A Production And Cost Modeling Methodology Of 2nd Generation Biofuel In The United States

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A PRODUCTION AND COST MODELING METHODOLOGY OF 2ND GENERATION BIOFUEL IN THE UNITED STATES

by

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B.S. Aerospace Engineering, University of Central Florida, 1994

A thesis submitted in partial fulfillment of the requirements for the Degree of Master of Science in the College of Graduate Studies at the University of Central Florida
Orlando, Florida

Summer Term
2012
ABSTRACT

The use of biofuels in the United States has increased dramatically in the last few years. The largest source of feedstock for ethanol to date has been corn. However, corn is also a vitally important food crop and is used commonly as feed for cattle and other livestock. To prevent further diversion of an important food crop to production of ethanol, there is great interest in developing commercial-scale technologies to make ethanol from non-food crops, or other suitable plant material. This is commonly referred to as biomass.

A review is made of lignocellulosic sources being considered as feedstocks to produce ethanol. Current technologies for pretreatment and hydrolysis of the biomass material are examined and discussed. Production data and cost estimates are culled from the literature, and used to assist in development of mathematical models for evaluation of production ramp-up profiles, and cost estimation. These mathematical models are useful as a planning tool, and provide a methodology to estimate monthly production output and costs for labor, capital, operations and maintenance, feedstock, raw materials, and total cost. Existing credits for ethanol production are also considered and modeled.

The production output in liters is modeled as a negative exponential growth curve, with a rate coefficient providing the ability to evaluate slower, or faster, growth in production output and its corresponding effect on monthly cost. The capital and labor costs per unit of product are determined by dividing the monthly debt service and labor costs by that month’s production value. The remaining cost components change at a constant rate in the simulation case studies.

This methodology is used to calculate production levels and costs as a function of time for a 25 million gallon per year capacity cellulosic ethanol plant. The parameters of interest are calculated in MATLAB with a deterministic, continuous system simulation model. Simulation results for high, medium, and low cost case studies are included. Assumptions for the model and for each case study are included and some comparisons are made to cost estimates in the literature.
While the cost per unit of product decreases and production output increases over time, some reasonable cost values are obtained by the end of the second year for both the low and medium cost case studies. By the end of Year 2, total costs for those case studies are $0.48 per liter and $0.88 per liter, respectively. These cost estimates are well within the reported range of values from the reviewed literature sources. Differing assumptions for calculations made by different sources make a direct cost comparison with the outputs of this modeling methodology extremely difficult.

Proposals for reducing costs are introduced. Limitations and shortcomings of the research activity are discussed, along with recommendations for potential future work in improving the simulation model and model verification activities.

In summary, the author was not able to find evidence—within the public domain—of any similar modeling and simulation methodology that uses a deterministic, continuous simulation model to evaluate production and costs as a function of time. This methodology is also unique in highlighting the important effect of production ramp-up on monthly costs for capital (debt service) and labor. The resultant simulation model can be used for planning purposes and provides an independent, unbiased estimate of cost as a function of time.
To my loving wife who has been very supportive of my educational pursuits,

To my children for bearing with me during this time,

To my friends for cheering me on, and telling me to just “Get ‘er Done!”
ACKNOWLEDGMENTS

I wish to thank Dr. Peter Kincaid for his willingness to support me in this research and his shared interest in the further investigation of alternative energy and renewable fuels. The advice he provided was much appreciated, as was his guidance, his ideas, and his great patience. I would also like to thank Mr. Anthony Radich at the Energy Information Administration for his expertise and willingness to answer my renewable fuel questions. His economic inputs were very valuable. Mr. Mac Statton was also a great help to me in my research, answering questions about production methods, industry technology, and providing some good “rules of thumb.”

I would also like to thank Dr. Mansooreh Mollaghasemi and Dr. Christopher Geiger for agreeing to serve on my thesis committee. Their participation was welcome and appreciated.
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5</td>
<td>5% biodiesel or less by volume mixed with petroleum diesel</td>
</tr>
<tr>
<td>B20</td>
<td>20% biodiesel or less by volume fuel mixed with petroleum diesel</td>
</tr>
<tr>
<td>B100</td>
<td>Pure biodiesel</td>
</tr>
<tr>
<td>CBPTC</td>
<td>Cellulosic Biofuel Producers Tax Credit</td>
</tr>
<tr>
<td>E10</td>
<td>10% Ethanol or less by volume fuel mixture</td>
</tr>
<tr>
<td>E85</td>
<td>85% ethanol or less by volume fuel mixture</td>
</tr>
<tr>
<td>EISA</td>
<td>Energy Independence and Security Act</td>
</tr>
<tr>
<td>FFV</td>
<td>Flexible Fuel Vehicle</td>
</tr>
<tr>
<td>GGE</td>
<td>Gallons of Gasoline Equivalent</td>
</tr>
<tr>
<td>MTBE</td>
<td>Methyl Tertiary Butyl Ether</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>PADD</td>
<td>Petroleum Administration for Defense Districts</td>
</tr>
<tr>
<td>PPI</td>
<td>Producers Price Index</td>
</tr>
<tr>
<td>PV</td>
<td>Product Value</td>
</tr>
<tr>
<td>RFS</td>
<td>Renewable Fuel Standard</td>
</tr>
</tbody>
</table>
CHAPTER ONE: INTRODUCTION

In 2011, the United States transportation sector consumed 8.76 million barrels of refined motor gasoline per day, and 3.89 million barrels of distillate fuel per day. Most of the distillate fuel was in the form of diesel fuel. The total of this gasoline and diesel fuel accounted for 66.8% of the 18.93 million barrels of crude oil consumed (average) in the United States each day of 2011 [1].

At this rate of usage, the United States transportation sector consumed 6.91 billion barrels of petroleum in 2011. The use of petroleum, while widespread and commonplace will at some point become unsustainable. No new oil is being created. Proven reserves worldwide are 1.471 trillion barrels as of January 1, 2011 [2]. Tapping these proven reserves in many cases involves more labor intensive, more difficult to reach sources. This makes them more expensive to exploit and recover. While new sources may be found, it is clear that this country and the world must begin to research, develop, and make commercially available new renewable sources of liquid fuel. The most promising alternative liquid fuels are bioethanol and biodiesel. Both are made from biomass-vegetative waste and various plant materials.

Another reason for developing and employing alternative liquid fuel sources would be to decrease the US dependence on foreign oil to supply the needs of the transportation sector. In 2011, the US imported 49-50% of its petroleum. This percentage has been decreasing each year since 2005; however, the country is still dependent on world markets and foreign countries’ production capacity. A country that has achieved energy independence and produces close to 50% of its transportation fuel from bioethanol is Brazil. Brazil produces almost all of its ethanol from sugar cane, and is a net renewable fuel exporter. This has the dual effect of favorable trade balance of energy products as well as promoting national energy independence.
Most academic research of biofuels recently has been concentrated on chemical composition, methods of extracting fuel from feedstock, public policy, or the benefits of moving towards biofuels for reduction in greenhouse gas emissions. This research will focus on the production of biofuel types, and the cost to develop and provide the end product to the consumer. The primary questions that the author hopes to answer are: Can a commercial-scale cellulosic ethanol plant ramp-up production quickly (6 months to two years) enough to demonstrate the ability to replace or greatly reduce the consumption of petroleum in this country? If so, can the price of a gallon of biofuel compete with the price of a gallon of gasoline or diesel fuel? Deterministic production and cost models will be implemented in a continuous system simulation to demonstrate possible scenarios, and provide data to analyze and possibly answer these compelling questions.

