary chamber through which air is supplied and the secondary chamber where combustion occurs.

Fluidized bed combustors have a high efficiency. The different types of technologies that can be used are circulating fluidized and bubbling fluidized beds. Air is injected from below into a self-mixing suspension of gas and solid bed material. The solid bed could be made up of silica sand, dolomite, limestone or any non-combustible material. Operating temperatures are 700-1000°C. In this system, good mixing of the fuel increases the flexibility.

These combustion technologies are used for power production and heat generation through steam turbines, steam-piston engines, water-tube boilers and superheaters [44].

3.3 Feedstock Supply

3.3.1 Corn Stover

Corn is the third leading cereal crop in the world following wheat and rice. The composition of corn is 64-78% starch, 8.3-11.9% cellulose fiber, 5.9-6.6% pentoses, 0.5-3.3% sucrose and minor amounts of glucose, fructose and raffinose [48]. The large amounts of starch present in corn makes it a valuable feedstock for ethanol production. The starch is broken down into simple sugars, which is then fed to the yeast to produce ethanol. In the year 2014, U.S produced 171 bushels of corn per acre. [49] Modern ethanol production techniques produce about 2.75 gallons of ethanol per bushel of corn.

Corn stover is an agricultural residue that is left over after the corn has been harvested. It refers to the stalks, cobs and leaves of the plant. The yield of corn shows that there is a large area that is being harvested and hence, corn stover yields will be very high. For the year 2014, 80.7 million acres was harvested for corn. So, the corn stover yields will be significantly high.

The amount of corn stover that is left-over is almost always on a 2000kg of corn stover/bushel of corn that is harvested on a dry basis [48]. Stover on a dry-matter basis accounts for approximately 50% stalks, 22% leaves, 15% cobs and 13% husks [50]

Hence, this acts as a potential biomass feedstock in the production of ethanol. Although there is research and development going on to produce ethanol directly from corn stover, the immediate concern ought to be the current technologies that are employed in the ethanol production and means to make it sustainable. This can be done by using the corn stover as a feedstock for the process heat generation at corn-ethanol plants as it would replace natural gas as a source.

3.3.2 Harvest techniques

Corn is planted in April or several weeks later and harvested in late October or early November. Corn stover should be allowed to dry down to 20% moisture before it is harvested and the average harvest window for corn stover is typically 40 days after corn grain harvest [51]The amount of corn stover that can be harvested from a field depends on various factors, including the tillage and crop management practices, the type and sequence of operations, the efficiency of the equipment and the environmental constraints. The total amount that is available in an area depends not only on the stover yield and collection fraction but also, on the proportion of corn acreage around the ethanol plant and the number of farmers who are contracted to sell the stover [52].

Corn stover is still considered as an agricultural residue and not as a co-product of farming because harvest practices and development concentrate more on maximizing corn grain harvest [53]. Stover can be collected in the form of chopped or baled stover and may require some pre-processing, such as chop retrieving or debaling/chopping, before it is used in the process of combustion. The final collection depends largely on the harvest window, moisture content, weather

changes and soil contamination which cause hindrances for the conventional stover harvest. Slower field drying is possible when stover is windrowed, and raked but, if there is a short harvest window then baling at low moisture contents becomes a challenging process. To reduce soil compaction, farmers may use a "rotating collection" approach where they can collect half of the corn stover from a part of the acre in the first year and collect another half from the other part of the acre in the following year. [53]

Recent interest in the use of corn stover as a potential source for bioenergy production has renewed research to develop alternate stover harvest systems that could reduce the number of field operations along with increasing the harvest efficiency. There are typically three harvesting techniques.

1. One-pass system: this system uses a configured combine which can be attached to a collection equipment. This system size-reduces the stover on the combine and can be either configured with a forage wagon to collect chopped stover or with a baler.

   Advantages- Higher stover yield with low ash content

   Disadvantages-Reduced grain harvest rate, and high combine power consumption.

2. Two-pass system: this system uses a combine that is modified to create a stover windrow during the harvest. This windrow is then harvested with a forage wagon or baler.

   Advantages-Requires fewer modifications than one-pass systems, may allow for some stover drying.

   Disadvantages-Lower yield as compared to the one-pass system with ash content

3. Three-pass system: this system uses a combine that is modified to create a windrow followed by shredding with a flail shredder. This is then harvested with the help of a forage wagon or a baler.

Advantages-Allows for drying of corn stover, increases the density of bales.

Disadvantages-Higher ash content due to soil contamination.

The baler is typically selected on the size required and it can be a round or a rectangular baler. A combine is a piece of farm equipment which processes and transports the grain and non-grain fractions in separate streams and can be modified. These systems can use either an ear-snap header where the husk, cob and some leaf and upper stalk are collected or a whole plant header where the whole plant above the ground is collected. [54] The selection of these techniques entirely depends on the type of yield required, density of the bales, the harvest window, the moisture content and the quality of the soil.

3.3.3 Transportation and Storage systems

Storage is essential for corn stover as it is harvested at a particular time of the year and is generally required by the ethanol plant throughout the year for process heat. In addition, efficient storage improves the drying of stover and increasing the process of pre-treatment, if any. The storage facility can be located at the plant, at the farm or at a location in between the plant and farm. Irrespective of the location of the storage facility, the collected stover has to be transported from the farm to the plant facility.

The stover that is collected can be stored indoors or outdoors. If the stover is baled, then it can be uncovered or plastic-wrapped whereas the chopped stover can be saved in large piles or bunker silos. For the three-pass systems, any of the storage options may be considered. For the two-pass and one-pass systems, uncovered storage of bales cannot be an option as they would be wet for aerobic storage. Typically, outdoor storage is a more economical option even though there would be some amount of dry matter loss. The indoor storage requires extra cost of a storage structure area which is greater than the cost of dry matter loss and hence, is generally not preferred.

For bales, the least expensive option was outdoor storage of wrapped bales. For wet, chopped stover, the least expensive option was storage in silage bags. [54]

3.4 Summary

Based on the literature review, as the combustion technologies require corn stover to be dry, no further discussion on chopped stover is considered. This is because baling is a more reliable option and has more energy density. As the harvesting methods depend on various factors and since this model has been designed to apply to any location, all the three methods have been considered separately and a best estimate of their costs has been given.

CHAPTER 4 : MODELING TECHNIQUE AND APPROACH

4.1 Introduction

There has not been much research on considering corn stover as a potential heat source for ethanol production as most of the research is currently inclined towards cellulosic ethanol. For cellulosic ethanol, agricultural residues such as corn stover can directly be converted to ethanol instead of corn grain. This is an innovative approach for sustaining the industry and even though there are cellulosic ethanol plants that are being developed, this industry might take a while to be sustainable. Hence, there is a need to sustain the current ethanol plants. For the current plants that use natural gas as a heat source, biomass combustion can be considered as an alternative heat source and a model to check the feasibility of such an approach is described below.

A model describing the heating requirements for ethanol and the amount of corn stover required was created to better understand the viability of using corn stover combustion as a heat source and assess the economics of the process. It takes into account the ethanol plants located in or around the corn farms to provide a reasonable pay back period. The model designed for this project is a spreadsheet-model which considers user-defined values for the ethanol plant and inputs for the harvesting equipment. The output data gives the harvesting costs for three different scenarios which enables the user to choose the best technique possible depending on the investment for the plant and the local weather conditions.

The model basis approach that is considered is technically precise and transparent. This model was designed based on the works of Kumar (2008) and Ehrke (2012) except that they worked on solar energy instead of biomass combustion. Using solar energy for heating purposes is a viable option but, considering that most of the ethanol plants are located in the Midwest, solar energy may not be as reliable or a particularly economically-desirable option. Corn stover is more

reliable as a potential source as the combustion technologies are well developed and as an advantage, corn stover is a source that is readily available from the farms which are producing the corn to make ethanol.

Hence, the model developed here incorporates corn stover combustion and takes into account the current and projected market prices to estimate yearly energy requirements, costs involved for the supply of corn stover and the pay-back period for the installation of these plants. This can be used for various locations of the ethanol plants and different market conditions. The following sections discuss the approach followed to calculate these output data from the user-defined values.

4.2 Feedstock Requirement

This section helps determine the amount of natural gas that is being used at the plants and the amount of corn stover required to produce the same amount of heat relative to natural gas. In addition, it calculates the amount of corn stover required based on the heating requirement of the plant and determines the land acreage that is needed to produce the required corn stover. User-defined values are as shown in Table 4.1.

Table 4.1 Ethanol plant inputs and typical values on the spreadsheet model.

Ethanol Plant Inputs			
	Input	**Units**	**Typical Values**
Ethanol Plant Capacity (PC)		Million liters per year (MLY)	3-1200 MLY
Heating Energy Requirement (Q_E)		MJ/liter	9.67 MJ
Total Heat Requirement (Q_{tot})		MJ/year	$29.01*10^6$-$11500*10^6$ MJ/year

The typical values are available online and in many other peer-reviewed papers [55]. The input cells of the model are yellow and the output cells are green. The first entry in the model is the plant capacity in MLY. All values are considered for anhydrous ethanol unless otherwise mentioned. The nameplate capacity is the main factor that determines the energy use for the facility. To estimate the total heating requirement that is needed by the plant, Equation 4.1 can be used.

$$Q_{tot} = PC * Q_E \tag{4.1}$$

The total heating requirement (Q_{tot}) in MJ/year is calculated by multiplying the plant capacity with the heat requirement to produce one liter of ethanol. On an average, a typical plant requires 9.67MJ to produce one liter of ethanol [34]. This need not be true for every plant as studies show that the heat requirement for ethanol plants is gradually decreasing [35] and hence, it is not necessary that every plant experience the same heat requirement. This value determines the output data hence, making the model flexible.

To calculate the output data, the process requires a step-by-step approach. Given the scale of some ethanol plants, the following criteria have been calculated.

1. Amount of natural gas required.
2. Amount of corn required.
3. Land acreage needed for the necessary amount of corn.
4. Amount of corn stover required that is required for the current plant.
5. Amount of corn stover that is actually available.
6. Thermal energy generated from the available stover.

The first two steps are calculated based on the input data. All calculations are on a yearly basis unless otherwise noted. The amount of natural gas required is based on the heating requirement of the plant (Q_E) whereas the amount of corn required is determined by the plant capacity (PC).

The amount of natural gas, A_{NG}, required for the necessary heat requirement is calculated using the following Equation (4.2).

$$A_{NG} = \frac{PC*10^6 \frac{liters}{year} * Q_E \ \frac{MJ}{liters}}{38 \frac{MJ}{m^3}} \tag{4.2}$$

The amount of natural gas used is calculated by multiplying the plant capacity with the heating requirement to produce one liter of ethanol. This value is divided by a factor that is

provided in the literature [34]. The conversion factor of 38 MJ/m^3. The plant capacity has been multiplied with 10^6 as the units are in million liters per year.

The amount of corn, A_C, that is required to produce ethanol based on the nameplate capacity is calculated using the Equation (4.3)

$$A_C = \frac{PC*10^6 \frac{liters}{year}}{2.76\frac{gallons}{bushel}*3.78\frac{liters}{gallons}} \tag{4.3}$$

The amount of corn grain required is calculated by dividing the plant capacity with a factor. Some studies show different results for the amount of ethanol produced from a bushel of corn; i.e., the USDA has reported that about 2.76 gallons of ethanol is produced with a standard deviation of 0.07 gallon/bushel of corn. As 1 gallon is 3.78 liters, the conversion factor has been used.

The amount of land acreage, A_S, to produce the required amount of corn is calculated using the Equation (4.4)

$$A_S = \frac{A_C\ bushel}{130\frac{bushels}{acre}} * 0.004\frac{km}{acre} \tag{4.4}$$

The land acreage is calculated by dividing the amount of corn required by a factor of 150. There exists an average yield of 150 bushels/acre and as one acre is 0.004 km, the conversion factor has been multiplied with the result.

The model also calculates the amount of corn stover that is actually available. As corn stover is the residue that is left behind once the corn is harvested, this is the value that is calculated from the amount of corn that is used. It is calculated using the Equation (4.5)

$$A_{CSA} = \frac{A_C\ \frac{bushels}{year}}{42\frac{bushels}{dry\ tons}} * 0.5 * 907.2\ \frac{kgs}{dry\ tons} \tag{4.5}$$

The actual corn stover, A_{CSA}, that is available on the field is calculated by dividing the amount of corn that is used, by 42. This value is then multiplied by a harvest index. Approximately 42 bushels of corn, yield 1 dry ton of corn stover. As 1 dry ton is equal to 907.2 kgs, the conversion factor has been used to convert A_{CSA} from dry tons to kgs. The harvest index is the ratio of the grain yield to that of the above-ground portion of the plant [56]. The harvest index depends on weather management practices and is given by Equation (4.6)

$$Harvest\ Index = \frac{kgs\ of\ grain}{(kgs\ of\ stover + kgs\ of\ grain)} \qquad (4.6)$$

Equation (4.6) helps in calculating the harvest index based on the corn grain and stover yields. As grain yield increases, the corn stover yield increases. Hence, the harvest index usually appears as a constant. In a normal year, the harvest index is 0.5 although it may range from 0.47-0.56. For this model, the harvest index that has been considered is 0.5.

The actual amount of corn stover can help determine the amount of thermal energy, Q_{Act}, that is generated from the set yield. The thermal energy that is generated is calculated using the Equation (4.7)

$$Q_{Act} = A_{CSA} \frac{kgs}{year} * 16 \frac{MJ}{kg} \qquad (4.7)$$

The thermal energy is the energy that is available from the corn stover and is calculated by multiplying the corn stover yield with a conversion factor that is given by 16 GJ/Mg (16 MJ/kg). Note that all the values are for yearly calculations and Q_{Act} is compared with Q_{tot}. From calculations, Q_{Act} is a fairly higher amount of thermal energy that is available and hence, the project costs also need to be considered.

The output results for these calculations are given in Table 4.2

Table 4.2 Spreadsheet model outputs for Ethanol plant

Output	**Value**	**Units (Yearly)**
Amount of natural gas used (A_{NG})		m^3
Amount of corn used (A_C)		bushels
Acreage required (A_S)		km
Corn stover available (A_{CSA})		kgs
Thermal Energy Available (Q_{Act})		MJ
Corn stover required (A_{CS})		kgs

As can be seen, this approach leads to the amount of corn stover that is actually required to produce the required thermal energy. The amount of corn stover, A_{CS}, that is required in terms of heat requirement is calculated using the Equation (4.8)

$$A_{CS} = \frac{Q_{tot} \frac{MJ}{year}}{16 \frac{MJ}{kg}} \tag{4.8}$$

As can be seen, the amount of corn stover required is calculated by dividing the yearly heat requirement in MJ by a conversion factor that is developed in the literature [34].

4.3 Project Costs

The investment costs and pay-back periods are the major considerations for the realization of a new business. The ability for the business to make a profit is one of the main concerns for a business owner. This is true for an ethanol plant that is considering shifting its heat source to a viable renewable energy source. This model considers realistic production costs of harvest, storage and transportation systems. It also gives an estimated pay-back period and the costs of implementation.

The major reason that corn stover combustion systems are not being realized at a plant level is the potential costs for harvesting, storage and implementation. Hence, this model is also designed to estimate the harvesting, storage, and implementation costs along with estimating the pay-back periods to find a realistic solution for the combustion systems. This model is split into two parts.

1. Determine the costs of feedstock supply.
2. Determine the cost of heat systems based on the feedstock supply.

4.3.1 Costs of feedstock supply

The feedstock that is considered here is corn stover and the costs of feedstock supply are divided into the harvesting costs, the transportation costs and the storage and preparation costs. As the corn stover is considered a waste product, there will be no consideration of a cost of the raw material.

