ENGINEERING ECONOMIC ANALYSIS OF THE QUICK-GERM / QUICK-FIBER MODIFIED DRY GRIND ETHANOL FRACTIONATION PROCESS

BY

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THESIS

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ABSTRACT

It has been widely debated whether producing ethanol from corn is sustainable in the long term. Environmentally, the major concern is that producing ethanol from corn involves intensive water and energy consumption. Economically, recent fluctuations in petroleum, ethanol, and corn prices have driven several large producers of ethanol into bankruptcy. The ethanol industry is vulnerable to periods of economic weakness because its product value varies with oil prices but its raw material (corn) varies with food prices.

To improve the economic sustainability of corn-to-ethanol production, several modified dry grind processes had been developed at the lab scale. The Quick-germ / Quick-fiber (QQ) process is one of them. However, there has been no analysis of the QQ process that provides detailed information related to the energy, water, and economic performance at a commercial scale. To determine the both environmental and economic performance, a process simulation model was developed on the SuperPro Designer® platform to simulate the QQ process, and compared to the conventional dry grind model.

Results indicate that germ and fiber recovery as done in the QQ process improves the process capacity of a conventional dry grind ethanol facility by approximately 24%. Because of germ and fiber recovery at the front end, the ethanol concentration has been increased to 15% (w/w) as compared to 10.9 (w/w) in the conventional dry grind process. The QQ process reduces the energy and water consumption by 32% and 17.8%, respectively.

The QQ process produces more value-added coproducts, including corn germ, corn fiber, and a modified distillers dried grains with solubles (DDGS), but has a lower ethanol yield rate due to some starch losses to the recovered germ and fiber fractions at the front end.

A detailed cost and benefit analysis of the QQ process, based on the market prices in April 2009, shows that despite its higher capital investment costs, the QQ process reduces the payback period to 6.5 years, compared to 9.2 years for the conventional dry grind process. Increased ethanol production, more value-added coproducts, as well as significant reduced utility costs are three major contributors to improve the economic performance of the QQ process. This work lays the foundation for the similar studies on the sustainability performance for other modified dry grind ethanol processes.

To my family

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TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

Renewable energy offers an opportunity to put our civilization on more sustainable ground, and it also offers countries around the world an opportunity to achieve energy independence and can spur economic development. Biofuels are one of many renewable energy technologies. Although biofuels collectively offer many promising alternatives, ethanol constitutes 99% of all biofuels in the United States (Farrell et al., 2006). The production of ethanol has increased rapidly from 227 million liters (60 million gallons) in the mid 1970s to 34 billion liters (9 billion gallons) in 2008 (RFA, 2009). Currently, corn is the primary feedstock source providing ethanol in the U.S., and the recent ethanol plant expansions in the industry are mainly based on the dry grind process.

It has been widely debated whether producing ethanol from corn is sustainable in the long term. Environmentally, the major concern is that producing ethanol from corn involves intensive water and energy consumption. Economically, recent fluctuations in petroleum, ethanol, and corn prices have driven several large producers of ethanol into bankruptcy. On the food supply issues, significant increase of ethanol production increases the demand of corn proportionally, driving the corn price to reach historically high levels. The increased amount of corn used for biofuel production may reduce the supply for food and animal feed production and decrease corn exports to the developing world. The ethanol industry is vulnerable to periods of economic weakness because its product value varies with oil prices but its raw material varies with food prices. When corn prices are high and ethanol prices are low, the dry grind processors lose money rapidly. Wet milling is a more stable method of ethanol production because of its coproduct values. When corn prices are high, coproduct value increases to offset the lower ethanol prices. However, when ethanol prices are strong, the dry grind processors do not have the capital requirement of wet milling and the coproduct value is not important to economic performance. To stabilize ethanol production, dry grind ethanol processors need to develop their coproducts in order to get through the times when ethanol prices are low and corn prices are high.

Despite all these challenges, 136 billion liters (36 billion gallons) of biofuels are projected to be produced in the US by 2022 (EPA, 2009). Aiming to achieve this ambitious goal, our long-term research objective is to develop biofuels production techniques that provide sustainable alternative energy sources that contribute to energy independence and spurring our rural economic development, without harming the supply for human food and animal feeds.