1.1: First-Generation Biofuels

A first-generation biofuel is one that is currently being produced and consumed in large quantities, and is made primarily from a specific type of plant material, or feedstock. The largest current feedstock for bioethanol is corn in the United States, and sugar from sugarcane in Brazil. Together these crops and countries accounted for more than 87% of the bioethanol produced worldwide in 2009 [12]. In the last year, corn was used to produce approximately 12 billion gallons of ethanol. Some of this ethanol was blended with refined motor gasoline in an 85% ethanol, 15% gasoline volume split, more commonly known as E85. The vast majority of the refined ethanol produced was blended with gasoline in a 10% ethanol, 90% gasoline split, more commonly known as E10. In this capacity, ethanol is used as an oxygenate and as an octane enhancer. This allows it to be used in place of methanol, or MTBE, which has been found to be toxic. An oxygenate is a substance which, when added to gasoline, increases the amount of oxygen in that gasoline blend.
In Brazil, the sugarcane crop used for making ethanol takes up approximately 1.5% of the arable land in that country, but produces close to 50% of the liquid fuel used [2]. Some 4.1 million hectares of sugarcane produced approximately 21.1 billion liters (5.5 billion gallons) of ethanol in 2011. This represents a yield of approximately 5,000 liters per hectare, or 530 gallons per acre. (NOTE: 1 hectare = 2.471 acres)

The largest current feedstocks for biodiesel are waste oil and soybeans here in the US, and rapeseed in Europe. Palm oil is used heavily in Southeast Asia, primarily in Singapore and Malaysia.

1.2: Second-Generation Biofuels

A second-generation biofuel consists of an ethanol or biodiesel product made from feedstock that is not also a major food crop. These feedstocks are currently not being used to produce quantities of biofuel on a large scale, and the methods of production are not yet considered technically mature or economically competitive. Some examples of feedstocks being used to produce initial quantities of biofuel are corn stover, forest residues, miscanthus, vegetative waste, woody biomass, jatropha, camelina, switchgrass and other cellulosic sources. Most of the best potential feedstock sources are drought-resistant, hardy plants that need a minimum input of irrigation, fertilizer, and in ideal cases, non-dedicated land. For example, jatropha has been found to be able to grow alongside food crops without the need for additional dedicated land use [13].

The current legislation driving the recent dramatic increase in ethanol production in the United States is the Renewable Fuel Standards regulations in the Energy Independence and Security Act (EISA) of 2007. This regulation, or law, mandates that 36 billion gallons of ethanol be produced and used in the United States by the year 2022 [14]. This is an increase from 9 billion gallons of renewable fuels by 2008. The legislation caps the amount of ethanol produced from corn feedstock at 15 billion gallons per
year, with the rest coming from cellulosic sources and biodiesel. At the time of this writing, the amount of biodiesel produced in a given year is approximately 1 billion gallons, and the amount produced from cellulosic sources is in the millions of gallons. This is an indication that the ethanol industry is quite a bit behind on meeting the mandated targets set out in the EISA mandate without using more corn feedstock. There are currently 12 plants in the United States generating ethanol from cellulosic sources, biomass, municipal solid waste, and/or algae. These are all pilot, or demonstration, scale plants and none are considered producing at commercial levels. They are generating less than 4 million gallons per year of renewable fuels [15].
CHAPTER TWO: LITERATURE REVIEW

2.1: Types of feedstock used to produce bioethanol

As discussed in Chapter One, the primary feedstock used to produce bioethanol in the United States is corn. A possible and likely very useful feedstock for cellulosic ethanol production is the biomass from crop residue leftover from corn ethanol production. The crop residue from corn processing is in the form of the corn stover. Crop residue from other sources include rice straw, sorghum straw, barley straw, wheat straw, and sugarcane bagasse [3].

Another source of feedstock is non-food energy crops. These consist mainly of perennial forage crops such as switchgrass, bermudagrass, alfalfa, and napiergrass. Switchgrass in particular is mentioned frequently in the literature because of its adaptability to growth on low quality land, its lower water and nutrition input needs, and its positive impact on the environment [18]. Switchgrass is generally considered a leading candidate in the category of forage crops due to widespread distribution from Central America to Southern Canada. The type of soil seems to have little impact on how well the crop grows; however, the soil must have good water-holding characteristics.

Another potential source of feedstock is fast growing tree species, known as woody energy crops, or forestry residue. As with non-food energy crops, or forage crops, desirable characteristics would be relatively high yield potential, large geographical distribution, and lower levels of input needed (water, fertilizer, pesticides, etc.) than annual crops. Common tree species that meet some or all of these criteria are poplar, willow, and eucalyptus.

Despite the higher yields and lower inputs required, both perennial forage crops and woody energy crops are not completely immune from the food versus fuel debate. The crops should not be
grown and harvested on land displacing food crop production or grazing pastures. In certain cases, these crops could be grown on land that would not otherwise be used productively for annual food crops or for grazing activity.

**2.2: Current methods of cellulosic ethanol production**

The three primary components of biomass being considered as feedstock for 2\textsuperscript{nd} generation ethanol production are lignin, cellulose, and hemicellulose. In most promising feedstock, these three components account for 80-90\% of the biomass composition. The lignin and hemicellulose form a protective sheath around the cellulosic fibers, while the cellulose itself is a rigid polymer of cellobiose that is difficult to break up. Cellulose and hemicellulose are what are known as polysaccharides, and must be hydrolyzed to yield the five and six-carbon sugars from their composite matrix [5].

The three components must be separated from each other so that the sugars can be extracted from the treated cellulose and hemicellulose. These sugars can then be fermented into ethanol. The lignin is a leftover residue that cannot be used to make ethanol, but could be used to produce electricity for the plant to make it self-sufficient, or to provide electric power back to the grid.

To produce ethanol from a lignocellulosic feedstock is much more complicated than fermentation of sugar from current feedstock sources such as corn or sugarcane. Pre-treatment of the feedstock is necessary to clean and size the input biomass. It is also used to destroy the cell structure of the biomass to make it more accessible to further chemical or biological treatment. In some cases, the hydrolysis of the hemicellulose is classified as a pre-treatment step. See Figure 1 for picture of the cell structure.
The cellulose must be broken down to free sugar molecules by the addition of water, a process called saccharification, or hydrolysis. Acid, in a dilute or concentrated form, or enzymes can be used in the hydrolysis of cellulose, and in the removal of lignin from the biomass [5]. Figure 2 is a schematic of the biochemical ethanol production process.
One of the difficulties in producing ethanol this way, and thus increasing costs, is the need to reduce the size of the biomass inputs to very small chips (from 1 mm to a few centimeters). This requires a costly and inefficient mechanical pre-treatment process.