4.3.1.1 Harvesting costs

There are three types of harvest methods of corn grain and corn stover. As described in Chapter 3, the three types of systems are one-pass system, two-pass system and the three-pass system. The harvest systems that have been considered are the one-pass system with an ear-snap

and whole-plant header, and two-pass and three-pass systems with an ear-snap header. The collection system considered is the baling option. As a brief review, one-pass systems use a combine to harvest the grain and stover and baling. The two-pass systems use a combine to harvest the grain and stover and then in the second pass, the stover is baled. The three-pass systems use a combine, a second pass for shredding the stover and in the third pass, the stover is baled. The one-pass system is a new technology, considered to be highly efficient and hence, is expanding. For the sake of consistency, the model considers the harvest of both grain and stover as the one-pass system is considered. The model also gives the costs only for the baling option for those plants that need only the stover from a particular field.

The model to determine the costs needs some user-defined values. If not specified, then costs are considered based on the market prices of the equipment.

As a note, a round baler over the rectangular baler has been considered as the power requirements and purchase prices are lower. A large tractor is used with the shredder and the baler. To understand the harvest systems that are considered and the type of equipment that are used in these systems, refer to Table 4.3

Table 4.3 Different harvest scenarios and the type of equipment used for each.

Harvest scenario	**Equipment Used**
One-pass	Combine modified at the rear with an accumulator and a baler
Two-pass	Combine, Baler (Tractor)
Three-pass	Combine, Shredder (Tractor), Baler (Tractor)

An engineering approach was used along with ASABE standards EP 496.3 and D497.5 [57] [58]. This has been provided in the literature [54] and has been verified through various other works [59] [60] [61].This approach has been modified according to the needs of the model.

There are two types of costs that are to be considered, the operating costs and the ownership costs. Table 4.4 presents the input values required to calculate these costs.

Table 4.4 Spreadsheet inputs and typical values for the harvesting costs section.

Equipment	**Price ($)**	**Typical Values ($)**
Combine		$325,000-500,000
Ear-snap header		$100,000-130,000
Whole-plant header		$125,000-150,000
Flail Shredder		$20,000-37,000
Round Baler		$35,000-80,000
Large Tractor		$90,000-300,000

The ownership costs consist of depreciation, simple annual interest, insurance, taxes and housing. These are called as fixed costs as they are independent of the machine hourly use. Depreciation, D, is the cost that results from wear, and the age of a machine. It is calculated using the Equation (4.9)

$$D = \frac{purchase\ price - salvage\ price\ (\$)}{useful\ life\ (years)} \qquad (4.9)$$

Simple annual interest, SI, is based off at 8% of the purchase and salvage price and is calculated using the Equation (4.10)

$$SI = .08 * \left(\frac{purchase\ price + salvage\ price}{2}\right) \qquad (4.10)$$

The other annual costs, Misc., such as insurance, taxes and housing are calculated at 2% of the purchase price and is calculated using the Equation (4.11). Insurance is needed for the equipment to ensure replacement in case of damage. If there is no insurance, then the risk is added to the farm business.

$$Misc. = 0.02 * purchase\ price \qquad (4.11)$$

Table 4.5 gives the economic details of the machinery that has been used in the calculations of Equations (4.9-4.11) [54]. These costs are then added to estimate the total annual ownership costs and the sum is then divided by the total hours of use to give the ownership costs by hour of use. This is shown in Equation (4.12)

$$Hourly\ Ownership\ Costs = \frac{D + SI + Misc.}{annual\ use(hours)} \qquad (4.12)$$

Table 4.5 Typical economic details for the stover harvesting equipment's used.

Equipment	Useful life (years)	Annual Use (hours)	Salvage %	Repair Factor	
				RF1	RF2
Combine	12	300	18	0.04	2.1
Ear-snap header	12	300	18	0.04	2.1
Whole-plant header	12	300	18	0.04	2.1
Flail Shredder	10	200	30	0.46	1.7
Round Baler	10	200	28	0.43	1.8
Large Tractor	12	500	27.5	0.007	2.0

Purchase price, PP, is a user-defined value while the salvage price, SP, is calculated using the salvage percentage for each of the pieces of equipment. Salvage price is an estimated cost of the machine at the end of its economic life. It is an estimate of the used value for the equipment. In general, the salvage price is given by the equation (4.13)

$$SP = \frac{salvage\ \%}{100} * PP \qquad (4.13)$$

Based on these calculations, the hourly ownership costs are given in Table 4.6.

Table 4.6 Spreadsheet model outputs for the ownership costs section.

Equipment	**Salvage price ($)**	**Depreciation ($/year)**	**Simple annual interest ($/year)**	**Misc. costs ($/year)**	**Hourly ownership costs ($)**
Combine					
Ear-snap header					
Whole-plant header					
Flail Shredder					
Round Baler					
Large Tractor					

The next step is to calculate the operating costs which are also variable costs. These variable costs include labor, fuel and lubricant consumption, and repair and maintenance costs.

Repair and maintenance costs are calculated using the repair factors listed out in Table 4.5. Repair costs are the costs that occur due to routine wear and tear, and accidents. The Equation (4.14) is given by ASABE is used to calculate these costs.

$$R\&M\ cost = \frac{\left[(RF1)*(list\ price)*\left(\frac{lifetime\ hours}{1000}\right)^{RF2}\right]}{lifetime\ hours} \tag{4.14}$$

The list price is regarded as the purchase price and the lifetime hours are calculated by multiplying the useful life and annual use.

Fuel and lubricant costs are calculated based on the equations from Grisso *et al.* [62] for all field operations. The average consumption for gasoline and diesel engines are estimated. For gasoline engines, Equation (4.15) is used and for diesel engines, Equation (4.16) is used.

$$Q_{avg} = 0.305 * P_{pto} \tag{4.15}$$

$$Q_{avg} = 0.223 * P_{pto} \tag{4.16}$$

Q_{avg} is the average consumption in L/hour and P_{pto} refers to the power of the equipment that is used in kW. The rated power of each tractor is measured at the rated engine speed and is typically measured at the power take-off (PTO) and is referred to as rated PTO. A diesel tractor approximately uses 73% as much fuel in volume as a gasoline tractor and hence, the second equation is 0.305*0.73=0.223. The above equations are limited to tractors. Hence, they cannot be used for specific operations other than those which use tractors.

For a specific operation, the following approach has been followed, based on literature recommendations [58] [62]. The average consumption, Q_i, is calculated using the Equation (4.17)

$$Q_i = Q_s * P_T \tag{4.17}$$

The average consumption is given by Q_i in L/hr, Q_s is the specific volumetric fuel consumption for the given tractor in L/kW•h and P_T is the PTO equivalent power for the particular operation in

kW. Typical fuel consumption is given by farm tractor and combine engines above 20% load which are modeled by the Equations (4.18)-(4.20). Equations (4.18) and (4.19) give the volumetric fuel consumption for full throttle.

Gasoline $$2.74X + 3.15 - 0.203\sqrt{697X} \tag{4.18}$$

Diesel $$2.64X + 3.91 - 0.203\sqrt{738X + 173} \tag{4.19}$$

At partial loads and full throttle

$$Q = \left(2.64X + 3.91 - 0.203\sqrt{738X + 173}\right) * X \ \frac{L}{kWh} * P_{PTO}\ kW \tag{4.20}$$

Here, Q is the diesel fuel consumption at partial load in L/h and X is the ratio of of equivalent PTO power (P_T) to rated PTO (P_{PTO}). Equivalent PTO power is given by ASAE D 497.7 standards and the rotary power requirement is a function of the size and feed rate of the implement. It is given by Equation (4.21)

$$P_{PTO} = a + b(w) + c(F) \tag{4.21}$$

The parameters (a, b, c) for the harvest equipment are given by D497.4 standards. [58] where a is in kW, b is in kW/m and c is in kW/ton. The implement working width, w, in ft. can be taken from Table 4.7 and the material feed rate, F, in ton/hr is estimated to be 9 Mg/ha [54]. For the sake of the equation, 9 Mg/ha is converted to ton/h. The feed rate is multiplied by 1.1 tons to convert it from Mg to tons. Then the resultant is divided by the hourly machine requirements of the harvest systems to obtain a feed rate in ton/h for the different systems.

After calculating PTO for each system, the average consumption is multiplied by the fuel cost in \$/L to give an estimate of the fuel costs. Equation (4.22) gives the fuels costs, FC.

$$FC = Q\frac{liter}{hr} * fuel\ cost\ \frac{\$}{liter} \tag{4.22}$$

The power of each equipment along with width, field speed and capacity is as provided in Table 4.7. [54].

Table 4.7 Typical size and field speed of equipment used.

Harvest Scenario/equipment	Capacity Mg	Width m	Size and power kW	Field Speed kmh^{-1}
Three-pass combine	-	9.1	242	6.5
Two-pass combine	-	9.1	242	5.8
Single-pass whole plant header	-	9.1	242	3.7
Single-pass ear snap header	-	9.1	242	6.5
Flail shredder	-	5.8	-	6.5
Round Baler	-	-	-	3.8
Large Tractor	-	-	112	-
Bale Wagon	6.9	-	-	-

Lubrication costs, L, are estimated at 15% of the fuel costs. Labor costs are estimated based on the average labor rates. Labor costs, LC, were estimated at $20/hr including benefits for combine operations and for all other tasks at $18/hr.

The total operating costs is given by Equation (4.23)

$$Operating\ Costs = R\&M\ costs + LC + FC + L \qquad (4.23)$$

Based on these calculations, the operating costs are as shown in Table 4.8

Once, the hourly ownership and operating costs have been calculated, the next step is to calculate the hours required to perform operations. For this, the values for speed and width from Table 4.7 are to be considered.

Table 4.8 Spreadsheet model outputs for the operating costs.

Harvest Equipment	R&M costs ($/h)	Labor costs ($/h)	Fuel costs ($/h)	Lubrication costs ($/h)
Combine				
Ear-snap header				
Whole-plant header				
Flail Shredder				
Round Baler				
Large Tractor				

The capacity (ha/hr) is the parameter that tells how large a machine has to be. [58]. It is given by the Equation (4.24)

$$capacity\left(\frac{ha}{hr}\right) = \frac{s\,\frac{km}{hr} * w\ (m) * \eta}{10} \qquad (4.24)$$

The speed and width are provided in Table 4.7. The efficiency, η, is considered to be 80%. For three-pass systems, the effective width of baling is assumed to be double that of the shredder while in the two-pass systems, the effective width of baling is assumed to be the same as that of the combine. Then, the ownership and operating costs are divided by the capacity to determine the total cost for all operations. The final output data for this section is as shown in Table 4.9.

Table 4.9 Spreadsheet model outputs of the harvesting costs for different scenarios

Harvest Scenario	Ownership Costs ($/ha)	Repair Costs ($/ha)	Fuel Costs ($/ha)	Labor Costs ($/ha)	Total Costs ($/ha)	Total Costs ($/Mg)
Three-pass						
Two-pass						
One-pass ear snap						
One-pass whole plant						

The cost per hectare values are now subtracted by a constant cost of conventional grain harvest and then divided by the stover yields. The stover yields for the three-pass systems is 4.2 Mg/ha, for two-pass systems is 4.8 Mg/ha, for one-pass whole plant is 4.8 Mg/ha and for one-pass with ear-snap is 1.4 Mg/ha.

4.3.1.2 Transportation Costs

There are two scenarios that are considered for transportation: (1) in-field to on-farm storage, and (2) on-farm storage to the plant. For the first scenario, a wagon with a small tractor is considered and for the second, a truck with a trailer is considered. The following approach is used to calculate the total cost of transport.

The wagon has a capacity of 6.9 Mg and hence, it is assumed that 12 bales of 580kg will be transported. The time taken to load the wagon is 2minutes per bale. The number of wagon loads

is determined by the amount of corn stover that is required annually to run the ethanol plant. This is given in Equation (4.25)

$$Number\ of\ wagon\ loads = \frac{A_{CS} * 0.001\ Mg}{6.9\ Mg} \tag{4.25}$$

Here, 0.001 is a factor that is used to convert kgs to Mg and 6.9Mg is the wagon capacity. The next step is to calculate the number of loads/h. This is determined with Equation (4.26)

$$\frac{Loads}{hr} = \frac{Number\ of\ wagon\ loads}{8760\ hours} \tag{4.26}$$

In addition, this section requires user-defined values for the distance travelled in the field and the speed of the wagon. These values help calculate the number of hours that are used to determine the number of wagons that are required. These are determined using the Equations (4.27) - (4.28)

$$Hours = \frac{distance}{speed} \tag{4.27}$$

$$Number\ of\ wagons = hours * \frac{loads}{h} \tag{4.28}$$

Once these are calculated, the hourly cost of transportation, TC, is calculated using Equation (4.29)

$$TC = number\ of\ trucks * cost\ of\ one\ wagon\ load \frac{\$}{h} \tag{4.29}$$

The cost of transport for the truck is a similar procedure but, the capacity of the truck changes from 6.9Mg to 20.9Mg (580kg*36). Note that the user-defined inputs change as well.

Table 4.10 refers to total costs calculated for the wagon and the truck.

Table 4.10 The model inputs and outputs to calculate the cost of transporting biomass

Vehicle	Mg/load	Distance (km)	Speed (km/h)	Loads/h	Total cost ($/h)
Wagon	6.9				
Truck	20.9				

4.3.1.3 Storage Costs and Fuel Preparation

As mentioned earlier, bales can be stored either outdoors or indoors. They can be either wrapped in plastic or unwrapped. The major drawback of storing outdoors is that there will be high amounts of dry matter losses. For this model, bales are considered to be stored indoors which are dumped and piled using a front-end loader. The estimated costs of receiving, storing and delivery for boiler use are taken from the literature. [34]. The bales are received by the plant and are stacked indoors. When they need to be used, the bales are sent on a belt conveyer and grinded on a hammer mill. This final solid fuel is delivered to the boiler. The costs are given in Table 4.11

Table 4.11 The estimated costs for receiving, storing and delivery of biomass to boiler.

Operations	Cost ($/Mg)
Receiving biomass	2.22
Storing biomass	4.77
Reclaiming biomass	4.34
Fine grinding	5.41
Delivery	2.21
Total (+30% overhead)	24.64

In Table 4.11, an overhead of 30% has been added for the costs of any extra labor or operation requirement.

As a summary, the total delivered cost for biomass up to the boiler use is given in Table 4.12. The total delivered cost is the cost involved for harvesting the corn stover, transporting it from the farm to the plant and storing the biomass until it is retrieved. This is considered in three different harvesting systems and the stover yields vary for each system. Hence, there are different costs involved.

Table 4.12 The total delivered cost

Harvesting / Operation	3-pass ($/Mg)	2-pass ($/Mg)	1-pass ear snap ($/Mg)	1-pass whole plant ($/Mg)
Collection/Harvesting				
Transport				
Storage and fuel preparation				
Total cost				

4.3.2 Investment Costs

For this section of the model, the amount of heat required by the plant is given by Q_{tot}. A biomass fired steam boiler system has been proposed to replace a natural gas fired system. The necessary heat demand is met by the corn stover that is available. This model will perform an analysis with the existing natural gas plant to predict the annual cost savings and payback period.

4.3.2.1 Capital Costs (CC)

The capital cost of the system is defined as the equipment and installation costs. This value is usually between 85-340 \$/kW [63]. The procedure followed to calculate the investment costs and payback period is similar to that used by Mani *et. al*. (2010), but it is modified to fit into this model.