Corn-based ethanol remains the most viable biofuel available on the market today, and it will continue to be an important renewable fuel source in the near future. EPA proposed that corn-based ethanol is projected to produce 57 billion liters (15 billion gallons) by 2022. It seems imperative for the industry to find a better approach to making the corn-to-ethanol process sustainable, in order to facilitate migration to other bioenergy feedstocks in the future. There is a need to evaluate the sustainability of different corn-to-ethanol process technologies in order to improve the economic viability as well as reduce the environmental impacts of the biofuels industry.

There are three corn-processing techniques commercially in use today: dry grind, dry milling, and wet milling. Of these three techniques, dry grind and wet milling are processes used for fuel ethanol production from corn (Singh and Eckhoff, 1997), while the dry milling process is not used for ethanol production. Dry milling is primarily a physical separation process of corn components to produce the products including but not limited to corn grits, corn meals, and corn flours (Singh et al., 2001).

The current ethanol plant expansion in the industry is mainly based on the dry grind process. The conventional dry grind process is designed to ferment as much of the corn kernel as possible, to produce ethanol, distillers dried grains with solubles (DDGS) and carbon dioxide. Given such a relatively simple process, with few options, dry grind ethanol plants is vulnerable to market fluctuations. Due to its high fiber content, DDGS, the only marketable coproduct from the dry grind process, can be only sold for ruminant animal diets. Expansion of the dry grind ethanol production will increase the supply of DDGS proportionately, but the current low market value of DDGS and its limited utilization will result in even lower prices.

In response to this need, several modified dry grind processes have been developed to improve the profitability of ethanol production, and significant improvements have been observed on the processing efficiency and the nutritional characteristics of coproducts at the laboratory scale (Singh et al., 2005). Quick-germ / Quick-fiber (QQ) process (Singh and Eckhoff, 1996; Singh et al., 1999) is one of these modified dry grind processes, which uses part of the wet milling process (the germ and fiber recovery system) with the dry grind process. This process has three key advantages: 1) Recovered fiber and germ can be further processed to generate value-added coproducts such as germ oil, corn fiber oil and corn fiber gum. 2) Removal of germ and fiber can increase the protein content of the DDGS, making this coproduct suitable as a feed for non-ruminant animals such as swine and poultry. 3) Separating the nonfermentable fractions before fermentation will improve the process efficiency by 14% (Singh et al., 1999, Singh et al., 2005). Recently, Li et al. (2010) and Rodriguez et al. (2010) developed a detailed engineering economic spreadsheet model that showed the QQ process improves the economic viability of the dry grind process at the commercial scale.

Although economically viable, there has been no analysis that details the energy and water consumption of the QQ process and compares the process sustainability to the dry grind process. Therefore, the objective of the present study was to identify and compare the energy consumption, water usage, and economic performance of the QQ process and the conventional dry grind process. The USDA developed a simulation model for an ethanol facility using conventional dry grind technology, and the results proved that process simulation modeling is an effective approach to predict the actual industrial scale operating performance (Kwiatkowski et al., 2006). Thus, the current rationale is that simulation modeling would be an effective approach to further consider the QQ process. It is expected that at the completion of this project, by comparing to the energy and water demands, as well as the economic performance of the conventional dry grind process, the QQ simulation model will provide decision support for the adopting the QQ process technology at the industrial scale.

CHAPTER 2: RESEARCH OBJECTIVES

The objective of this research is to provide decision support information relating to the economic and environmental sustainability performance of the QQ and the conventional dry grind ethanol processes. To achieve this research objective, the following specific goals are proposed:

1. Develop a simulation model on the SuperPro Designer® platform to simulate an ethanol facility using the QQ process technology and compare it with the USDA's conventional dry grind process model.
2. Quantify and compare the energy and water demands of the QQ and the conventional dry grind processes.
3. Identify and assess the quantity and quality of products of the QQ and the conventional dry grind processes.
4. Evaluate the economic performance of the QQ and the conventional dry grind processes in terms of the differences on the capital investment costs, operating costs, and revenues.