The pre-treatment process can be handled by several methods. The preferred method for pre-treatment is a dilute acid pretreatment. In this treatment, dilute sulfuric or nitric acid is used to break down the cell structure and separate the hemicellulose with liquid from the solids which still contain the lignin and cellulose. The acid is combined with lime to neutralize or remove it from the solids before it reaches the fermentation stage. This produces gypsum as a byproduct of the reaction, which must be disposed of [21]. Some technologies allow the recycling of the acid, thus reducing production costs, and limiting the amount of gypsum disposal.

Another pre-treatment method is an alkaline pretreatment method. In this case, a base consisting of sodium hydroxide or calcium hydroxide is used to break down the biomass. This process removes the lignin and hemicellulose while increasing the reactivity of the remaining cellulose. It has the effect of rendering the hemicellulose unavailable for fermentation as it creates an insoluble, polymeric form.
Another disadvantage of this method is the use of these salts is expensive, and raises environmental concerns. Their use can result in prohibitive costs for recycling, wastewater treatment, and residue disposal [5].

Some physical methods for pre-treatment include use of a steam explosion process, a liquid hot water (LHW) process, or an ammonia fiber explosion (AFEX) process. These methods require the biomass to be treated with large quantities of water and at hotter temperatures and pressures than the catalyzed methods mentioned above. Most of the steam treatments yield high hemi-cellulose solubility and low lignin solubility, which is desirable. However, the steam explosion process results in lower cellulose yields. The LHW process is very promising but is still in its infancy as a technology [5].

The hydrolysis process can be accomplished by means of dilute acid, concentrated acid or enzymatic methods. The acid treatments are part of a two-step process that begins in the pre-treatment step. Concentrated acid hydrolysis is effective at catalyzing more cellulose than dilute acid and results in higher ethanol yields, but the necessary equipment required is more expensive and the conditions harsher than the dilute acid hydrolysis [5, 21]. The enzymatic hydrolysis is the preferred method because it results in higher yields than acid hydrolysis, occurs at milder conditions of temperature and pressure, maintenance costs are lower because of no corrosion problems (inherent with acid hydrolysis), and lower environmental impact of the whole process [5, 21].

Another process to produce ethanol from biomass is a thermochemical process where the biomass is converted into synthetic gas, or syngas, and is reconstituted into acetic acid through a catalytic conversion. This product is a base for producing the resulting ethanol. This technology is not generally considered to be as mature as the biochemical process mentioned above. A sample process flow for thermochemical conversion of biomass to ethanol is included in Figure 3.
2.3: Production record and data

Most ethanol facilities operate at or above their nameplate capacity. According to a source at the Energy Information Association [6], the grain-based ethanol plants that are in operation today are able to ramp-up to full rate production within a month or two. This is chiefly because the technology and processes used to convert corn into ethanol are well understood, and have been commercialized for many years. This is not the case for ethanol production from biomass, and other cellulosic sources.

Production data for commercial-scale cellulosic ethanol plants is nonexistent because there are no current facilities in the United States that produce more than 1 million gallons per year. Data from pilot or demonstration-scale facilities was not available, mainly due to the proprietary nature of the data. The only data available was in the form of aggregate production data per defense district (PADD), or for the industry as a whole. This type of aggregate data is not useful for the purposes of examining production ramp-up at individual cellulosic ethanol plants, therefore a set of assumptions were made based upon
likely ramp-up profiles. These assumptions and the rationale for use of the modeling are explained in detail in Chapter 3. A graph of grain-based ethanol production in the United States is shown in Figure 4.

Figure 4. Yearly Production Values of Grain-Based Ethanol in the United States (1980-2010)

2.4: Cost estimates for cellulosic ethanol production

There are four primary cost categories associated with production of cellulosic ethanol. These categories are capital costs, operations and maintenance costs, feedstock cost, and other raw materials. Costs associated with other raw materials include costs for catalytic agents, enzymes, acid, and/or other chemicals used in the pretreatment, hydrolysis or fermentation steps in the biochemical ethanol process.
2.4.1 Capital Costs

As pertains to capital costs, the typical facility designed for cellulosic ethanol production—regardless of feedstock type—costs more than five times a comparable capacity starch-based ethanol production plant [4]. Teharipour and Tyner estimated a 100 million gallon cellulosic ethanol facility would cost $400 million. This would equate to roughly $100 million for every 25 million gallon capacity, or stated another way, a capital intensity of $4/gallon of yearly production [16]. Kenkel and Holcomb assumed that for a DOE grant investment of $385 million in 2007 for six cellulosic ethanol plants, a total private equity input of an additional $600 million would be needed to produce the desired total of 140 million gallons per year capacity at these six sites. This would result in a capital intensity of $7/gallon of yearly production [17]. Carriquiry and Du [3] note the price for a biochemical cellulosic ethanol plant of 220 million liter capacity (58.5 million gallons/year) would be $262.4 million including start-up costs and working capital. That value is inflation adjusted to 2008 US dollars from an earlier source [7].

Some recent capital cost figures can be found in the current industry news. Recent quoted figures for two facilities in the Midwest were $250 million for a 25 million gallon facility that began construction in March 2012 in Emmetsburg, Iowa, and $132.4 million loan guarantees ($350 million total investment) for a 23 million gallon facility in Hugoton, Kansas. Note that these are current budgeted costs, and therefore estimates. True construction and startup costs will not be known until the plants are built and begin production. The actual total capital costs for facilities that finish and begin production may never be revealed to the public, particularly if the investors are eager to keep that information proprietary.

2.4.2 Operations and Maintenance Costs

The costs associated with the operations of a cellulosic ethanol plant include costs for the following: maintenance, overhead, water, residue disposal, insurance, taxes, and regulatory compliance.
Solomon and Barnes provide an estimate for these rolled-up costs of $0.094/liter (or $0.356/gallon) [7]. This value is in 2006 dollars. This would equate to roughly $0.12/liter in 2012 dollars if the amount is adjusted using the PPI from 2006 to April 2012. The cost values provided in Solomon and Barnes was referenced from a source written in 1999. That source written by Charles Wyman referenced a table of costs from a 1990 NREL report and case.

Another method of accounting for general overhead costs is documented in Kazi et al [19], where the assumption is that a 60% factor is applied to the salaries/labor costs for general overhead, maintenance, benefits, safety, general engineering, plant security, janitorial services, etc. McAloon et al, [29] assume a fixed cost and waste disposal value for seven different scenarios at $0.24-0.38/gallon. These values are in 2002 dollars. This is consistent with Solomon and Barnes estimate. True operations costs will not be known until several plants are built and have been in operation for several years at nameplate capacity or better.

2.4.3 Feedstock Costs

Costs of feedstock will vary by region and over time. However, some estimated values for many types of forestry residues, municipal solid waste, crop residues, and dedicated energy crops can be found throughout the literature. Table 1 has been recreated from two separate tables in Carriquiry and Du, [3] and contains the source, feedstock type and estimated cost in $ per ton of biomass and $ per liter of ethanol produced for crop and forest residues as well as a few woody energy crops. Table 2 contains the same information but for herbaceous energy crops. These dollar figures, except where noted, are for delivered product to the bio-refinery where ethanol production will occur, thus local transportation costs have been included.
Solomon and Barnes [7] used a figure of $0.182/liter ($0.69/gallon) for feedstock cost. This value was taken from an earlier source computed in 1999 and adjusted to 2006 dollars by accounting for changes to the producer price index for pulp, paper and allied products. This compares favorably to values for several feedstock sources listed in Table 1 and Table 2.