The heat required by the plant is Q_{tot} in MJ/year. First, we need to convert this to hourly basis so we can convert it into Watts. This conversion is shown in Equations (4.30)-(4.32)

$$Q_{tot} = x \frac{MJ}{year} * \frac{year}{8760 hours} * \frac{hours}{3600\, seconds} \quad (4.30)$$

$$1 \frac{J}{sec} = 1\, Watt \quad (4.31)$$

$$\Rightarrow Q_{tot} = \frac{x}{31.53} Watts \quad (4.32)$$

where x is the amount of heat that has been calculated in Table 4.1. Here, the design capacity is considered as Q_{tot} in Watts.

In this system, biomass is burned to produce steam. The flue gas is released to the atmosphere through an electrostatic precipitator, ESP, a filtration device. The generated steam is at 0.5MPa pressure and 152°C temperature [63]. This value is based on the values provided in the literature [64]. The assumption made here is that the capital cost for the biomass fired boiler is 250\$/kW and the capital cost of ESP is \$50/kW. To match this, the natural gas capital cost to produce the same amount of heat is given by \$150/kW.

The annual costs are thus, calculated as given in the following equations (4.33-4.36).

Biomass Fired Boiler $$Capital\ costs_1 = 250\ \frac{\$}{kW} * \frac{x}{31.53} * 0.001\ kW \quad (4.33)$$

ESP $$Capital\ costs_2 = 50\ \frac{\$}{kW} * x * \frac{x}{31.53} * 0.001 kW \quad (4.34)$$

Biomass System $$Total = Capital\ costs_1 + Capital\ costs_2\ in\ M\$ \quad (4.35)$$

Natural gas system $$Capital\ Costs = 150\ \frac{\$}{kW} * \frac{x}{31.53} * 0.001kW \quad (4.36)$$

4.3.2.2 Operation and Maintenance Costs

The operation, maintenance, labor costs and debt payment are lumped together in the category "Operation and Maintenance Costs". The operation cost is due to internal electricity consumption and does not include the consumption of chemicals used to treat the boiler feedwater [63]. The estimated operation costs are to be calculated which are assumed as a 2% of the thermal input and electricity is sold to the grid at $51/ MW-h. Maintenance costs are given as 3% of the capital costs [63]. Labor cost of the plant requires some inputs from the user such as the number of people per shift and the annual salary of each person. If there is no input, then the model considers the default values of 5 people per shift at $50,000 salary annually. The costs are determined with Equations (4.37-4.42)

Biomass System $$Operation\ costs = 51\ \frac{\$}{MWh} * 0.02 * \frac{x}{31.53} * 10^{-6}MW \quad (4.37)$$

$$Maintenance\ costs = 0.03 * Total \quad (4.38)$$

$$Labor\ Costs = 5 * \$50{,}000 \quad (4.39)$$

Natural gas system $$Operation\ costs = 51\ \frac{\$}{MWh} * 0.02 * \frac{x}{31.53} * 10^{-6}MW \quad (4.40)$$

$$Maintenance\ costs = 0.03 * Capital\ Costs \quad (4.41)$$

$$Labor\ Costs = 5 * \$50{,}000 \quad (4.42)$$

4.3.2.3 Annual Fuel Consumption (A_{FC})

The annual fuel consumption for the biomass system is given by A_{CS} in tons which is converted to Mg which through Equation (4.43). The annual fuel consumption for the natural gas system is given by a factor. 1Mg = 33.4GJ. This is given by Equation (4.44).

Biomass System $$A_{FC} = A_{CS} * 0.001\ Mg \quad (4.43)$$

Natural gas System $A_{FC} = \frac{Q_{tot}\ \frac{Joule}{sec} * 8760 * 3600\ \frac{sec}{year}}{33.4 * 10^{9}\ \frac{Joule}{Mg}}$ *(4.44)*

4.3.2.4 Fuel Costs (TFC)

Fuel costs are based on the collection, storage, and transportation costs. Refer to Table 4.12 for the costs involved. The total cost is then multiplied with the annual fuel consumption which is calculated with Equation (4.45)

$$Annual\ fuel\ cost = A_{FC}\ Mg * total\ cost\ of\ biomass\ delivered\ \frac{\$}{Mg} \quad (4.45)$$

4.3.2.5 Ash Disposal Costs

Ash hauling distance is considered to be 25km and the hauling cost is taken as \$0.157/Mg-km. The ash content of corn stover is taken as 5.1%. The ash spreading cost is given by \$21.8/Mg-ha with ash application of 1Mg/ha.

4.3.2.6 Total annual costs (TAC)

Total annual costs are given by the summation of annual operations and maintenance costs, annual fuel costs and annual ash disposal costs. These can be found using Equations (4.46) and (4.47)

Biomass System $TC = O\&M\ costs + TFC + ash\ disposal\ costs$ *(4.46)*

Natural gas System $TC = O\&M\ costs\ +\ TFC$ *(4.47)*

4.3.2.7 Total annual savings (TS)

The total annual savings is a simple and straightforward calculation. It is the difference of the total annual costs of natural gas and biomass systems.

Table 4.13 gives the calculated costs for the biomass fired system with different harvesting scenarios and the natural gas system.

Table 4.13 Technical and economic data for the process heat generation system.

Economic parameters and Technical Data	**Corn Stover**				**Natural gas**
	3-pass	**2-pass**	**1-pass ear-snap**	**1-pass whole plant**	
Total capital costs(M$)					
O&M costs(M$)					
Annual fuel consumption(Mg)					
Annual fuel costs(M$)					
Annual ash disposal costs(M$)					
Total annual costs(M$)					
Total annual savings(M$)					

4.4 Payback Period

Payback period, P, is a measure of the length of time it will take for the cumulative annual savings to exceed the initial investment cost. Simple payback period does not consider inflation or change in energy costs. It is given by the equation (4.48)

$$P = \frac{CC}{TS} \quad (4.48)$$

The price of natural gas changes every year and hence, the simple payback period might not be so accurate. The model considers the natural gas price to be increasing by the year at a steady rate. The input for this section of the model is shown in Table 4.14.

Table 4.14 Natural Gas inputs for the calculation of cumulative savings

Price of Natural Gas (P_{NG}) ($/GJ)		$3.00-$12.00
Increase of the price per year (y)		0-5%
Number of years (n)		15-30

The Table 4.14 requires the input of the current natural gas price and increase of price per year. The number of years is life expectancy of the boiler being considered for the project. This section of the model calculates the fuel price per year based on the increase per year and then calculates the fuel costs using the Equation (4.49-4.50)

$$P_{NG_i} = P_{NG_{i-1}} * (1 + y) \quad (4.49)$$

$$TFC_i = AFC * P_{NG_i} * 53 \quad (4.50)$$

Here, 53 is the higher heating value of natural gas in GJ/Mg. [63]Once, these are calculated, the effective cost of natural gas system (EC_{NG}) is calculated by subtracting the fuel costs from the capital costs of the natural gas system. This effective cost is deleted from the capital cost of biomass capital costs to get the cumulative savings. The cumulative savings is given by Equation (4.51), where i=1 and n=number of years.

$$CS = -CC_{BS} + \sum_{i=1}^{n} EC_{NG_i} \quad (4.51)$$

4.5 Evaluating the model

The model has been used to evaluate 6 locations with different nameplate capacities to check the viability of using corn stover as a heat source. The plants were selected from each PADD district whose nameplate capacities are available from EIA. The plants are located in California, Colorado, Iowa, Nebraska, New York, and Texas. Relevant data has been taken from their respective websites [65] [66] [67] [68] [69] [70]. These can be seen from Table 4.15 and Table 5.10.

Table 4.15 Plant Locations and their respective nameplate capacities

Plant Location	Nameplate Capacity
Medina, NY	208 MLY
Iowa Falls, IA	302.4 MLY
Columbia, NE	1183 MLY
Plainview, TX	446 MLY
Windsor, CO	151.2 MLY
Stockton, CA	226.8 MLY

4.6 Summary

A model was developed to check the viability of corn stover combustion as a potential heat source at corn Ethanol plants. The harvesting, storage, and transportation costs along with the investment costs have been developed. This model is then validated and the results from using the model are discussed in the Chapter 5. The model is used to evaluate six locations and gives a brief summary on each of the model sections. This is used to check the viability and the economics of the project at the six locations and the payback period for each of the location is calculated.

CHAPTER 5 : VALIDATION OF THE MODEL AND DISCUSSION

5.1 Introduction

The output values from the model were validated with theoretical and experimental data available from the literature. The values were analyzed to determine the feasibility of using crop residue as a biomass combustion feedstock to replace nonrenewable resources as the heat source for producing ethanol from corn. As described in Chapter 4, there are four models in this project - the feedstock requirement, the harvesting technique model, the transportation model and the investment costs; these have each been verified separately. These models have been integrated to function together but, the harvesting model is slightly independent from the others in the sense it does not use any plant inputs. The calculation of payback period is dependent on these models and hence, the input variables were varied to show their influence on the model.

5.2 Verifying and evaluating feedstock requirement model

The feedstock requirement model was verified by comparing the results with experimental data obtained from the literature [34] [63] [64]. First the model outputs, A_{CS} and Q_{tot} were evaluated to determine the most realistic feedstock requirement and then compared with the amount of natural gas, A_{NG}, that is required for the same heat requirement. The heat requirement of an ethanol plant is usually 9.67 MJ to produce 1 liter of ethanol. But, the heat requirement of a plant is dependent on its age and location and studies show that this value is decreasing [35]. The heat requirement ranges from 6.5-20 MJ/liter.

First the model outputs for the amount of corn used, A_C, was checked with three of the plant locations [67] [68] [69]. Table 5.1 illustrates this validation.

Table 5.1 Output values for the corn used and comparing it with literature data and ethanol plants.

Parameters	**Model Input and Output Ethanol Plants**		
	NY	**TX**	**IA**
PC (MLY)	208	446	302.4
A_c Million bushels	19.94	42.75	28.99

The nameplate capacities of the NY plant, TX plant and the IA plant are 55 MGY, 118 MGY and 80 MGY respectively. MGY stands for million gallons per year. The model uses MLY-million liters per year and hence, the nameplate capacities have changed to 208, 446 and 302.4 MLY for the NY, TX and IA plant respectively where the conversion factor is 1 gallon is 3.78 liters. The NY plant requires about 20 million bushels of corn, the TX plant requires about 42 million bushels of corn and the IA plant requires 35 million bushels bushels of corn. The model output values for the amount of corn required, A_c, is shown in Table 5.1 and can be seen that the values are almost similar to the actual values.

The amount of corn stover, A_{CS} and the amount of natural gas, A_{NG}, required is compared with literature data [63] and is shown in Table 5.2.

Table 5.2 Comparison of the amount of corn stover and natural gas requires for the necessary heat requirement with literature data

Parameters	Model Input and Output	Literature Data [34] [63]	Model Input and Output
Plant Capacity PC (MLY)	170	170	170
Heat Requirement Q_{tot} (MJ/liter)	9.67	9.67	11.17
Heat Requirement Q_{tot} (MJ/year)	$1.64*10^9$	$1.9*10^9$	$1.9*10^9$
Amount of natural gas A_{NG} (Gg)	49.07	56.61	56.68
Amount of Corn stover required A_{CS} (Gg)	99.63	121.27	115.08

The input values for the model were the same as the literature data but, there was a slight change in the output, as the literature considered $1.9*10^9$ MJ/year which is equivalent to 60 MW whereas the model output requirement of $1.64*10^9$ MJ/year was equivalent to 52.3 MW. If the same outputs are desired, then the model input for the heating requirement has to change to 11.17 MJ/liter and the outputs would match that of the literature. Thus, the amount of corn stover required, the amount

of natural gas, and corn used for the necessary production of ethanol were consistent with literature data.

The second step of the analysis is to estimate the amount of corn stover required for a real application and hence, the six locations mentioned in Chapter 4 have been evaluated. The estimated amounts of corn stover required for each of these plants is shown in Figure 5.1.

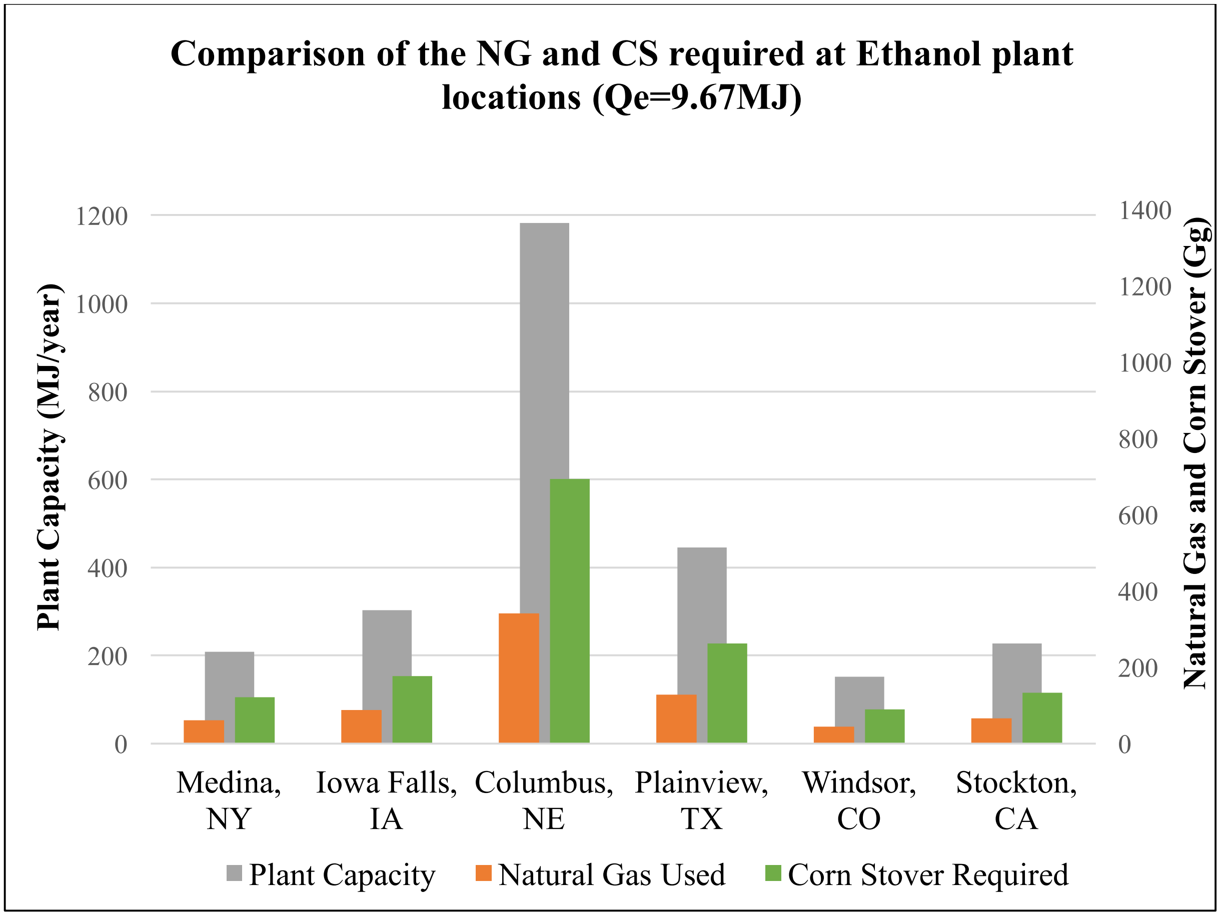

Figure 5.1 Comparison of the amount of natural gas and corn stover required at ethanol plant locations (Q_e=9.67MJ)

Figure 5.1 outlines the six plants against which the nameplate capacity of each plant in MJ/year is plotted along with the amounts of natural or corn stover required in Gg. The nameplate capacities

have been taken from EIA and verified with their corresponding websites. [55] [68] [67] [69] [70] [71] As the nameplate capacities vary by a high margin, the heat requirement for producing 1 liter of ethanol has been considered to be the same i.e., 9.67 MJ. As can be seen from Figure 5.1, the amount of corn stover required, A_{CS}, is almost double that of the natural gas, A_{NG}, required. This stands true from literature where the amount of natural gas, $A_{NG,}$ required for 60MW was 56.61 Gg while the corn stover required for the same of heat requirement was 121.27 Gg.