CHAPTER 3: LITERATURE REVIEW

3.1 DIFFERENT CORN-TO-ETHANOL PROCESS TECHNOLOGIES

In the corn based ethanol industry, dry grind and wet milling are the two major processing technologies. The major difference between these two technologies is whether corn is steeped at the beginning and is further separated into different fractions before fermentation.

The conventional dry grind ethanol process is designed to ferment as much of the corn kernel as possible. Without steeping and separation system, the dry grind ethanol process demands less capital investment and generates higher ethanol yield than wet milling process. Because of this, most recent ethanol production expansions are based on the dry grind process. In this process, the whole corn kernel is first hammer-milled to achieve size reduction, and then goes through cooking, liquefaction, saccharification, fermentation and distillation. The mash in the fermentation tank mainly consists of starch, protein, germ, and fiber fractions. Among these fractions, starch is the only fermentable material. The other three fractions dilute the fermentable substrates and decrease the ethanol productivity of the plant as a result. Apart from ethanol, CO_2 and DDGS are the products from the conventional dry grind process, although DDGS is the only marketable coproduct. The primary market is as a feed for ruminant animals, because of its high fiber content. Due to the low value of DDGS, the conventional dry grind process is highly dependent on ethanol sales. Several economic failures of this process have occurred in the recent years due to the fluctuation of corn and ethanol prices. Some large ethanol producers even filed for bankruptcy in 2008 due to the significant fluctuation of corn prices (Wall Street Journal, 2009).

Wet milling is a complex process that can be divided into five sections: steeping, germ recovery, fiber recovery, protein recovery, and starch washing and processing. Each of these sections is unique but all sections are interconnected with the flow of process water. Steeping is the heart of the wet milling process as it softens the corn kernel to facilitate the following fractionation works. Ethanol, gluten meal, gluten feed, and crude corn oil are major products from wet milling ethanol process.

In order to improve the sustainability of corn based ethanol production, several modified dry grind processes have been developed at the lab scale in the last decade (Johnson and Singh, 2004; Singh and Eckhoff, 1996; Singh et al., 1999; Wahjudi et al., 2000). Most of those works incorporated prefractionation technology to separate nonfermentable materials at the front end, improving the fermentation operation efficiency. In addition, these recovered materials can be processed to produce more value-added coproducts.

Singh and Eckhoff (1996) proposed changes to the dry grind ethanol process by recovering the germ before grinding the remaining material, which is called the “Quick Germ” process. By using a soak time of 12 hr and soak temperature of 59 ℃, the germ can be recovered at levels comparable to those derived from the wet milling process (Singh and Eckhoff, 1996). Singh and Eckhoff (1997) reported that the DDGS produced in the Quick Germ process would be lower in fat and protein content.

The Quick Germ process has the potential to increase the coproduct credits, but the fermentability of the remaining corn slurry after germ recovery had not been tested. For this purpose, Taylor et al. (2001) conducted a research to measure the fermentation rate and yield of the Quick Germ process. The results showed that the concentration of suspended solids decreases significantly in the fermentation tank, which would reduce the operating costs.

Singh et al. (1999) proposed they have been able to recover corn coarse fiber with a process similar to the germ recovery. This process has a potential to produce more coproducts such as corn fiber gum (CFG) and corn fiber oil. The results showed that CFG yields in the quick fiber samples were comparable to that from the wet-milled coarse fiber samples.

In 1999, a new modified process, called Quick-germ / Quick-fiber (QQ), was further developed (Singh et al., 1999; Wahjudi et al., 2000). The QQ process allows the removal of germ and pericarp fiber as coproducts at the beginning of the dry grind corn process. This process has three key advantages: 1) Recovered fiber and germ can be further processed to generate valued coproducts such as germ oil, corn fiber oil and corn fiber gum. 2) Removal of germ and fiber can increase the protein content of the DDGS, making this coproduct suitable as a feed for non-ruminant animals such as swine and poultry. 3) Separating the nonfermentable fractions before fermentation will improve the process efficiency by 14% (Singh et al., 1999, Singh et al., 2005).