Factors that contribute to different price ranges among sources are the “different perspectives on the sizes of yields, distances to conversion facilities, and storage needs, as well as the margin garnered by the grower as return on investment in producing feedstock versus other uses of land.” [3]
Table 1. Estimated Feedstock Costs for Crop and Forestry Residues [3]

<table>
<thead>
<tr>
<th>Source</th>
<th>Feedstock Type</th>
<th>Estimated Cost ($/ton)</th>
<th>Estimated Cost ($/Lt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallagher et al. (2003)</td>
<td>Corn Stover</td>
<td>17.13-18.21</td>
<td>0.0591-0.063</td>
</tr>
<tr>
<td>Perlack &amp; Terhallow (2003)</td>
<td></td>
<td>43.10-51.60</td>
<td>0.149-0.178</td>
</tr>
<tr>
<td>Petrolia (2008)</td>
<td></td>
<td>57-69</td>
<td>0.188-0.224</td>
</tr>
<tr>
<td>Petrolia (2006)</td>
<td></td>
<td>38-43</td>
<td>0.131-0.148</td>
</tr>
<tr>
<td>Tokgoz et al. (2007)</td>
<td></td>
<td>76.00</td>
<td>0.262</td>
</tr>
<tr>
<td>Frederick et al. (2008)</td>
<td></td>
<td>54.67</td>
<td>0.189</td>
</tr>
<tr>
<td>Gallagher et al. (2003)</td>
<td>Winter wheat, continuous</td>
<td>20.16-28.04</td>
<td>0.070-0.097</td>
</tr>
<tr>
<td>Gallagher et al. (2003)</td>
<td>Winter wheat, fallow</td>
<td>38.18</td>
<td>0.132</td>
</tr>
<tr>
<td>Gallagher et al. (2003)</td>
<td>Spring wheat, continuous</td>
<td>24.17</td>
<td>0.083</td>
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<td>Gallagher et al. (2003)</td>
<td>Sorghum</td>
<td>21.25-23.16</td>
<td>0.079-0.086</td>
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<td>Barley</td>
<td>21.78</td>
<td>0.070</td>
</tr>
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<td>Gallagher et al. (2003)</td>
<td>Oats</td>
<td>23.18</td>
<td>0.089</td>
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<td>Gallagher et al. (2003)</td>
<td>Rice</td>
<td>25.21</td>
<td>0.090</td>
</tr>
<tr>
<td>NREL (1998)</td>
<td>Hardwood primary mill residue</td>
<td>33.9</td>
<td>0.113</td>
</tr>
<tr>
<td>NREL (1998)</td>
<td>Softwood primary mill residue</td>
<td>34.6</td>
<td>0.115</td>
</tr>
<tr>
<td>NREL (1998)</td>
<td>Hardwood secondary mill residue</td>
<td>30.5</td>
<td>0.102</td>
</tr>
<tr>
<td>NREL (1998)</td>
<td>Softwood secondary mill residue</td>
<td>30.4</td>
<td>0.102</td>
</tr>
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<td>Junginger et al. (2005)</td>
<td>Primary forest fuel (residues)</td>
<td>27</td>
<td>0.09</td>
</tr>
<tr>
<td>Frederick et al. (2008)</td>
<td>Yellow poplar</td>
<td>48.1</td>
<td>0.160</td>
</tr>
<tr>
<td>Frederick et al. (2008)</td>
<td>Loblolly Pine</td>
<td>67.0-71.5</td>
<td>0.22-0.24</td>
</tr>
<tr>
<td>Manzone et al. (2009)</td>
<td>Poplar</td>
<td>110-132</td>
<td>0.365-0.438</td>
</tr>
</tbody>
</table>

Note: Costs are adjusted for inflation to 2008 dollars.
Table 2. Estimated Feedstock Costs for dedicated herbaceous energy crops [3]

<table>
<thead>
<tr>
<th>Source</th>
<th>Feedstock Type</th>
<th>Estimated Cost a ($/ton)</th>
<th>Estimated Cost a ($/Lt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epplin et al. (2007)</td>
<td>Switchgrass</td>
<td>50-67</td>
<td>0.167-0.222</td>
</tr>
<tr>
<td>Graham et al. (2000)</td>
<td>Switchgrass</td>
<td>44-71</td>
<td>0.147-0.237</td>
</tr>
<tr>
<td>Pimentel &amp; Patzek (2005)</td>
<td>Switchgrass</td>
<td>29</td>
<td>0.097</td>
</tr>
<tr>
<td>Mapemba et al. (2007)</td>
<td>Grassy Biomass</td>
<td>27-59</td>
<td>0.090-0.197</td>
</tr>
<tr>
<td>Duffy (2007)</td>
<td>Switchgrass</td>
<td>116</td>
<td>0.387</td>
</tr>
<tr>
<td>Babcock et al. (2007)</td>
<td>Switchgrass</td>
<td>92-121</td>
<td>0.307-0.402</td>
</tr>
<tr>
<td>Vadas et al. (2008)</td>
<td>Switchgrass</td>
<td>56-60</td>
<td>0.187-0.200</td>
</tr>
<tr>
<td>Hallam et al. (2001)</td>
<td>Switchgrass</td>
<td>56-67</td>
<td>0.187-0.223</td>
</tr>
<tr>
<td>Perrin et al. (2008)</td>
<td>Switchgrass</td>
<td>46-88b</td>
<td>0.153-0.293b</td>
</tr>
<tr>
<td>Vadas et al. (2008)</td>
<td>Alfalfa</td>
<td>77-90</td>
<td>0.257-0.3</td>
</tr>
<tr>
<td>Hallam et al. (2001)</td>
<td>Alfalfa</td>
<td>78-83</td>
<td>0.26-0.277</td>
</tr>
<tr>
<td>Hallam et al. (2001)</td>
<td>Reed canarygrass</td>
<td>65-98</td>
<td>0.217-0.327</td>
</tr>
</tbody>
</table>

Note: a Costs are adjusted for inflation to 2008 dollars. b Does not include transportation costs to the bio refinery.

2.4.4 Other Raw Material Costs

One of the primary raw materials used to remove lignin from cellulose during the hydrolysis process in a biochemical cellulosic ethanol plant is cellulose enzymes, normally referred to as cellulase. As early as 2004, at least two companies have demonstrated they can produce and provide the enzymes for cellulosic hydrolysis for a cost of $0.026-0.053/liter ($0.10-0.20/gallon). [27] More recent cost data was not available in the industry news or literature.

Other raw materials needed for ethanol production from biomass, in the case of the biochemical conversion process, are lime, sulfuric acid, glucose, and other nutrients. The costs for these are estimated in one source as between $0.02 and $0.03/liter ($0.10-0.20/gallon) [7]. The acid is used primarily in a diluted form in pretreatment of the input biomass. The lime is added prior to the hydrolysis and fermentation
steps, and acts as a neutralizer for the concentrated acid. Microbes and other fermenting organisms constitute the nutrient raw material needed for the conversion process.