To illustrate this, Figures 5.2 and 5.3 have been provided.

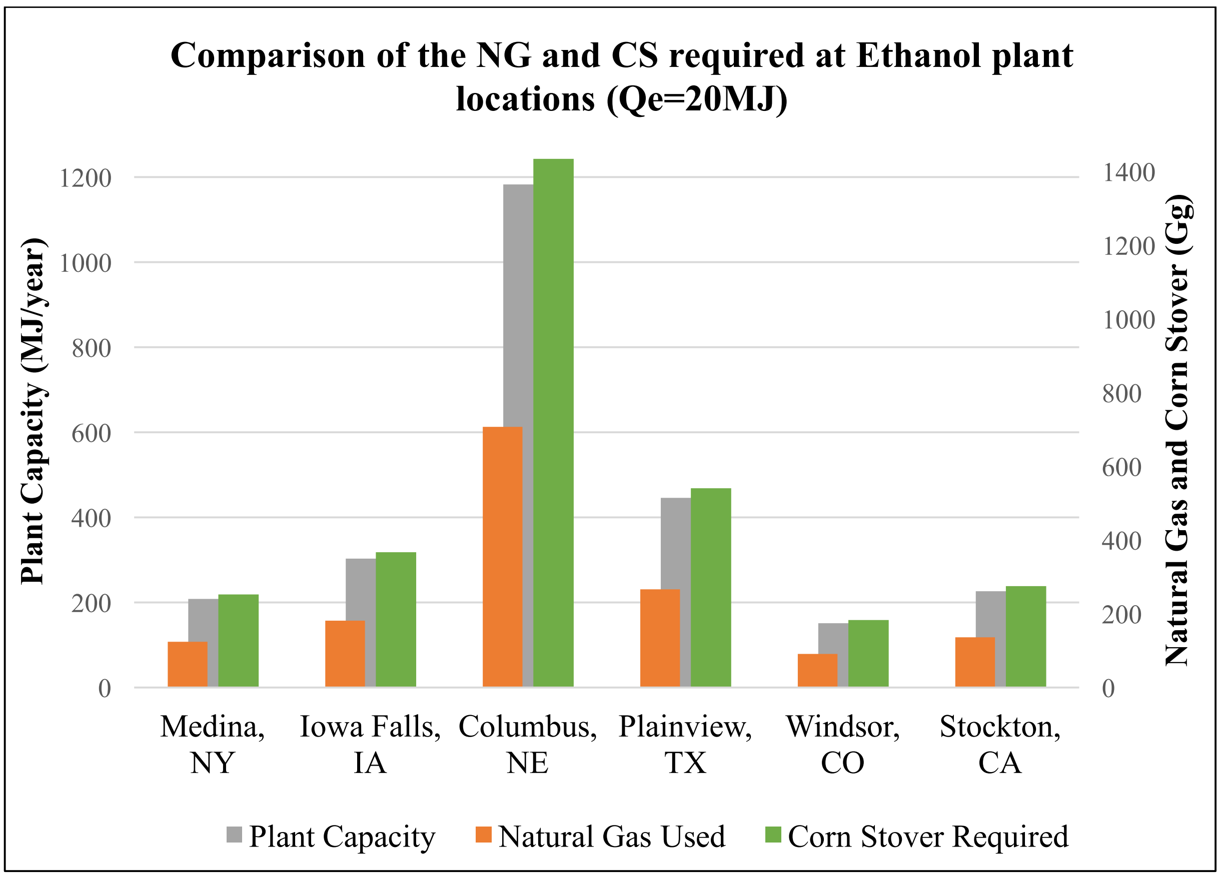

Figure 5.2 Comparison of the amount of natural gas and corn stover required at ethanol plant locations (Q_e=20MJ)

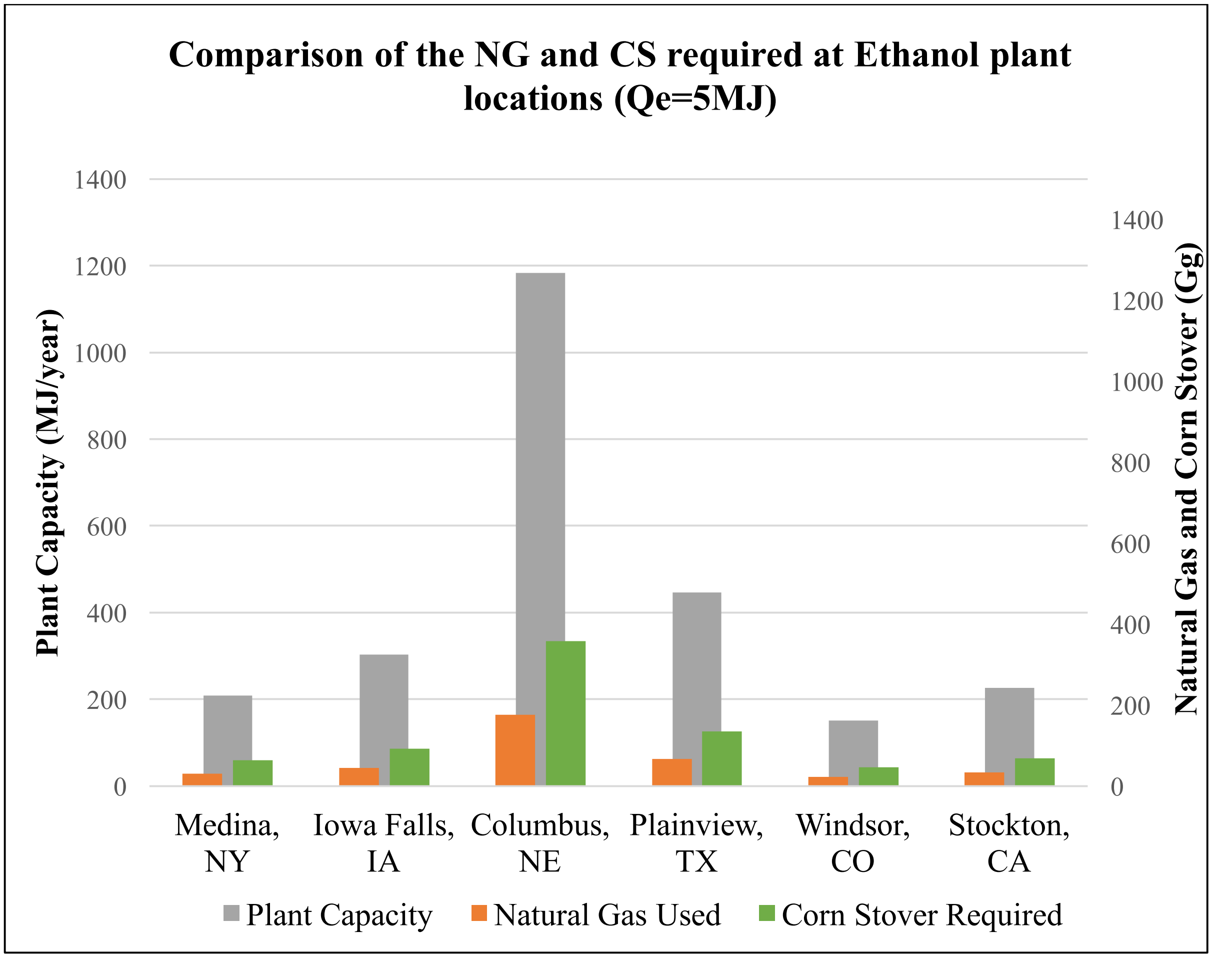

Figure 5.3 Comparison of the amount of natural gas and corn stover required at ethanol plant locations (Q_e=5MJ)

Figure 5.2 compares values for heating requirement of 20MJ/liter of ethanol. Although, this is marginally a high heating requirement, it has been provided to show that the amounts of corn stover, A_{CS}, and natural gas, A_{NG}, vary with the heating requirement. Figure 5.3 compares the amounts of corn stover, A_{CS}, and natural gas, A_{NG}, for heating requirement of 5MJ/ liter of ethanol. It is clear from Figures (5.1) - (5.3) that the amount of corn stover, A_{CS}, is double that of the amount of natural gas, A_{NG} irrespective of the plant capacity (MLY).

Figures (5.4)-(5.5) show the amount of corn stover that is available, A_{CSA}, and required, A_{CS}, for the six locations with different plant capacities (MLY). The evaluation shows that the amount of corn stover available, A_{CSA}, is double that of the amount of corn stover required, A_{CS}, at the respective plants. This shows that although the amount of corn stover required, A_{CS}, is double that of the natural gas used, A_{NG}, there is enough corn stover available, A_{CSA}, on the farm to fulfill the plant's demand for the heat requirement.

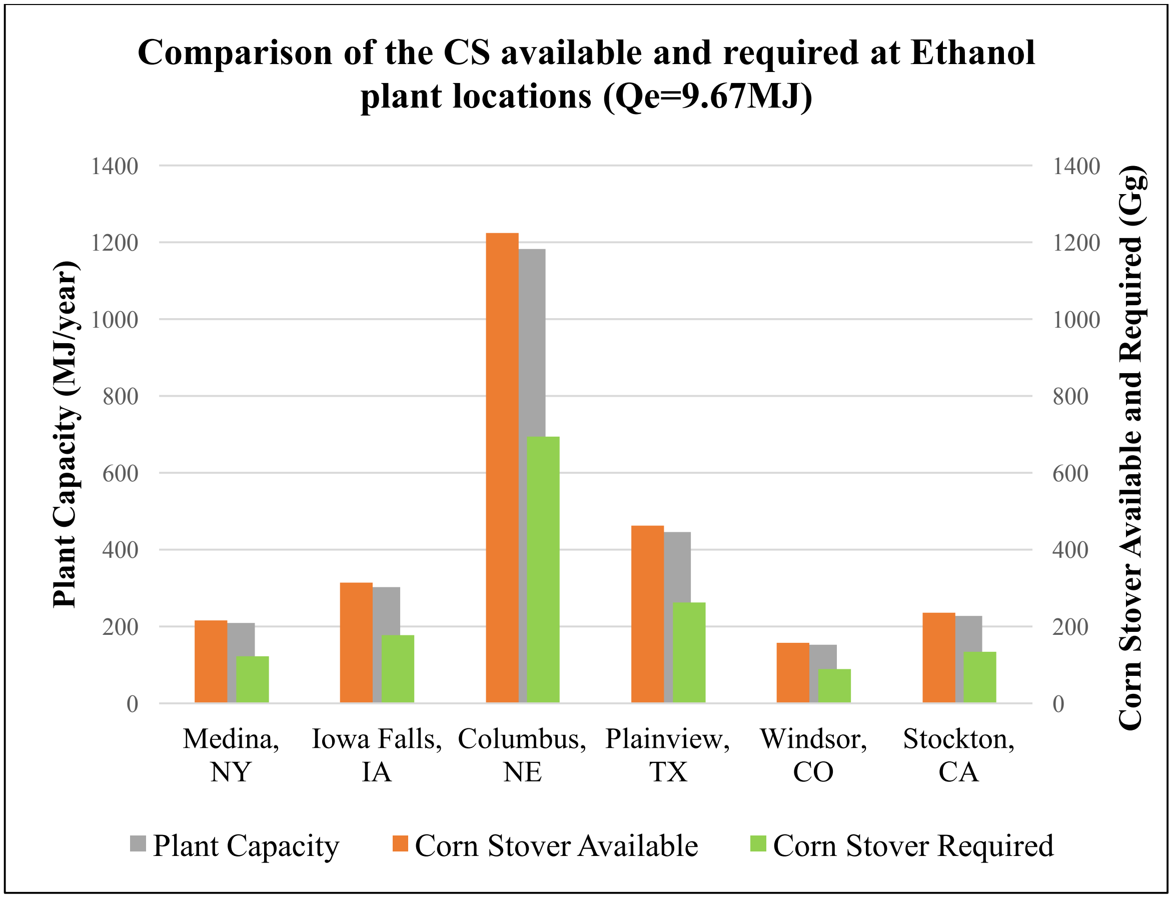

Figure 5.4 Comparison of the amount of corn stover available and required at ethanol plant locations (Qe=9.67MJ)

As the heat requirement increases, the amount of corn stover available, A_{CSA}, is almost equal to the amount of corn stover required, A_{CS}. The increase in heat requirement per liter of ethanol is

very unlikely and as stated earlier, there is ongoing research to reduce the heat requirement necessary to produce a liter of ethanol rather than to increase it. Hence, the scenario where a plant requires a high amount of heat (MJ/liter) might not be possible implying that there would be enough corn stover for the plant to utilize.

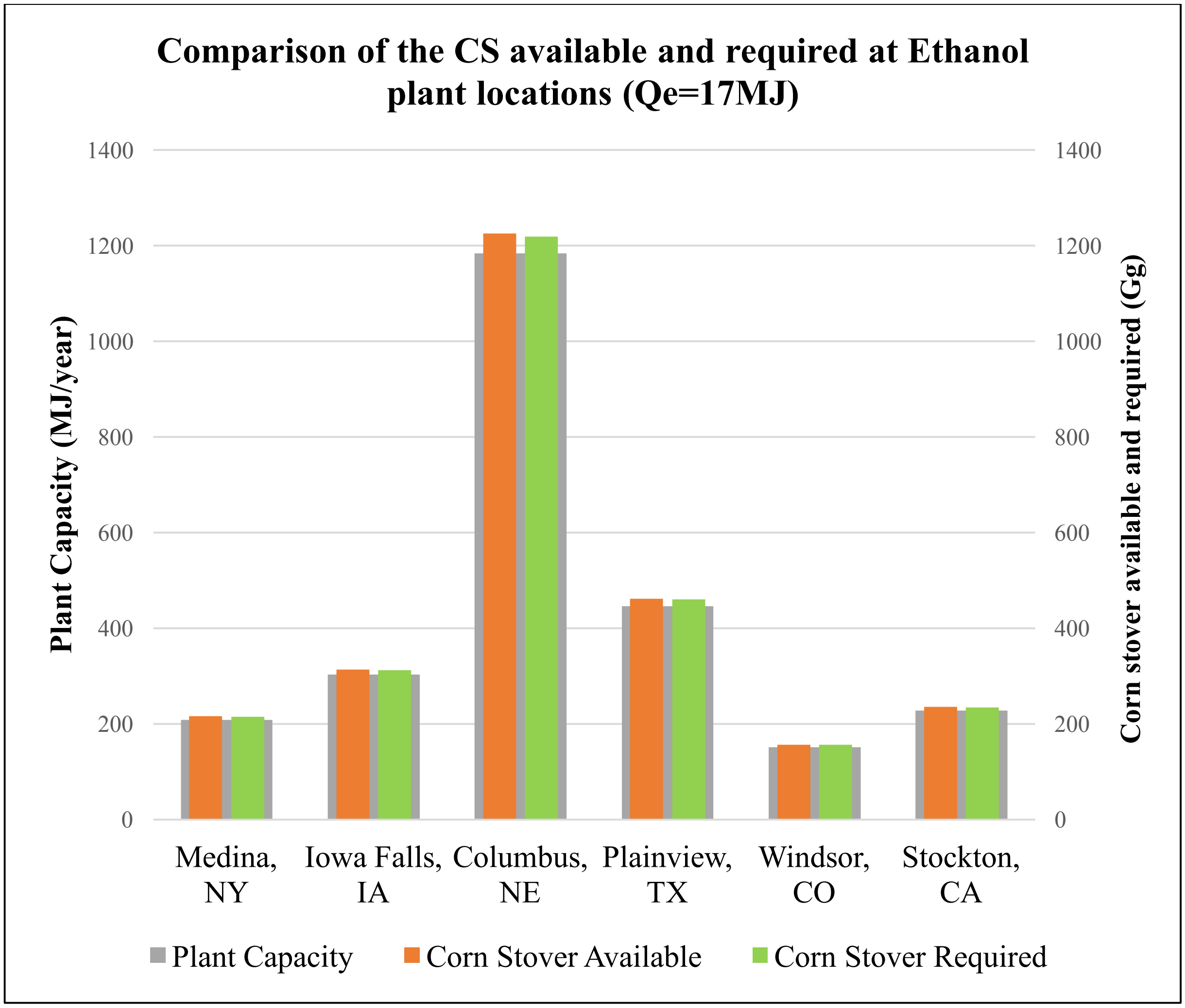

Figure 5.5 Comparison of the amount of corn stover available and required at ethanol plant locations (Qe=17MJ)

The price involved in installing a biomass sytem and the relevant harvesting and transportation costs are to be taken into account. These are discussed in the following sections.