2.5: Issues with ethanol production and use

Ethanol is by no means a perfect replacement fuel for gasoline. There are several issues and challenges with the fuel that should be highlighted in any discussion or comparison with gasoline. The primary issue with ethanol as a drop-in, or mix-in, replacement is that its energy density is approximately 67% of gasoline by volume [20]. This means that close to 50% more pure ethanol would be required to replace the energy from one gallon of gasoline. In the most likely dedicated blend of ethanol, E85, the user would experience a reduction in miles per gallon, or kilometers per liter of roughly 27% [22].

A flex-fuel vehicle that can use either gasoline with less than 10% ethanol content, or E85, has been modified from its basic configuration to allow operation at higher compression ratios, and higher octane. Some of these modifications include use of upgraded plastic and rubber parts within the fuel system to make the fuel system resistant to corrosion [23]. This is necessary because ethanol is more abrasive in a fuel system than gasoline, and its combustion produces more oxygen. Another important modification of the FFV is an onboard sensor in its fuel system to monitor the actual amount of ethanol in the fuel. This information is used by the FFV’s fuel system computer to automatically adjust the fuel injection and spark timing to the proper values for the given mixture of fuel. While these modifications aren’t expensive per vehicle ($100 to $200), the driver would want to purchase a FFV from the manufacturer, as aftermarket conversion kits violate the manufacturer’s warranty.

Another major issue with ethanol is it is more difficult to transport than gasoline. Because it mixes with water it cannot be shipped via the United States pipeline system—a common and inexpensive method of transport for gasoline and oil [20]. It would require dedicated shipping by truck or rail to get it
to refinery or to its final destination for sale to the consumer. This may not be a large factor provided the feedstock supply and ethanol plant are in portions of the country near the associated blending refinery and final point-of-sale. However, as can be seen in Figure 5, it would be a large problem for the western states in the US. Large biomass resources exist, as well as biodiversity, in the eastern and Midwestern US, but not in the western states. Some notable exceptions exist in northern California, Oregon and Washington State.

Figure 5. Geographic Distribution of Biomass & Lignocellulosic Sources in the United States [8]
2.6: Biodiesel

An alternative fuel that has not been discussed here in much detail is biodiesel. A good definition for biodiesel is found in Pinto et al, “‘a fuel obtained from mixtures, in different proportions, of fossil diesel and alkyl esters of vegetable oils or animal fats’. Technically speaking, biodiesel is the alkyl ester of fatty acids, made by the trans esterification of oils or fats, from plants or animals, with short chain alcohols such as methanol and ethanol. Glycerin is, consequently, a by-product from biodiesel.’ [25] It can be produced from plant oils, animal fats, waste vegetable oil, or even algae.

This thesis will discuss biodiesel at least briefly since it is an important component in any biofuel portfolio. Biodiesel is a drop-in replacement or supplement for diesel fuel. It has some benefits that ethanol does not. Pure biodiesel (B100) energy density is only 8% lower than diesel derived from crude oil [24]. B100 fuel can also be used in a newer vehicle designed to run on diesel with no, or very little, modifications to the vehicle.

Other common mixtures found in industry and mentioned in the literature are B5 and B20 [25]. These mixtures are better at ensuring combustion during cold weather than higher volume mixtures of biodiesel. Even a small amount of biodiesel mixed with petroleum diesel has benefits in reducing emissions of carbon monoxide, particulate matter and unburned hydrocarbons [26].

Other positive features of biodiesel are that it increases the lubricity of the fuel. Also, it is safer to handle than regular diesel fuel. This is due to the fact that it has a higher flash point and is much less toxic when a spill occurs.
CHAPTER THREE: MODELING METHODOLOGY

To achieve a better understanding of the production levels and costs associated with generation of ethanol from lignocellulosic biomass, this thesis presents a set of mathematical models developed to estimate ramp-up of ethanol production for a cellulosic plant in the early stages of technology. Also, a set of mathematical models are created to estimate the costs per unit of product ($/Liter, or $/Gallon), based on values found in the literature and on a set of assumptions that will be presented later in this chapter. These models will be implemented in MATLAB/Simulink as a continuous system simulation, with values for production levels and costs output over a period of 10 years. An emphasis will be placed on production and costs for the first 5 years of production. The focus on the first five years is based on an assumption that all capital costs incurred through debt or an equity stake by private investors will be retired within five years of plant start-up. According to a source at the EIA, debt from capital expenditures is typically retired within five to ten years of plant start-up [9].

The costs are estimated to be heavily influenced by the capital investment for the actual facility and associated labor costs as the plant comes on-line. Unlike the grain-based ethanol plants which have benefited from decades of technology development and refinement of processes to maximize ethanol yield and reduce costs, the cellulosic ethanol industry is still in its infancy. The learning curve is expected to be steep, and the latest fits and starts within the industry are a definite sign that going from the lab and small pilot or demonstration plants to full-scale commercial facilities has not been a trivial endeavor. A list of all modeling assumptions is provided in Section 3.3.

3.1: Production Model

Initially, an assumption was made that the production profile would most likely follow a logistic function, or “S-shaped,” curve profile. See Figure 6. This was based on the fact that most product
market introductions follow this type of pattern. The shape can also be seen in the graph of corn-based ethanol produced over the years in Figure 4. While this makes logical sense for an entire product line or an aggregate production supply as demonstrated in Figure 4, it may not be an accurate representation of growth in output of product from a single plant. Typically if demand is high, the plant will make best efforts to maximize production as quickly as possible. NOTE: If the cost is favorable in relation to petroleum, then the demand will be high.

Figure 6. Logistic Function/Growth Curve (or S-Shaped Curve)

Since production at an individual plant will most likely be increased as quickly as possible, it is assumed for the purposes of this thesis that the growth in production resembles a negative exponential curve. The growth model follows the form of Equation 1,
In Equation 1, the term $A$ is used to control an increase in the rate of change of production, making it a rate coefficient. Larger values of $A$ result in achieving 90, 95, or higher percentage of nameplate capacity production more quickly. Figure 7 shows the growth profile for 4 different values of $A$. This is useful, as the model builder and the simulation user can control how quickly the plant reaches peak capacity. An analysis of the rate of production growth’s effect on labor and capital costs per unit of product can be completed.

$$y(t) = 1 - e^{-At}$$ (1)

![Negative Exponential Growth Profiles](image)

Figure 7. Production Ramp-Up Profiles (Function of Time and Rate Coefficient, $A$)
As the units for time are in months, the value of \( A \) will be divided by 12. Also, the nameplate capacity will be divided by 12 to yield the maximum monthly production value. This maximum monthly production value will be multiplied by the result of \( y(t) \) at each time step. This will give us the value for production for that month. For example, if the nameplate capacity of the cellulosic ethanol production facility is 25 million gallons per year, then the maximum monthly production value would be 2.1 million gallons. At some point in time, as the value of \( y(t) \) approaches 1, then the plant model will be producing close to its maximum value.