5.3 Verifying the harvesting model

The harvesting costs model was verified by experimental data and the values provided in the literature [54]. The harvesting costs, as mentioned earlier, are independent of the plant capacity or the heating requirement. But, these costs help in determining the fuel costs and the project costs at the plant. This section requires a set of different inputs for the harvesting equipment and data as discussed in Chapter 4. Though the literature provides all the necessary information to calculate costs for the three harvesting scenarios, it does not provide the flexibility to change the prices or the interest rates as the model built here.

The model has been used to change the prices within the ranges provided in Table 4.4 and harvesting costs have been calculated. These price ranges have been taken from the literature and John Deere website as the company has the technology for a one-pass system. The model allows the user to change the interest rates and accordingly the ownership and the operating costs change. It also allows the user to select either a diesel or a gasoline tractor, making the model very flexible and enabling the user to use it under different conditions.

The percentage for the annual interest is by default set to 0.08 but can be varied from 0.01-0.25 whereas the percentage for the other or misc. costs by default is set to 0.02 and can be varied from 0.01-0.25.

First the model outputs are verified by using the prices provided in the literature [54]. Table 5.3 lists out the input prices entered for the equipment and Table 5.3 lists out the output data of the model and that given in literature.

Table 5.3 Input data for the harvesting model

Equipment	Price
Combine	$325,000
Ear-snap header	$100,000
Whole-plant header	$125,000
Flail Shredder	$37,000
Round Baler	$55,000
Large Tractor	$124,000

Annual Interest %	0.08
Misc. costs %	0.02
Type of tractor	Gasoline/Diesel

The default values for the percentage of annual interest and the miscellaneous costs shown in Table 5.3 is provided in the literature as well [54]. The interest rates affect the ownership costs and the type of tractor affects the operating costs. As can be seen from Table 5.4, the model output is comparable to the literature data. They are not exactly the same as the machine hourly ownership differs. This is because the hourly ownership in ha/h are calculated using the width and speed listed in Table 4.7 and an efficiency. The efficiency considered in the literature was 0.9 for all operations but, this will not be true for all the equipment. An efficiency of 0.78 for the combine, 0.8 for the baler and 0.9 for the shredder was considered. Hence, the output values for the three harvest scenarios are different. Two tables, Table 5.4 and 5.5 are provided to show the difference in prices while using the diesel and gasoline tractors. Table 5.5 only shows the model output for the gasoline tractors, as the literature considers diesel tractors.

Table 5.4 Comparison of the model output with literature data for the different harvesting systems

Costs involved	Model Output				Literature Data			
	3-pass	2-pass	1-pass		3-pass	2-pass	1-pass	
			ear snap	whole plant			ear snap	whole plant
Total costs $/ha	145.47	128.87	86.96	154.92	151.43	136.53	85.49	164.47
Total costs $/Mg	19.40	13.96	14.29	19.37	20.42	14.76	19.81	98.79

Table 5.5 Model output when gasoline tractors are used

Costs involved	Model Output			
	3-pass	2-pass	1-pass ear plant	1-pass whole plant
Total costs $/ha	159.48	140.59	93.25	165.47
Total costs $/Mg	21.26	15.23	15.32	20.68

As can be seen from Table 5.4 and 5.5, the two-pass systems are 29% less in cost than the three-pass systems per Mg of stover. This is mainly because of the elimination of the shredding option, although no shredding involved a slightly higher price for baling. The three-pass system baling option costs $20.41/ha whereas for the two-pass system costs $26.02/ha. This subsequently increased the R&M costs as well. The cost of the single-pass whole plant baling system was 38%

higher than the single-pass ear-snap baling system per Mg of stover. This is because of the calculation of the machine hourly ownership rates as the speed of the whole-plant header was slow comparative to the combine with ear-snap header. This results in lower fuel costs and also, higher yields.

The single-pass whole-plant baling system costs 5% more per Mg of stover than the three-pass baling option and the single-pass ear-snap baling system costs 5% less per Mg of stover than the three-pass baling system. This is because of the differences in yield per hectare (ha) and the speeds at which the equipment travel. However, it is desirable to have single-pass harvesting system as it would result in less soil contamination and if the harvesting window is shorter, the single-pass systems could be more reliable.

The fuel costs per ha for the three-pass baling systems are 38% higher than the single-pass systems due to the higher fuel demands. The two-pass baling system is about 20% higher than the single-pass systems. All of these results have been compared with the literature data and they are slightly different because of the differences in the efficiencies of the operations used. The other literature data are somewhat different and this could account for the variations in the calculation methods and the assumptions considered.

The scenario of the change in total costs is verified in the Table 5.6 and 5.7 keeping the interest rates constant but increasing the combine and the header prices. The combine price has been increased by $175,000 and the header prices have been increased by $25,000. These changes affect the ownership prices which inturn affect the total costs.

For the diesel and gasoline tractors, there is a difference in the fuel costs per ha of 9-12% for each of the systems and hence, the related total costs per ha are higher for gasoline as compared to diesel. Although this change is noticed, in actuality there are no changes in the fuel costs for a

change in equipment price. The fuel costs per ha are related to the tractor power and the fuel consumption as mentioned in Chapter 4. The change in prices only affects the ownership prices.

There has been no evaluation of the six different locations for the harvesting model as average prices are taken to keep the final results consistent and as mentioned earlier, the plant capacity and the heat requirement do not affect these costs.

Table 5.6 Comparison of prices of gasoline and diesel tractors for the harvest scenarios with higher combine and header prices.

Costs involved	**Gasoline**				**Diesel**			
	3-pass	**2-pass**	**1-pass**		**3-pass**	**2-pass**	**1-pass**	
			ear-snap	**whole plant**			**ear-snap**	**whole plant**
Total costs $/ha	186.16	170.49	119.93	218.20	172.15	158.77	113.64	22.95
Total costs $/ Mg	24.82	18.47	19.7	27.27	22.95	17.2	18.67	25.96

5.4 Verifying and evaluating the transportation model

The transportation model has been verified using experimental data and assumptions of the distance travelled. This model is also flexible as the distance and speed can be varied along with the capacity of the vehicle that is transporting the stover. The reference for this model has been taken from [34]. The model in the literature considers only farm-to-plant costs. The model built here applies the same concept for in-farm transport considering a wagon. The default values for wagon distance and speed are 6.4 km and 16.4 km/h and the capacity being 6.9 Mg and for the

truck 140km at 50km/h and a capacity of 20.9 Mg [54] [34]. The capacity is calculated considering that each bale weighs about 580 kg and the wagon can transport 12 bales and the truck transport 36 bales. The costs involved were taken from the model built here and literature [34]. Table 5.7 compares the values for the truck from literature and the model output. The model considers a capacity of 14.4 Mg from the literature and has been compared with different scenarios. An assumption that the truck load costs $77/h has been made. [34]

Table 5.7 Comparison of the transportation model outputs with the literature

Parameters	**Scenarios**				**Literature Data**
	3-pass	**2-pass**	**1-pass ear-snap**	**1-pass whole-plant**	
Distance km	140	140	140	140	140
Speed km/h	50	50	50	50	50
Capacity Mg	14.4	14.4	14.4	14.4	14.4
Total costs $/h	239	239	239	239	249
Total costs $/Mg	4.94	7.25	37.08	19.00	9.98

As can be seen from Table 5.7, although the total costs per hour are almost similar with that of the literature, the total costs per Mg vary by a large margin and this is because of the large

difference in stover yields for each of the harvesting scenarios. The lower the yields, the higher the transportation costs will be. The time taken to load the vehicle also increases with lower stover yields. The literature considers 25 Mg/h which is similar to that of the three-pass and the two-pass systems of 48 Mg/h and 33 Mg/h respectively. The single-pass systems have less stover yields of 1.4 Mg/ha or less hourly ownership of 2.63 ha/h. Hence, the costs of the three-pass systems and two-pass systems are more in line with the transportation costs from the literature. Apart from being dependent on the distance, speed and capacity of the vehicle, the model is also dependent on the amount of corn stover required for the necessary heat requirement.

Hence, for the same capacity of the vehicle, the transportation costs decrease as the heat requirement decreases. This is compared in Table 5.8 where the model outputs are shown for the heat requirement of 13.6 MJ and 9.67 MJ and for the same inputs for distance, speed and capacity of the vehicle. As can be seen from Table 5.8, the total costs per hour and per Mg decrease with a decrease in heat requirement, for a constant plant capacity constant of 170 MLY. This is due to the amount of corn stover required decreasing with the decrease in heat requirement. A similar scenario occurs when the plant capacity is decreased while keeping the heat requirement constant.

Table 5.8 gives the values of the two different heating requirement scenarios. The costs per Mg for three-pass systems and the two-pass systems are higher than the single-pass systems. This model has been applied to a wagon to calculate the in-field transportation costs. They vary by a huge margin primarily because the distance and speed are much lower than that of a truck and the capacity is also lower. In addition, the cost to load the wagon is assumed to be $15/h and has been calculated using the model from the parameters given in literature [54]. The comparison of model outputs for a wagon and truck for the same A_{CS} is given in Table 5.9. The prices of the in-farm

transportation are very low as the wagon capacity is very low and hence, the number of loads for wagon increase and also, the speed and distance considered are very less compared to a truck.

Table 5.8 Comparison of the transportation model outputs with different heat requirement for the different harvest scenarios

Parameters	**13.6 MJ heat requirement**				**9.67 MJ heat requirement**			
	3-pass	**2-pass**	**1-pass**		**3-pass**	**2-pass**	**1-pass**	
			ear-snap	**whole-plant**			**ear-snap**	**whole-plant**
Distance km	140	140	140	140	140	140	140	140
Speed km/h	50	50	50	50	50	50	50	50
Capacity Mg	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4
Total costs $/h	239	239	239	239	170	170	170	170
Total costs $/Mg	4.94	7.25	37.08	19.00	3.52	5.15	26.36	13.51

Table 5.9 Comparison of the transportation model output for truck and wagon with the same heat requirement.

Parameters	Truck				Wagon			
	3-pass	2-pass	1-pass		3-pass	2-pass	1-pass	
			ear-snap	whole-plant			ear-snap	whole-plant
Distance km	140	140	140	140	6.4	6.4	6.4	6.4
Speed km/h	50	50	50	50	16.4	16.4	16.4	16.4
Capacity Mg	14.4	14.4	14.4	14.4	6.9	6.9	6.9	6.9
Total costs \$/h	239	239	239	239	14	14	14	14
Total costs \$/Mg	4.94	7.25	37.08	19.00	0.28	0.41	2.1	1.08

The transportation model has been evaluated for the six different locations based on their distance to the farm. Similar to the harvesting method, the parameters for the wagon are kept the same though they are user-defined values. For the analysis, only the transportation distance and the speed of the truck have been changed for each plant location based on the data available on their respective websites [67] [68] [70] [69] [66] [65]. The information for each plant is given in Table 5.10

Table 5.10 Input data for the transportation model for each plant location

Plant Location	**Distance** **km**	**Speed** **km/h**
New York, NY	8	32
Iowa Falls, IA	65.6	104
Columbus, NE	75	88
Plainview, TX	9.6	96
Windsor, CO	80	80
Stockton, CA	700	104

As mentioned earlier, the 14.4 Mg capacity for the truck is from the literature. To better match the model, 20.9 Mg of capacity is considered as each bale weighs 580 kg and a total of 36 bales are being transported. The input from Table 5.10 and the wagon inputs along with the respective capacities have been used to calculate the transportation costs using the equations discussed in Chapter 4. These costs have been calculated for each plant and for each harvesting scenario. These have been illustrated in Figure 5.4.

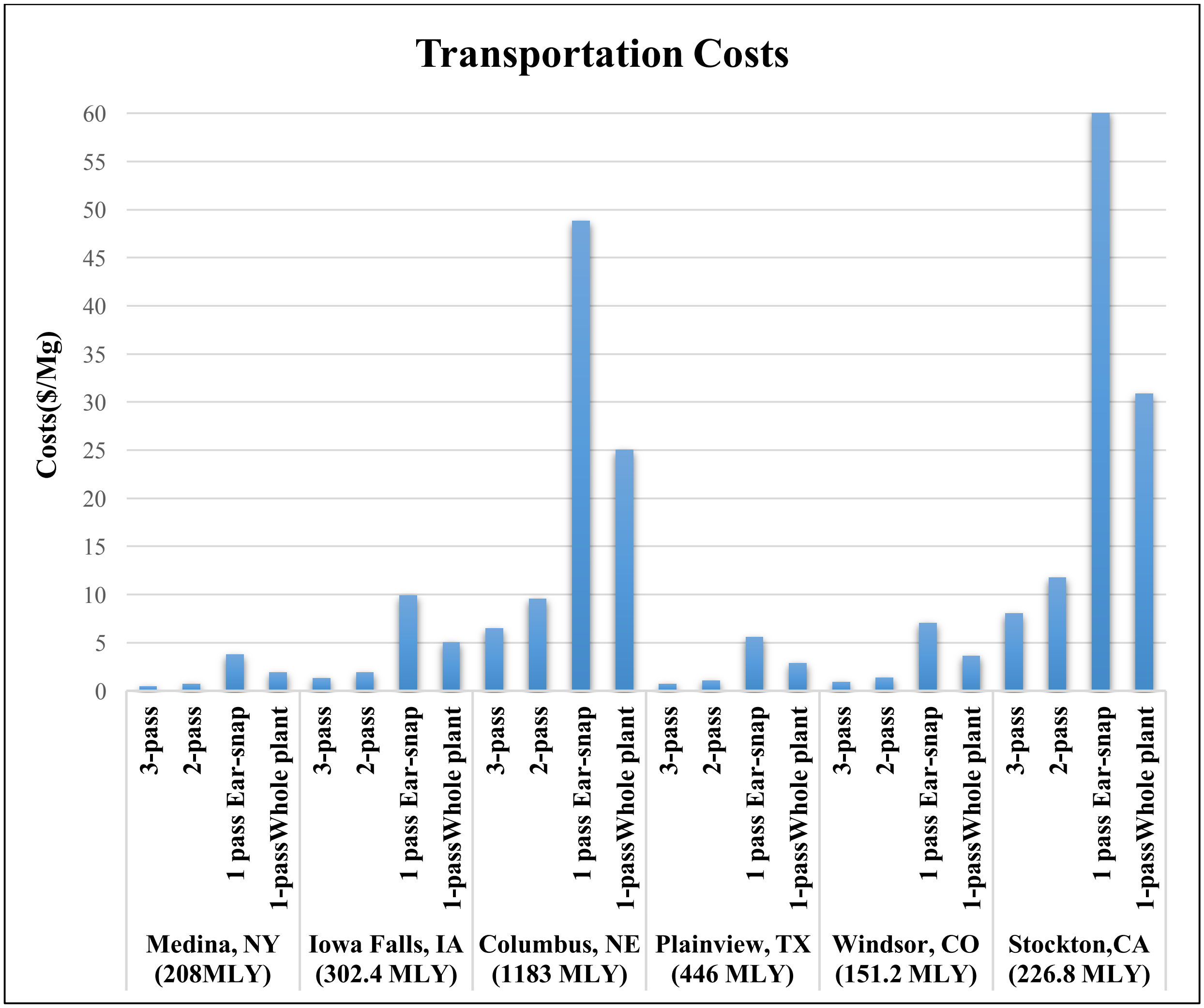

Figure 5.6 Model output of transportation costs for each location for different harvest scenarios

Each plant location has a different plant capacity although the heating requirement is kept constant. Hence, the values for each location vary by a high margin. The Columbus, NE produces about 1183 MLY of ethanol. The reason that the costs are changing is their distance from the corn farms or corn suppliers. Stockton, CA is about 700 km away from the corn supplier and hence, has high costs involved. The reason that the costs are high for the ear-snap header at every location is the low stover yields that are obtained during harvesting. This is not verified with literature data as there is less research on the transportation costs involved with such systems. This model can be used to predict the costs for each scenario and is not limited for these locations. The user is able to

edit any of the parameters to get the desired results or it can be used to get a picture on the costs involved.

5.5 Verifying and Evaluating the Investment costs

The projects costs depend mainly on the capital costs for the plant and the operation costs to maintain the plant in working condition. As in Chapter 4 where the costs have been divided into parts, the same procedure will be followed here. This model integrates the previous models as it depends on the heat requirement and also, the total delivered costs of biomass. Each of the parts in this model, as explained in Chapter 4 are calculated and compared with the literature. [63]. Then, this model is evaluated for the six different locations and the best scenario is predicted. Based on this model, the payback period of the plant is calculated.

5.5.1 Capital Costs (CC)

The capital costs are the costs that act as an investment for the plant systems. The plants are already running on natural gas plants but, in the model the natural gas system is compared as though it were to be installed. The capital costs depend only on the heat requirement and plant capacity and not on the harvesting or the transportation costs. The capital costs of the model are compared with the literature data [63] and are provided in Table 5.11 with the same heat requirement, 9.67 MJ/year and plant capacity of 170 MLY.

Table 5.11 Comparison of the model output of capital costs of the biomass fired system and natural gas systems with literature

Plant System	Model Output Capital Costs	Literature Data Capital Costs
Biomass Fired System	18.1 M$	18.89 M$
Natural Gas System	9 M$	8.62 M$

The capital costs are similar to the values obtained in the literature for the same heat requirement and the plant capacity. The total investment cost for the biomass system is double that of the natural gas system. This is because the biomass equipment requires a filtration device in addition to the boiler system. The natural gas system does not require this device. In addition, the biomass boiler system costs $250/kW whereas the natural gas system only costs about $150/kW.

This can be verified by evaluating the six different locations, as shown in Figure 5.5. Each of the locations has a different nameplate capacity and hence, the capital costs involved these changes for each location.

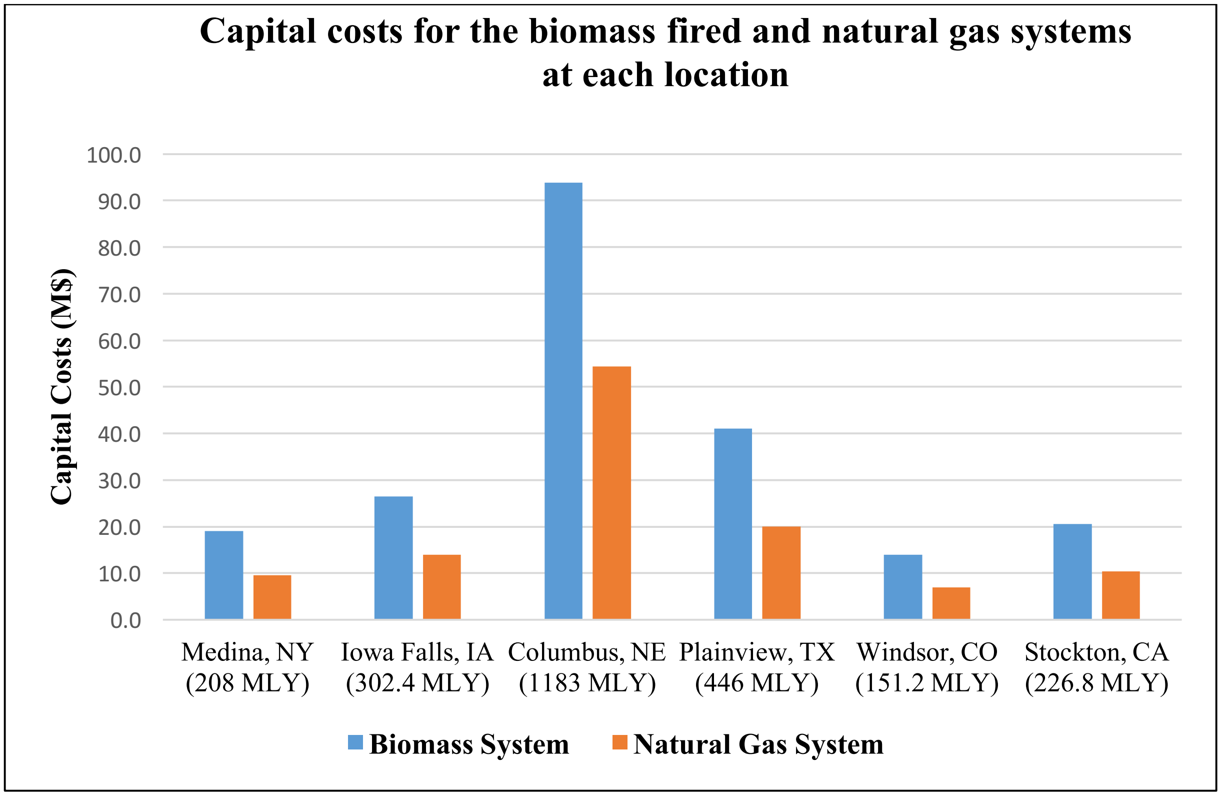

Figure 5.7 Comparison of the capital costs for a biomass fired and natural gas systems at each location

Figure 5.5 shows that at each location, the natural gas system costs less than that of a biomass system. Each of these locations has a different heat requirement in MJ/year depending on the respective plant capacities. Hence, this price is the highest for Columbus, NE as compared to the other locations.

5.5.2 Operation and Maintenance Costs

These costs involve the costs after the system has been installed and is running. These costs are verified with the values obtained from literature [63]. The operating and maintenance costs include operation costs, labor costs, maintenance costs and any debt payment that is applicable. The operation costs depend on the assumption of an average value of the thermal input as an

internal consumption and the price electricity is purchased from the electrical grid. The maintenance costs are considered as 3% of the capital cost. The labor costs depend on the number of workers and their annual salary. The debt payment is the debt interest rate multiplied with the capital cost. This section is flexible and enables the user to change the prices in electricity, the assumption considered for the thermal input, number of workers, their annual salary and also, the debt interest rate.

To compare with literature, an average value of 2% of the thermal input is taken with the price of electricity accounting for $51/ MW-h and five workers with an annual salary of $50,000 are considered. The assumed debt interest rate is 10.5%. This comparison of the model output with the literature is shown in Table 5.12.

Table 5.12 Comparison of the model output with the literature data for the operation and maintenance costs of a biomass and natural gas systems.

System	Model output	Literature
Biomass-Fired System	3.23 M$	3.24 M$
Natural Gas System	2.01 M$	2.02 M$

A change in any of the inputs results in a different output for the operation and maintenance costs. For the evaluation, electricity rates for different states has been estimated from EIA [72]. The default values for the thermal input is set to 2% and the debt interest rate at 10.5%. The number of workers per plant and their annual salary has been changed for each location to provide more realistic values for each of the locations. Figure 5.6 illustrates the comparison of these costs for different locations.

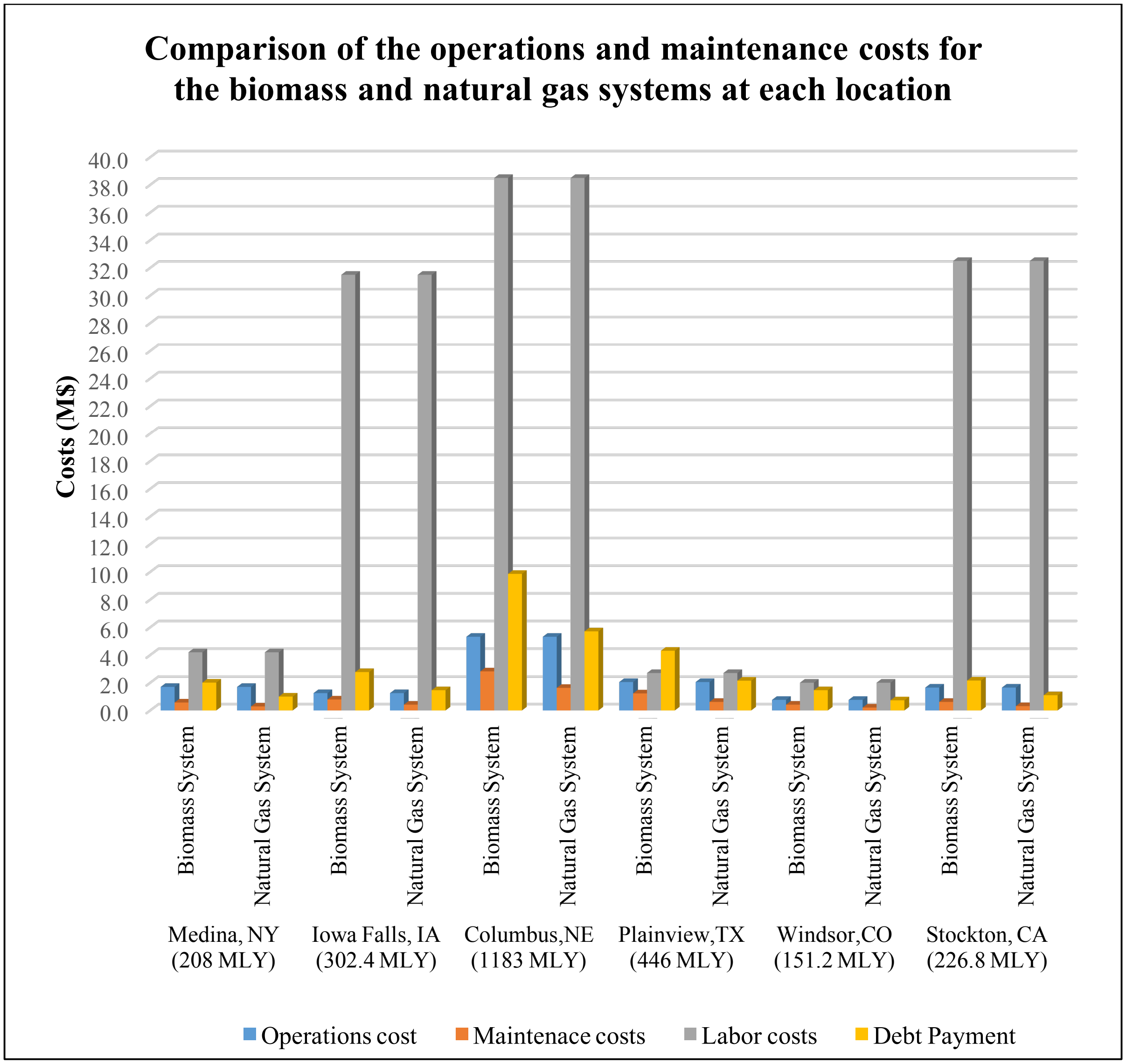

Figure 5.8 Comparison of the operations and maintenance costs for biomass and natural gas system at each location.

As can be seen from Figure 5.6, the labor costs for the California plant and Iowa Falls plant are equivalent to that of Nebraska plant as the number of workers are almost the same and the annual salary also is comparable. The debt payment is the highest for the Nebraska plant as the capital costs are the highest. The plant in Colorado has the lowest costs involved followed by the Texas plant. This is because the electricity rates are less as compared to the other locations. If a closer

look is taken, one can notice that the operation costs and labor costs for the biomass and natural gas systems is the same at every location. This is because these costs are independent of the heat requirement and the capital costs.

5.5.3 Fuel Costs (FC) and Ash disposal costs

Fuel costs are calculated on the basis of the annual fuel consumption of the system which is dependent on the amount of corn stover, A_{CS}, required and the heat requirement of the plant in MJ/year. The model output has been compared to the literature data and recorded in Table 5.13.

Table 5.13 Comparison of the fuel costs of the harvesting scenarios of the biomass system with the literature data.

	Scenario	Biomass-Fired System	Natural Gas System
Model Output	3-pass	5.78 M$	24 M$
	2-pass	5.31 M$	
	1-pass ear-snap	8.3 M$	
	1-pass whole-plant	7.11 M$	
Literature data		8.81 M$	24.42 M$

The model output gives the fuel costs for the available three harvesting systems and it can be noticed that the one-pass ear-snap header is more comparable with that of the literature data than the other scenarios. The natural gas system as listed out in the literature shows $15.54M but, when calculated manually, the fuel costs are $24M which is comparable to the model output. These fuel costs are highly dependent on the plant capacity and the heat requirement and also, include data from the harvesting, transportation and storage model.

The evaluation of the fuel costs for the six different locations is shown in Figure 5.7.