3.2: Cost Model

The cost models generally found in the literature are intended to calculate a net present value, or NPV, of the end product. Kazi et al, compute a product value, or PV, which is “defined as (the) value of the product needed for a net present value of zero with a 10% internal rate of return.” [19] Another source uses a discounted cash flow analysis that iterates on the selling cost of ethanol until net present value of the entire project reaches zero [30]. MaAloon et al, use a similar approach with the assumption that the values computed are for an \( n^{th} \) value second generation plant with proven, or mature, technologies [29].

Most of the aforementioned sources and others assume a cost of production based on an \( n^{th} \) plant, or \( n^{th} \) year for a single plant, in the future that is operating at optimum efficiency, with mature commercial scale technology. “One issue with cellulosic economic literature is that the literature reports costs/technologies for the \( n^{th} \) year for cellulosic platforms. For this reason there is a disconnect between what the current technology is and what the literature suggests the technology can be.” [11]

This thesis assumes that the cost per unit of product will vary over the life of the plant, and will initially be high. This is due to the high capital cost incurred and the need to repay the debt and investor equity stake in a timely manner (less than 5 years). The cost of labor and capital per liter will be
dependent on the actual production of the facility. As the amount of ethanol approaches the nameplate capacity of the plant, the labor costs and capital costs per unit will decrease and flatten out. Thus, it is very important to maximize production as quickly as possible to have a marketable and economically competitive product.

Solomon, Barnes, and Halvorsen give an equation that accounts for all of the known costs of cellulosic ethanol production. Equation 2 is the cost formulation.

\[
C_A = \frac{C_B}{95} + C_K + C_L + C_E + C_M + C_O - P_P
\]

\(C_A\) is the total cost per liter of ethanol produced from biomass. \(C_B\) is the feedstock in terms of $ per dry ton. The value of 95 in the denominator is based on an assumption of 95 gallons per dry ton conversion factor [7]. \(C_K\) is the cost of capital investment, \(C_L\) is the cost of labor, \(C_E\) the cost of energy to power the plant, and \(C_M\) represents the cost of raw materials. \(C_O\) is the cost of operations and maintenance not tied directly to the labor costs (such as overhead, water, residue disposal, insurance and property taxes). \(P_P\) is the credit received for power supplied back to the electrical grid from the processing of lignin [7]. The cost calculation performed by Solomon, et al was a fixed cost in dollars per unit of product (liter or gallon) for each cost component listed in Equation 2, with the exception of \(C_B\) and \(P_P\) which are converted from dollar per dry ton and cents per kWh respectively. This equation does not account for the Cellulosic Biofuel Producers Tax Credit, (CBPTC) which is currently $1.01 per gallon ($0.27 per liter) of cellulosic biofuel produced. This credit was mandated in the Food, Conservation and Energy Act of 2008 [21].

Another source [10] from the National Renewable Energy Laboratory separated the cost into five different components: feedstock; labor, supplies, and overhead; co-products; variable operating costs;
and depreciation of capital. This estimate did not account for the CBPTC, nor did it account for the producer’s credit for power supplied to the electrical grid.

Rismiller and Tyner [11] compute total cost to produce cellulosic ethanol for both the biochemical conversion process and the thermochemical conversion process. The categories of cost for their analysis are “feedstuffs”, capital, energy usage, enzymes, variable operating costs, and labor, supplies, and overhead.

For the purposes of this thesis and its associated cost model, an assumption is made that the producer’s credit for energy generation provided back to the grid is equivalent to the cost of energy for the ethanol plant. Also, costs of transportation are not included, or they have been included in the delivery portion of feedstock costs. The CBPTC credit is applied for at least the first five years of production to assist in offsetting the capital cost. Lastly, the feedstock cost is not modeled as a dollar cost per ton of biomass, but a dollar cost per liter. Most of the literature sources provide both values with some assumed conversion yield factors. The cost model provides a method for accounting for increases in yield by providing a decrease in the cost per liter over time. This rate of decrease can be modified by the user of the simulation model.

So the fixed cost model is a form of Equation 2, but more accurately reflected in Equation 3.

\[ C_A = C_K + C_L + C_B + C_M + C_O - CBPTC_{TC} \]  \hspace{1cm} (3)

In the continuous system cost model form shown in Equation 4, both \( C_K \)--cost of capital—and \( C_L \)--cost of labor—are functions of production value as well as time. The other terms are also functions of time.

\[ C(t)_A = \frac{C(t)_K}{P(t)} + \frac{C(t)_L}{P(t)} + C(t)_B + C(t)_M + C(t)_O - CBPTC(t)_{TC} \]  \hspace{1cm} (4)
3.3: Summary of Modeling Assumptions

A summary of each modeling assumption used for the purposes of this thesis and modeling methodology are listed below:

- The production ramp-up profile is modeled in this thesis as a negative exponential growth curve having the form of Equation 1. The rate of change in production value is simply the derivative of Equation 1, which is then passed through an integrator in the Simulink model.

- The costs of transportation are not included in this model.

- Costs of energy used and the producer’s credit for energy generation provided back to the grid are assumed equivalent and thus cancel each other. This is a simplifying assumption.

- All costs are in units of US dollars per liter, except for the costs of labor and capital which are in units of US dollars.

- It is assumed that the unit cost of capital and labor are a function of plant production.

- The CBPTC is $1.01 per gallon, or $0.27 per liter, and is assumed constant for the first five years.
4.1: Simulation Model

The MATLAB simulation consists of a MATLAB script file called main_exec.m that initializes parameters, computes the monthly debt service payment based upon the loan parameters, and then runs the Simulink model that computes values for monthly production as a function of time. The Simulink model also computes cost values as a function of time, and in the case of labor costs and capital expenditures as a function of monthly production value. The Simulink block diagram of the production and cost model is shown in Figure 8.

The model is run for a total of 120 units of time, or 120 months in this case. This time frame was chosen as the production should be at full capacity, and the remaining components of cost should be well understood and fairly predictable by this point. The variable-step solver is set to 0.10 month maximum step size. Outputs are in liters for production value, and in $/Liter for the total cost, and individual cost components.

The main_exec.m script then generates the desired plots for data visualization. A sample is shown in Figure 9.
Figure 8. Simulink Production and Cost Model
4.2: Simulation Assumptions and Conditions

The simulation model used is customizable. Parameters can be changed quickly by the user and the model rerun to examine the effect of changes in parameters, rates of decrease or increase, and other production or cost assumptions. For the purposes of this thesis, the following assumptions are made:

- The nameplate capacity of the plant is 25 million gallons (94.6 million liters) of ethanol per year.
- The capital cost is paid for and retired over the first five years (60 months) of operations.
- The nominal interest rate for the debt is 8%.
- The capital cost is paid for as 100% debt. (i.e. no debt/equity ratio)
- The monthly debt service payment follows a standard amortization model.
- The rate of change for the feedstock cost, maintenance and operations cost, and materials all decrease linearly at a rate of -$0.006 per year. This assumption is based on the belief that process improvements, yield increases (liters of product extracted per dry ton of biomass), and competition from suppliers of raw materials all result in lower costs for each category as time goes by.
- Lower limits are set for the feedstock cost of $0.06 per liter, $0.10 per liter for operations and maintenance, and raw materials cost. These are considered to be very low values that would be almost impossible to realize. The user can of course change those lower limits if they so choose.
- Labor cost is computed as a factor applied to the nameplate capacity, divided by 12 to achieve a monthly labor cost, and then divided by that month’s production to derive the labor cost per unit of product.
- Switch gates are used to change the monthly capital cost payment to zero, and CBPTC to a reduced value in two of the case studies at $t = 60$ months.

Table 3 contains a list of the parameters that will be used in evaluating three case studies, or scenarios: a high cost, medium cost, and low cost case. Each case study will draw appropriate values from the literature for feedstock, capital intensity, labor, raw materials, and operations and maintenance costs. Costs will be adjusted where necessary to account for changes in CPI or PPI since the date of published values. Dollar values are computed in 2012 dollars and are not adjusted for inflation over time.

The intent of analyzing these three possible cases is to capture a wide range of possible cost and production scenarios. By entering several unfavorable parameters—from a cost perspective—the values output by the simulation should provide a good approximation of the highest cost per unit of product. The alternative cases are made to generate values for more realistic and expected values of production and cost, and then an improbable situation where all the most favorable parameters are realized.

**Table 3. Input Parameter Values for Simulation Case Studies**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Cost</th>
<th>Medium Cost</th>
<th>High Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Intensity ($/gal per year capacity)</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Interest Rate</td>
<td>6%</td>
<td>8%</td>
<td>10%</td>
</tr>
<tr>
<td>Coef_a</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Initial Cost – Feedstock</td>
<td>$0.10/Lt</td>
<td>$0.20/Lt</td>
<td>$0.40/Lt</td>
</tr>
<tr>
<td>Initial Cost – Raw Materials</td>
<td>$0.10/Lt</td>
<td>$0.12/Lt</td>
<td>$0.18/Lt</td>
</tr>
<tr>
<td>Labor Factor (multiply by Nameplate capacity)</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Initial Cost – Operations &amp; Maintenance</td>
<td>$0.10/Lt</td>
<td>$0.20/Lt</td>
<td>$0.30/Lt</td>
</tr>
<tr>
<td>CBPTC Credit Reduction at 5 years</td>
<td>0%</td>
<td>50%</td>
<td>100%</td>
</tr>
</tbody>
</table>
4.3: Simulation Output

With the values for the high cost scenario in the model, the results—as plotted in Figure 9—show a large influence of capital cost and labor cost early in production. Total cost, as well as cost components for labor and capital, is plotted for each scenario. After 12 months, the total cost of a liter of ethanol is just under $2 per liter (~$7.50 per gallon). Production has not reached 90% of capacity yet. In fact, in this simulation case the production is at 62.2% of capacity 12 months after startup. By the end of the second year, the total cost per unit is $1.58 per liter (~$6.00 per gallon), and the plant is operating at approximately 86% of capacity. By Year 5, the cost is $1.38 per liter ($5.22 per gallon), and the plant is producing at 99.3% of nameplate capacity.

One month after the fifth year of plant operation, the capital cost has been retired. The simulation results show a cost at this point of $0.97 per liter (or $3.67 per gallon). The reason that the reduction in cost is not as severe as might be expected is that in this high cost scenario it has been assumed that the CBPTC credit is reduced to zero after Year 5.
As with the high cost scenario, the medium cost case—Figure 10—still shows a large influence of capital cost and labor cost early in production. After 12 months, the total cost of a liter of ethanol is just under $1 per liter (~$3.80 per gallon). Production has not reached 90% of capacity yet. In this simulation case, the production is at 85.6% of capacity 12 months after startup. By the end of the second year, the total cost per unit is $0.88 per liter ($3.33 per gallon), and the plant is operating at approximately 98% of capacity. By Year 5, the cost is $0.81 per liter ($3.07 per gallon), and the plant is producing at full nameplate capacity.
One month after the fifth year of plant operation, the capital cost has been retired. The simulation results show a cost at this point of $0.43 per liter (or $1.63 per gallon). The reduction here is more pronounced than in the high cost scenario, as the CBPTC credit has been kept but at a lower value of $0.50 per gallon.

Figure 10 Medium Cost Scenario
The low cost case—Figure 11—shows a large influence of capital cost and labor cost early in production, although these effects are less pronounced in this case and rapidly diminish within the first few months. After 12 months, the total cost of a liter of ethanol is $0.51 per liter (or $1.93 per gallon). Production has reached over 90% of capacity. The production is at 94.3% of capacity 12 months after startup. By the end of the second year, the total cost per unit is $0.48 per liter ($1.82 per gallon), and the plant is operating at approximately 99.7% of capacity. By Year 5, the cost is $0.45 per liter ($1.70 per gallon), and the plant is producing at full nameplate capacity.

Figure 11  Low Cost Scenario
One month after the fifth year of plant operation, the capital cost has been retired. The simulation results show a cost at this point of $0.08 per liter (or $0.30 per gallon). The reduction here is very pronounced as the CBPTC credit has been kept at the current rate of $1.01.

The benefit of this model is that the user can adjust any parameter and see its effect on the production output and the different cost components. As actual commercial scale plants come on-line in the near future, the available cost data and production statistics from these actual facilities—if available—could be entered into the model for further verification or validation purposes. Also, the production profile could be modified to be more representative of an actual ramp-up profile.

4.4: Discussion of Simulation Results

Using the modeling methodology discussed in this thesis, the output for the three case studies run in the simulation model demonstrate the effect on overall cost of the product per unit of capital costs and, to a lesser extent, labor costs. A range in cost of $0.51—2.00 per liter (or $1.93—7.50 per gallon) is computed after the first year of operation with all of the corresponding assumptions mentioned above, and in Table 3. This is reduced further to a range in cost of $0.48—1.58 per liter ($1.82—6.00 per gallon) at the end of Year 2 of operation. By the end of the fifth year, the production models are all producing at nameplate capacity, and the resulting cost range is $0.45—1.38 per liter ($1.70—5.22 per gallon). These results are based on the modeling assumptions stated in Section 3.3, and the simulation assumptions stated in Section 4.2.

Costs are further reduced as the learning curve is applied, and process improvements and efficiencies are realized. It is assumed a small amount of increased ethanol yield per ton of biomass/feedstock results in a slightly decreasing feedstock cost per liter. In all cases presented here, the
rate of decrease in feedstock cost was -$0.006 per liter per year. This value can be easily changed by the user of the simulation model.

This range of results for the case studies run compare favorably with the estimates provided in the literature which range from a very low estimate of $0.31/liter ($1.18/gallon) all the way up to $1.87/liter ($7.08/gallon, or $10.71/gallon of gasoline equivalent) [19]. Carriquiry et al, collected cost data from several sources documenting a range of cost from $0.38 to 0.69/liter (or $1.44 to 2.61/gallon) [3]. These values are in 2008 dollars and are not adjusted to be gasoline equivalent (GGE). Wright and Brown arrived at an overall lower value for ethanol production costs of $1.78/gallon GGE [4]. This converts to $0.31/liter of ethanol. In this case, the authors assumed the capital cost was 100% debt financed, at an 8% rate of interest, and a 20-year loan term. This could be a major driver for the much lower overall cost value.