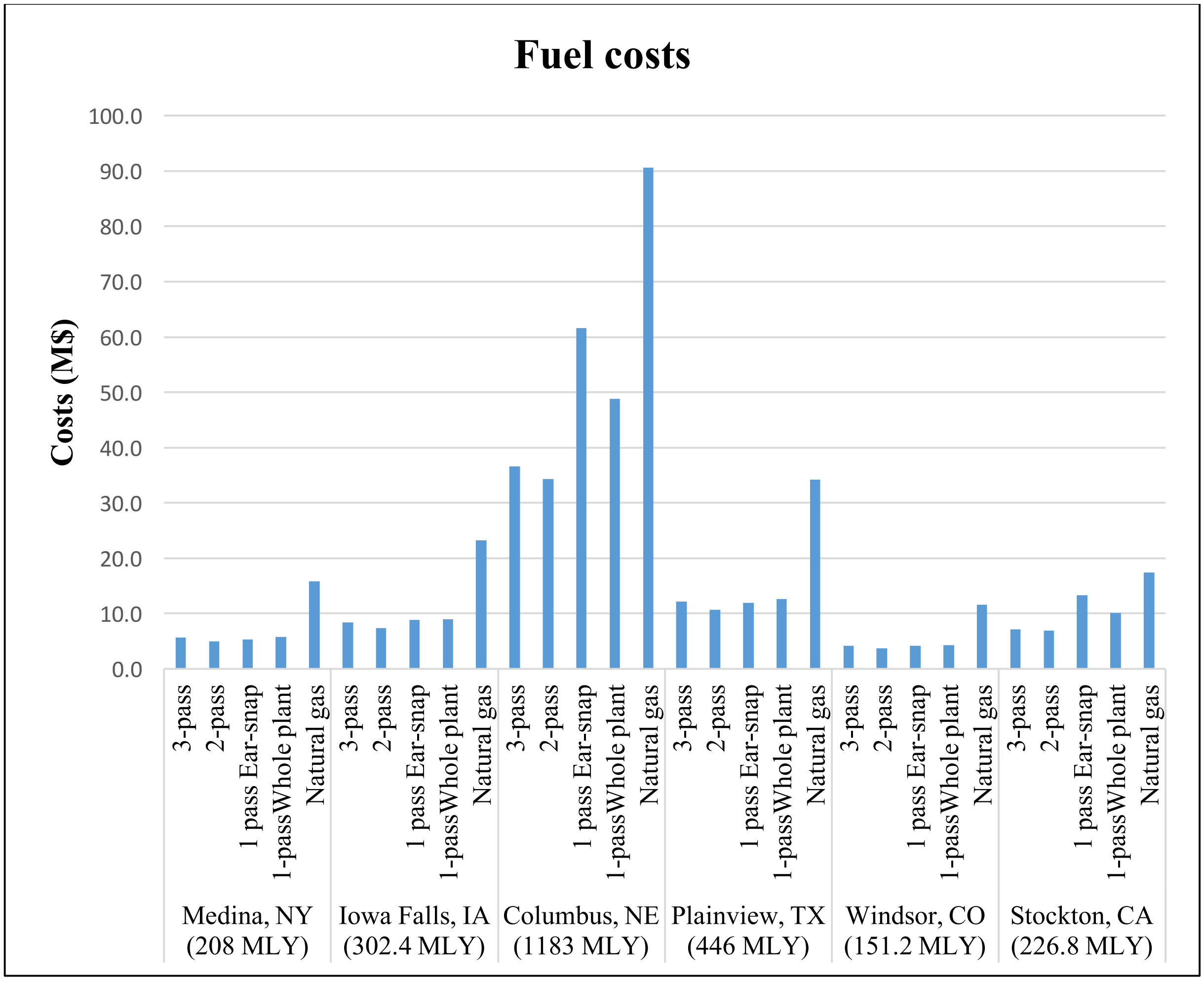

Figure 5.9 Comparison of fuel costs of the different harvest scenarios at each plant location.

It can be analyzed that the fuel costs for the natural gas system are almost double that of the biomass fired system even the fuel consumption is exactly that of the biomass combustion for the same amount of heat requirement. The fuel costs for the harvest scenarios depend on the stover yields and hence, the costs involved for ear-snap header is higher than the other systems and is almost equivalent with the natural gas systems.

The annual disposal costs are calculated only for the biomass system as the natural gas does not involve ash disposal. The parameter that can be varied here is the ash hauling distance

which is assumed to be 25 km unless otherwise noted. The other parameters that are taken from the data are the ash content of stover is 5.1 %, the ash hauling distance cost is $0.157/ Mg-km and the ash spreading cost is $25/Mg-ha.

Table 5.14 Comparison of the model output for annual ash disposal with the literature data.

	Scenario	**Biomass-Fired System**
Model Output	3-pass	0.06 M$
	2-pass	0.05 M$
	1-pass ear-snap	0.11 M$
	1-pass whole-plant	0.06 M$
Literature data		0.14 M$

The values in Table 5.14 give an estimated value of the ash disposal costs and is similar to the literature. As mentioned earlier, the ear-snap header costs are more comparable with that of the natural gas systems.

5.5.4 Total Costs (TAC) and Total Savings (TS)

The total costs involve all the costs that have been discussed prior to this section. In other words, it is the summation of the operations and maintenance costs and the fuel costs. For the biomass fired system, the annual ash disposal costs have also been added. The total savings for the project will be the difference of the total costs and the capital costs of the natural gas system with that of the biomass system. The total savings is calculated from the natural gas system as the biomass system has to replace the natural gas system. Figure 5.8 illustrates the final costs and

savings for each of the locations for different harvesting scenarios. The blue bars represent the capital costs for the whole plant and the orange and grey bars indicate the costs and savings for each harvesting system at each location. This kind of prediction would help the user to decide the best possible scenario to gain maximum profit.

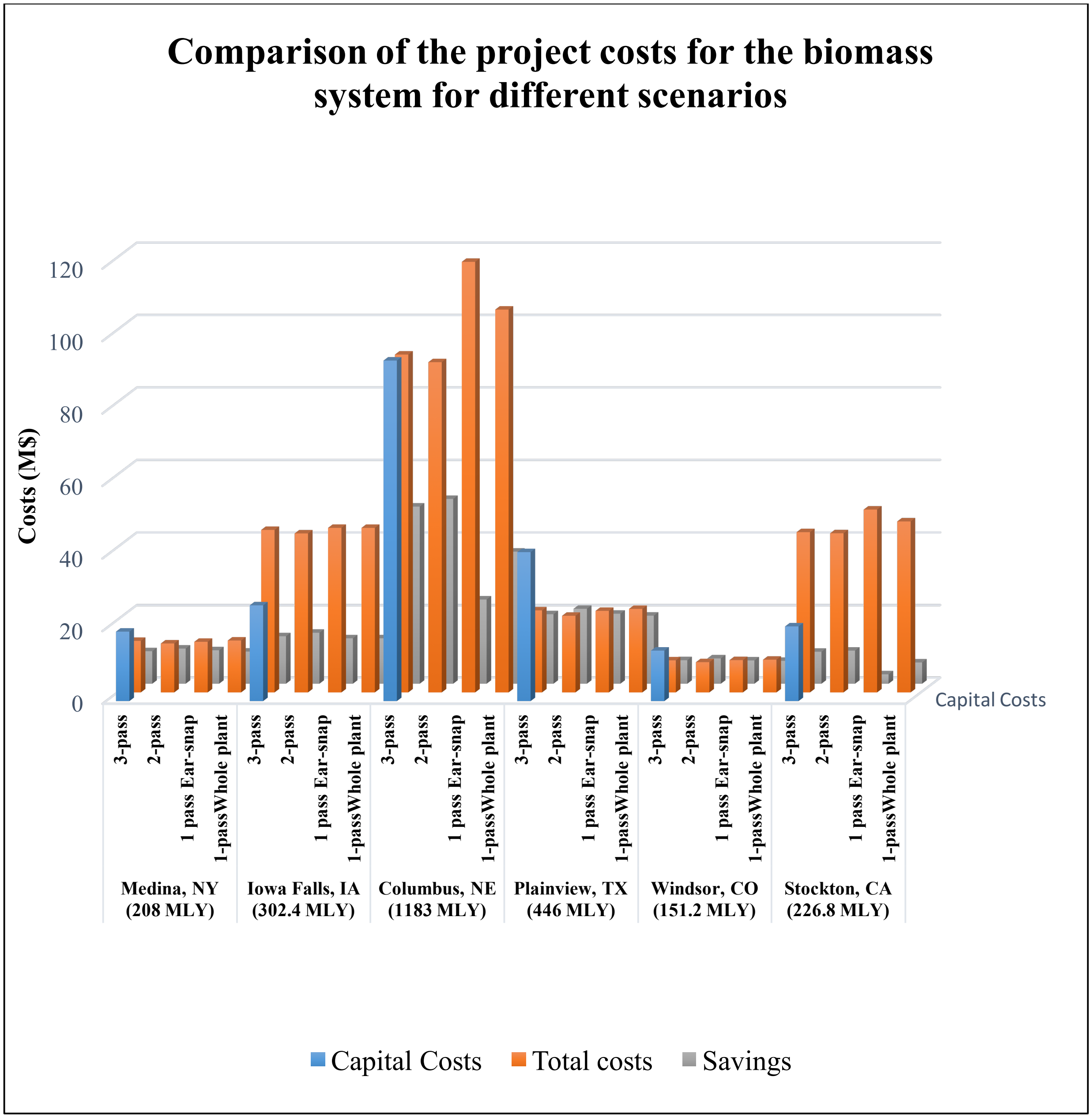

Figure 5.10 Comparison of the project costs for the biomass system for different scenarios at each location

The Nebraska location has the highest capital costs and therefore, higher costs and savings are involved. This is due to the high operation and maintenance costs and the higher fuel costs. The California location has less capital cost but has higher costs involved which is a result of the high number of workers at the location and their annual salary.

Analyzing the data that has been provided and the model outputs, it was seen that the single-pass ear-snap header was more closely related to the literature.

5.6 Payback Period

Payback period is a measure of the length of time it takes to earn profits from the amount invested. The payback period considered here is the simple payback period and is calculated for each location. This is shown in Figure 5.9.

The average payback period of the biomass system is 2-3 years and is proven from the model output (S. Mani, 2010). The payback period for the single-pass ear-snap at California plant is 8 years, a lot more than the average value. This is because of the projected costs and savings. If the parameters were to be changed according to the use, then the payback period also changes.

It has to be noted that the simple payback period changes with the capital costs and the operations and maintenance costs which are in turn dependent on the plant capacity, the heat requirement and the transportation, the harvesting and storage models.

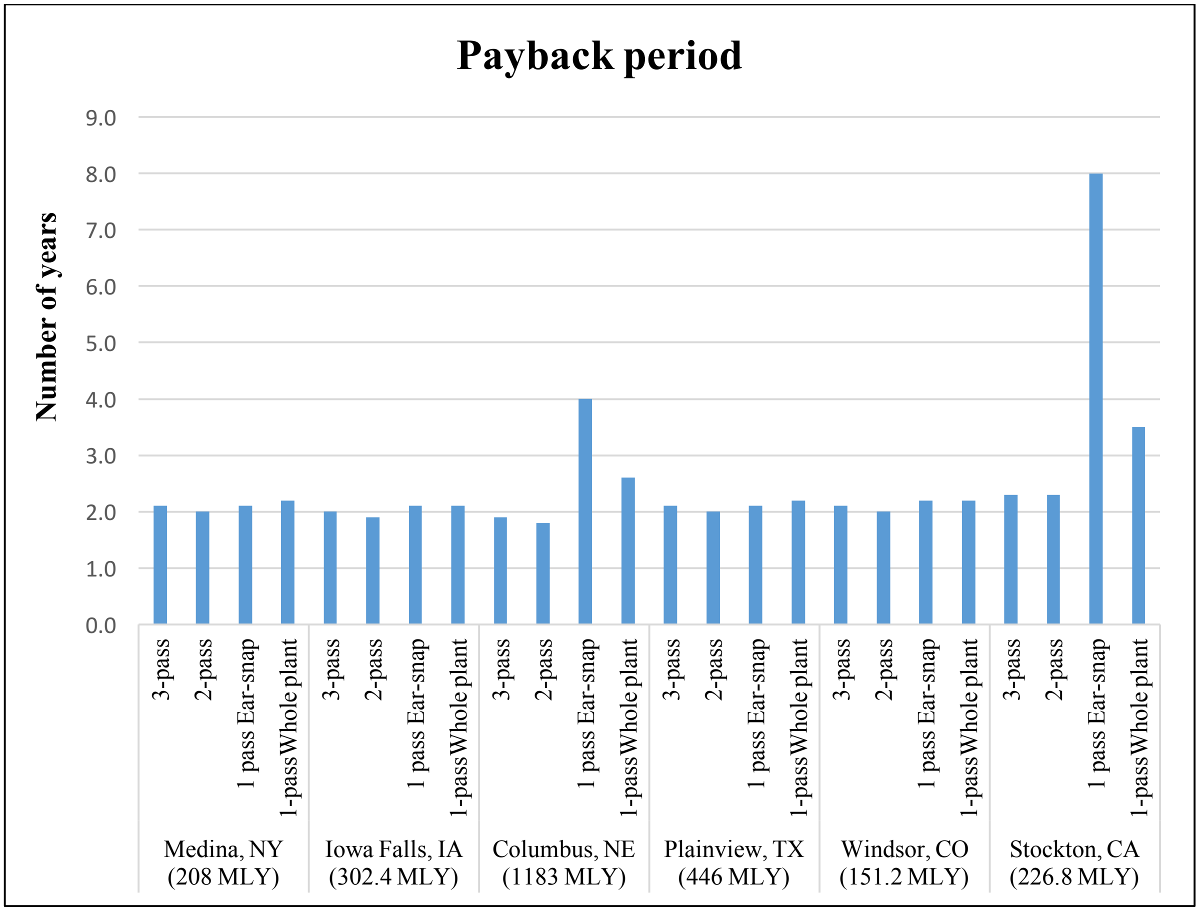

Figure 5.11 Model output for payback period of different location incorporating different scenarios

The price of natural gas is highly fluctuating which affects the cumulative savings and the payback period of the boiler system. The model, by default, consider 8$/GJ [63] as the price of natural gas and increases by 5% every year. The boiler system usually has a life expectancy of 15-20 years. Hence, by default, the model consider 20years to be the life expectancy. The resultant cumulative savings are as illustrated in Figure 5.10. For Figure 5.11, the %increase by year for natural gas has been changed from 5% to 3.3%.

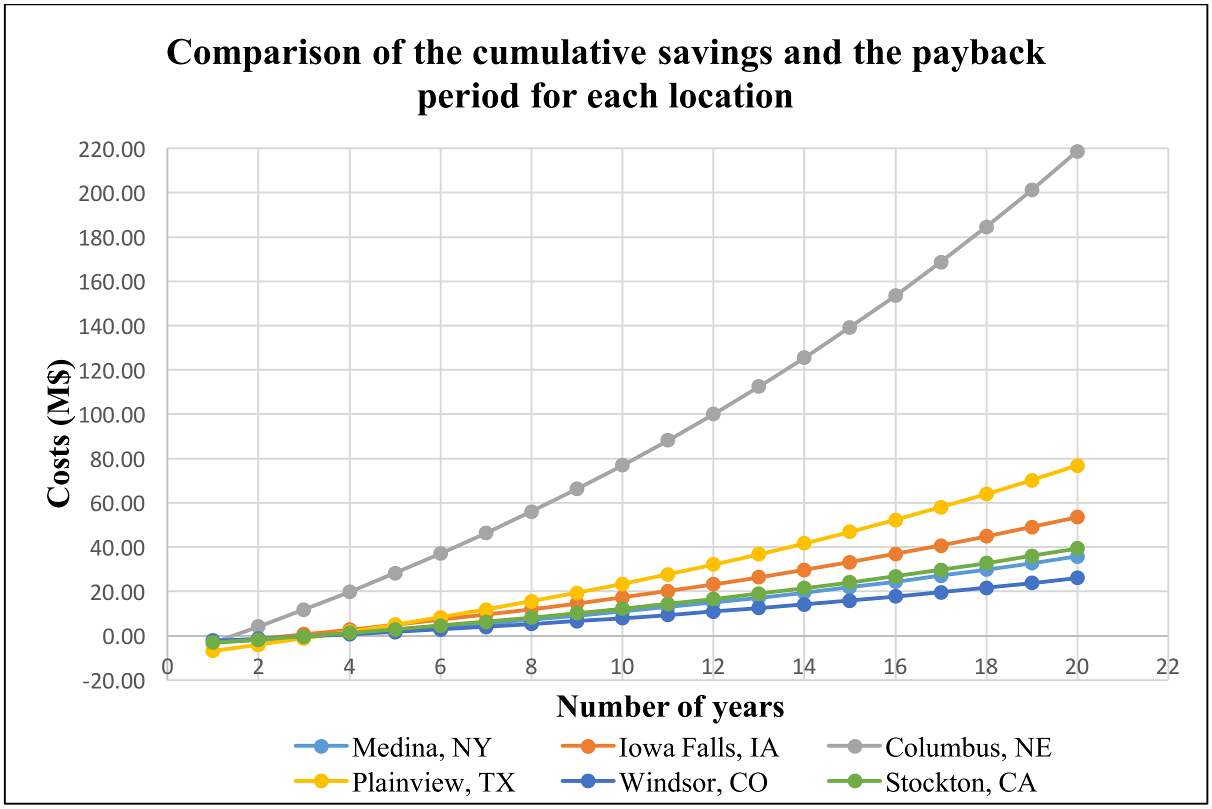

Figure 5.12 Comparison of the cumulative savings and the payback period for each location (Price=8$/GJ, %increase=5)

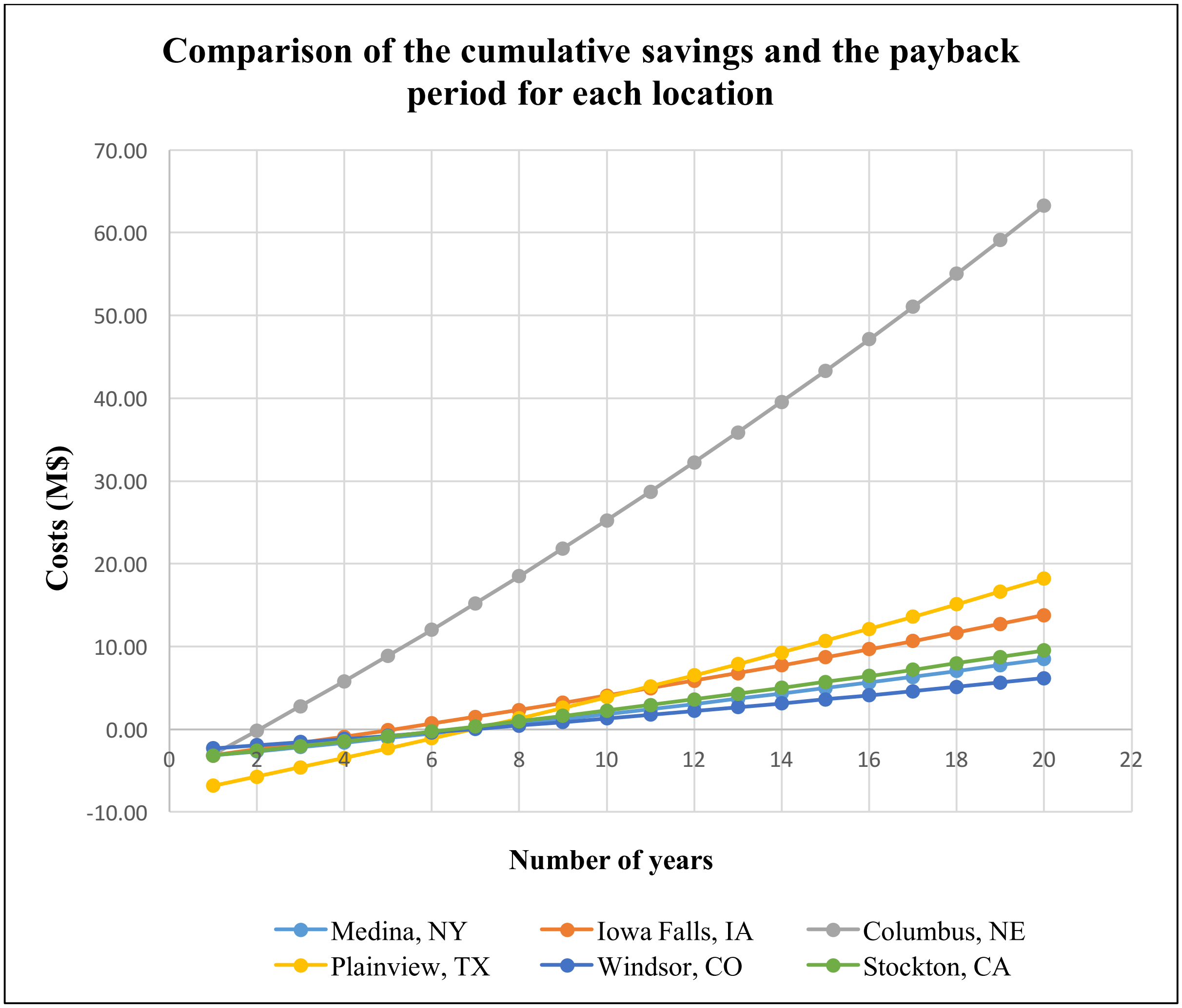

Figure 5.13 Comparison of the cumulative savings and the payback period for each location (Price=8$/GJ, %increase=3.3)

As can be seen from the two Figures (5.10) and (5.11), we notice that the payback period is being shown as higher for the steady increase rate of 3.3% than the steady increase rate of 5% as the model calculates the cumulative savings are calculated by subtracting the effective costs of the natural gas system from the capital costs of the biomass system. In both the cases, Columbia, NE has the lowest payback period as the operation and maintenance costs of this system are higher which results in a lower effective cost for the natural gas system. Columbia, NE has a payback

period of less than one and a half year for a steady rate increase of 5% and a payback period of about 2 years for the 3.3% increase. The other locations have a payback period of 2 to 5 years for a steady increase rate of 5% and a payback period of 3 to 7.5 years for the 3.3%.

This model can also be used if the natural gas price changes. The following Figures (5.12) and (5.13) show the cumulative savings for a price of 6$/GJ at a steady increase rate of 5% and 3.3% respectively.

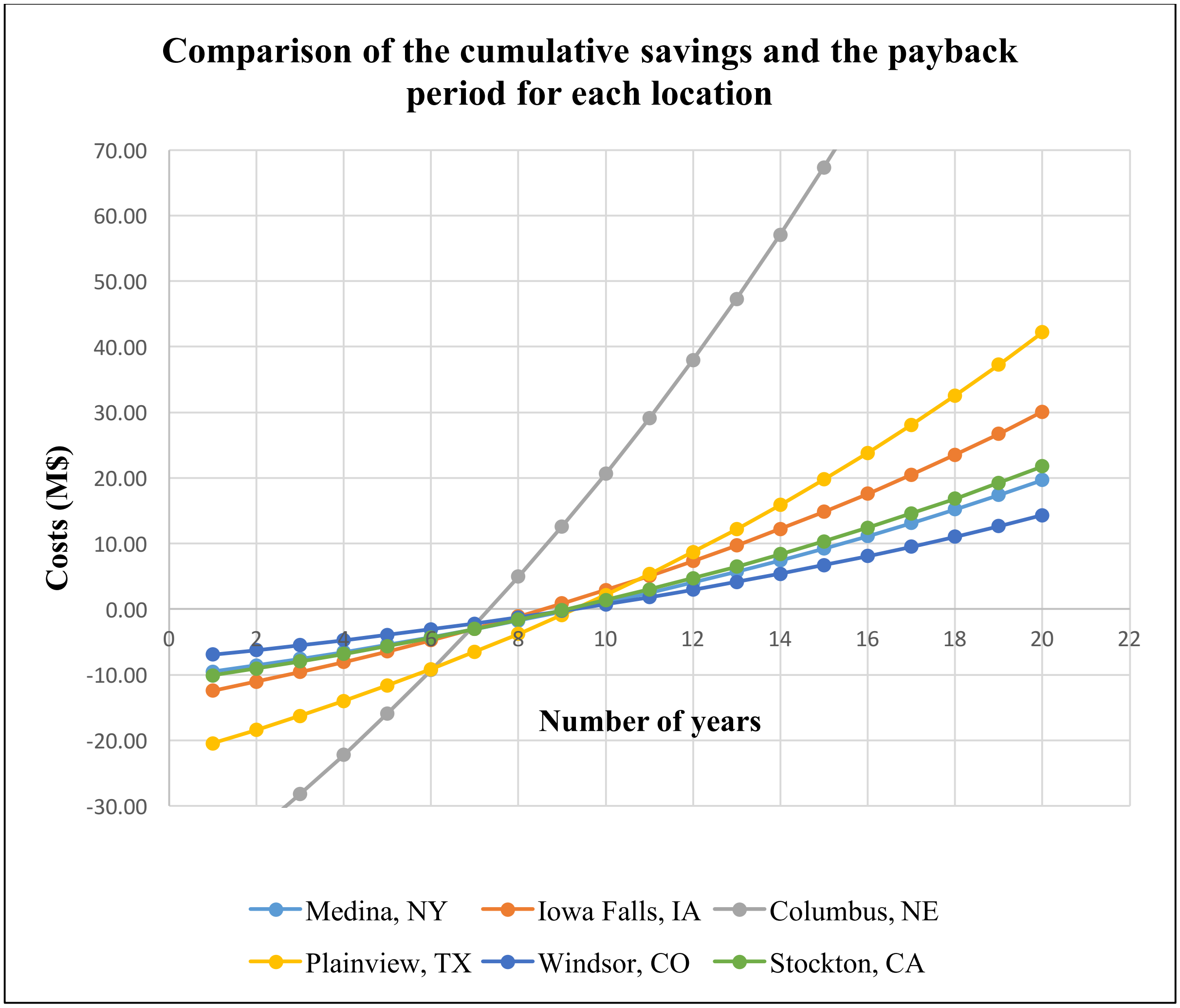

Figure 5.14 Comparison of the cumulative savings and the payback period for each location (Price=6$/GJ, %increase=5)

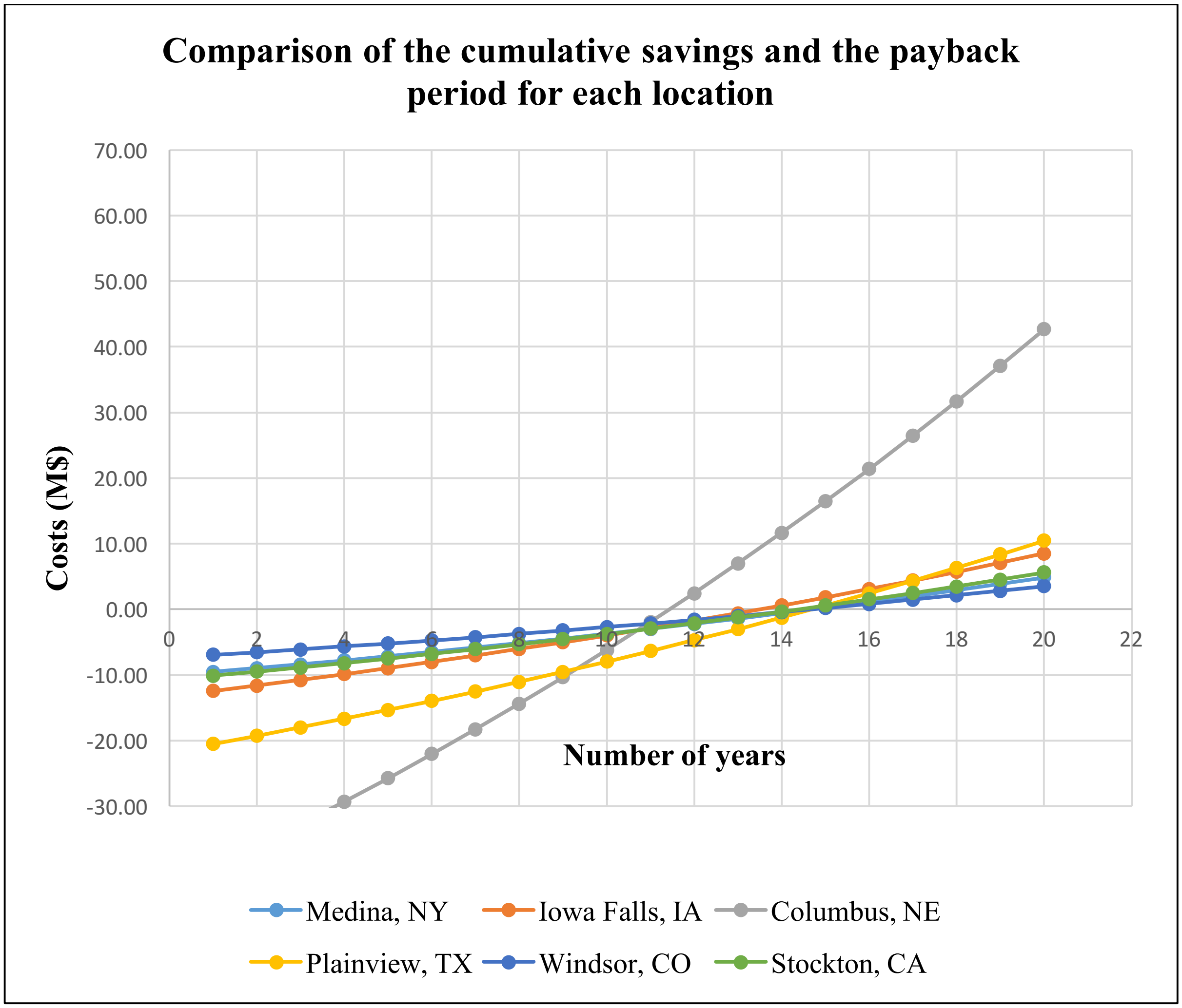

Figure 5.15 Comparison of the cumulative savings and the payback period for each location (Price=6$/GJ, %increase=3.3)

As stated earlier, the model calculates the cumulative savings are calculated by subtracting the effective costs of the natural gas system from the capital costs of the biomass system. Columbia, NE has a payback period of about 7 years for a steady rate increase of 5% and a payback period of 11 years for the 3.3% increase. The other locations have a payback period of 8 to 10 years for a steady increase rate of 5% and a payback period of 12 to 13 years for the 3.3%.

5.7 Summary

This model accurately estimates the raw material needed and the cost savings of a biomass fired

system. The changes in parameters can provide a wide range of project conditions and have differing effects on the outputs. The viability of corn stover as a heat source for ethanol plants has been evaluated at six different locations and have a decent payback period. For the installation/realization of the project, the major costs have to be considered which have been accurately estimated for different scenarios

CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Ethanol production plants are increasing in number every few years, as does the amount of natural gas that is required to produce the ethanol. This urges the nation to look for a renewable fuel that can make the biofuels industry sustainable. Biomass systems are an attractive option for reducing the fossil fuel consumption and this industry is said to grow in the next couple of years. The RFS mandates will continue to increase the production of ethanol in the nation. Biomass plays an important role as the combustion technology is well developed and the shift towards a renewable heat source will reduce fossil fuel consumption along with improving energy security. Ethanol opponents cite the larger requirements of heat requirement and the food vs. fuel debate as the leading factors against corn ethanol.

Natural gas systems can be completely replaced by biomass systems and then be used only when there is excessive energy needed which cannot be provided through the biomass system. The ethanol plants are located in close proximity to the farms and the raw material, i.e., corn stover, can easily be obtained from a nearly source which saves a considerable amount of money. As the installation of the biomass systems does not depend on the location, they can be installed anywhere in the nation.

The project costs involved along with the harvesting costs and the transportation costs are to be considered before realizing the project. The profitability of these systems depends on government incentives, the state electricity prices and the distance from the location of the source.

The model considers these factors to place a number on these costs and can be used to predict the development stages of the project. It is not to be expected as a decision maker for the

entire project. Although the harvesting costs are accurate based on literature, the model does not consider only the costs of stover alone but of both corn and corn stover. If the project considers a different source for corn stover, then another approach has to be followed. The harvesting technique only considers round bales and if the project is considering rectangular bales, then the fuel costs and the ownership costs for a rectangular baler will change which will affect the economics of the project. The model does not address the transportation costs by rail or sea nor does the model consider the outdoor storage systems. These would affect the project costs. Although, the model does not consider these scenarios, it considers almost every aspect required to estimate the installation project.

6.2 Recommendations

This model can provide information to ethanol plants for the feasibility and economics of corn stover as a heat source as ethanol plants. Information from this research can be used to initiate a project or to gain information on the different systems. Further investigation needs to be considered if the project is moving through to the next process. This could be in the form of an additional information model or merely changes in the equations of the current model. Ethanol plants can improve their public image by installing a renewable energy project and the biomass systems have reasonable payback periods.

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