While the technology used to convert the cellulosic materials to ethanol may be different from plant to plant, the production and cost model can be easily modified to account for the higher capital costs or labor costs based on the technology used. A higher capital intensity factor can be chosen for riskier technologies. If a higher risk technology has the benefits of reduction in waste products, reduction in materials needed for production (such as enzymes, lime, acid, etc.), or a reduction in operations or maintenance costs; then those factors and starting values can be adjusted in the model.

Based on the assumptions stated in Section 3.3 and 4.2 using this modeling methodology, the low and medium cost case studies appear to yield results competitive, at the time of this writing, with current gasoline prices, even when accounting for cost conversion to units of GGE. It is also readily apparent that without the CBPTC credit in force, only the low cost case study results are currently cost competitive with gasoline. However, these results do not factor in the increased price due to the costs of any state, local, or federal taxes, refining costs, delivery, marketing, and profit margins.
There may be ways to structure the retirement of the capital cost to enable the ethanol to be made more cheaply, such as having a longer loan payback period (7-10 years), or a way to have reduced payments until the plant is operating at full capacity. Lenders and investors may be reluctant to allow such an arrangement until these conversion technologies are demonstrated on a commercial scale.
CHAPTER FIVE: CONCLUSIONS

5.1: Conclusions

The problem of finding renewable sources of fuel for the transportation sector is an incredible challenge. No one solution can completely replace the petroleum consumed by the United States. However, efforts have been made for decades to increase the production of alternative fuels as a mix-in, a drop-in replacement, or as a supplement to gasoline and diesel fuel. Ethanol made from corn has the largest presence, the most mature conversion technologies, and the strongest political backing and lobbying of any alternative transportation fuel source to date. However, as mentioned previously, this is somewhat problematic in that corn is a major food source for humans and livestock in this country.

Production of ethanol from biomass, or lignocellulosic material, shows great promise. This technology could become the major solution for a replacement, or supplemental fuel source in various mixtures, with gasoline. Although it is not an ideal fuel in terms of energy density, and not having very similar chemical properties to gasoline, ethanol feedstock sources are incredibly abundant or could be grown, particularly in the Eastern and Midwestern United States. The challenge has been—and will be for the foreseeable future—the ability to convert any of the various and abundant sources of biomass into ethanol in a way that is cost competitive with gasoline, diesel or any other alternative “drop-in” fuel.

It is necessary for prospective conversion technologies to “prove” themselves—on a commercial scale. Government officials in charge of loan guarantees and grants, lenders, and investors will demand this occur before vast amounts of capital investment will flow into production facilities and other infrastructure to produce hundreds of millions and then billions of gallons of ethanol. An ability to keep labor, capital, operations and maintenance, and raw materials costs reasonable and trending lower is important to build confidence in any cost modeling or business case that might be presented.
The mathematical model presented here for production of ethanol from cellulosic sources is notional. But rationale has been provided for the type of profile used, and believable results have been demonstrated. The cost model is a modification of existing models, but with different assumptions and with an emphasis on the labor and capital costs being heavily dependent on production values as well as on time of operation.

Simulation results for assumed worst-case, nominal, and best case scenarios were presented and seem to fall within the range of the projected values from the various literature sources cited. Until a commercial-scale facility is built and begins producing cellulosic ethanol, it will remain difficult to predict the actual production profile. The actual costs to produce the ethanol, provide it to the refineries for blending, and then into the marketplace for purchase by the consumer, will remain just an estimate based on the assumptions given and the constraints of the modeling.

5.2: Contributions

The simulation model created here can be used as a planning tool, or to perform simplified cost analysis for different assumptions and parameter variation. This thesis highlights many of the difficulties of producing ethanol from lignocellulosic sources, including the fact that no definite standard exists for a conversion process, and discusses methods or strategies for reducing costs in order to make the conversion of ethanol from cellulosic sources more economically viable. This thesis also provides a useful simulation model that can analyze the effects of many input parameters over any timeframe desired.

Provisions exist within the simulation model to evaluate the effects over time of increases or decreases in feedstock, operations and maintenance or raw materials costs. The production profile can
also be modified by the user to support analysis of different ramp-up profiles, rates of production increase, and their corresponding effects on cost.

5.3: Future Work

Many opportunities exist to evaluate and improve the present simulation model used here. The model could be made more accurate by use of a capital cost equation which accounts for the payback provisions for a standard debt to equity ratio. For example, the terms are likely different for return on equity and the monthly debt service due to the lender. Those terms could be modeled and computed separately in the simulation.

There may be benefit to modeling the production profile accounting for randomness between plants or for different production processes. A set of different ramp-up profiles could be included that the user can easily select from. This would enable quick analysis of different profile assumptions without having the user do the mathematical modeling themselves.

It may be desirable to perform Monte Carlo simulation and analysis on the model to evaluate sensitivity to parameter variation. To do this, it would be necessary to make additional assumptions about the probability distribution for each parameter. Values for standard deviation and variance would have to be assumed as no current commercial-scale data exist for verification purposes. Still, these are exercises that may yield further confidence in the estimates provided by the model.

The cost components could be broken down further into items like insurance, taxes, legal fees, licensing fees, and profit margins. It would be necessary to develop good relationships and partnerships with pioneers in the industry who would be willing to assist the model builder in providing accurate estimates for these costs. In the near future, a willingness to provide actual data from operational plants
would be extremely valuable in adjusting the model inputs and calculations, and for further verification activities.
APPENDIX: MATLAB SCRIPT
The following is the MATLAB script used as the main executable for the production and cost simulation model used for this thesis.

```matlab
% main_exec.m

% Initialize default parameters for Production and Cost Model
NmCap = 25*10^6;   % Nameplate capacity of ethanol plant
CapInt = 6.0;      % Capital Intensity Factor $/gal yr production
IntRate = 6.0;     % Annual interest rate on debt
%ProfRate = 12.0;  % Profit margin (based on investor equity
                  % expectation (currently not used in model).

n = 60.0;      % 5 year payoff (60 month loan)
Princ = NmCap*CapInt; % Principal of capital cost/loan
%UltCap = 1.2; % Factor applied to nameplate capacity
              % represents percentage above max nameplate capacity
              % expected. (Currently not used)

ic_oandm = 0.10; % Initial cost per liter of Operations and Maintenance costs
ic_feed = 0.10;  % Initial cost per liter of feedstock
ic_raw = 0.10;   % Initial cost per liter of raw materials
Lab_fact = 0.10;  % Labor cost factor

coef_a = 3;    % Rate of production increase
tc_fin = 1.01; % VEETC credit after 5 years

% Conversion Factors
LtoG = 3.7854;
GtoL = 1/3.7854;
PercInt = IntRate/1200;

A = Princ*(((PercInt*((1+PercInt)^n)))/(((1+PercInt)^n)-1));

% Model is run.
sim('CostModel');

% Plot results.
subplot(2,1,1), plot (tout,Prod);
```
title('Monthly Production');
axis ([0 80 0 10000000]);
xlabel('Time(months)');
ylabel('Liters');
subplot(2,1,2), plot (tout,C_tot,tout,C_cap,tout,C_lab);
title('Cost versus Time');
axis([0 80 0 4]);
xlabel('Time(months)');
ylabel('Cost($/Lt)');
legend('Total','Capital','Labor')

% Print to a *.tif file for import to Word or Powerpoint
print ('-dtiff','figure1')

% End of script
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