Another process modification called enzymatic milling (E-Mill) has been recently developed (Johnson and Singh, 2004). In addition to recovering germ and pericarp fiber, E-Mill further allows recovery of endosperm fiber as a valuable coproduct. Singh et al. (2005) reported that higher fermentation rate and higher ethanol concentration were obtained with the E-Mill process compared to the conventional dry grind process. Moreover, DDGS that is recovered from the E-Mill process could be used as a non-ruminant feed.

The results of these laboratory investigations showed that these modified dry grind ethanol processes have several advantages: 1) recovery of more value-added coproducts, 2) an increase of final ethanol concentration, and 3) an improvement of the nutritional characteristics of DDGS. However, little work has been conducted on the sustainability analysis of those modified dry grind processes at the industrial scale. Because of the added separation system, those modified dry grind processes might demand higher capital investment costs and possibly increase the water and energy demands. A comprehensive understanding of both economic and environmental performance is preferred to consider the sustainability performance of these novel technologies.

3.2 SCALE UP ANALYSIS

To develop a sustainable biofuel production technology, it is important to understand not only the product quality but also its energy and water demands to identify whether it is environmentally friendly as well as economically viable. Based on the previous laboratory research results, our hypothesis is that modified dry grind ethanol processes will have inherent benefits on both environmental and economic aspects at the industrial scale. For the scale up analysis, several models have been developed to analyze the cost and benefits of the conventional dry grind ethanol process, and the results demonstrated that modeling analysis is an effective tool to evaluate the actual processing performance (Dale and Tyner, 2006; Kwiatkowski et al., 2006; Li et al., 2010; Rodriguez et al., 2010; Tiffany and Eidman, 2003).

To evaluate a modeling performance for a corn-to-ethanol process, it is critical to understand its operating performance. Economically, the ethanol and coproducts yield rate and coproducts compositions are the most important factors for a prospective ethanol investor. Environmentally, energy and water demands from the ethanol production process are the critical pieces of information, where there are significant concerns aroused considering whether it is sustainable to produce fuel via processing corn. In addition, easy accessibility by the public would be another important factor of the modeling analysis. Therefore, five criteria are used for the sustainability analysis of corn-to-ethanol process, including mass balance, compositional driven, water balance, energy balance, and user accessibility (Table 3.1).

Table 3.1. Comparisons of previous scale-up models for various corn-to-ethanol processes.

	Compositional Driven	Mass Balance	Energy Balance	Water Balance	User Accessibility
Conventional					
Tiffany and Eidman (2003)					√
Dale and Tyner (2006)		√			√
Li et al. (2010); Rodriguez et al. (2010)	√	√			√
McAloon et al. (2000)	√	√	√	√	
Kwiatkowski et al. (2006)	√	√	√	√	
Modified					
Li et al. (2010); Rodriguez et al. (2010)	√	√			√

The model by Tiffany and Eidman (TE model) is clear and easy to understand the economic factors associated with the performance of dry grind ethanol plants. However, the TE model is not mass balanced (Tiffany and Eidman, 2003). That is, the amount of ethanol and DDGS produced from each bushel of corn is chosen as an input based on the industrial survey, rather than calculated based on the efficiency of each unit process. Without a mass balance, the TE model cannot predict the composition of DDGS. Thus, it lacks the ability to evaluate those modified dry grind ethanol processes with additional coproducts. Moreover, though the parameters in the TE model are well researched and have been confirmed with plant managers, results are very sensitive to the input values chosen by the user (Dale and Tyner, 2006).

The model by Dale and Tyner (DM model) is mass balanced and feed backward. It allows the user to enter several parameter values of the dry grind process, such as the plant capacity, the composition of corn, and the physical condition at each step, to determine the necessary hourly flow rates of inputs and outputs at each step throughout the process (Dale and Tyner, 2006). Then, the hourly flow rates are used to calculate the equipment size and the capital cost. The hourly flow rates can also be used to calculate the utility consumption, and to estimate the operating costs. Based on these principles, the DM model is useful to conduct sensitivity analysis of the dry grind process, particularly with respect to the plant capacity. However, the mass balance of the DM model is only limited to starch, not for other components, such as proteins and fiber. Thus, it requires significant work to modify the DM model to conduct the analysis of a modified dry grind process.

Both the TE and DM models are focused on the economic analysis, whereas the energy and water consumption rates are input parameters that based on the industrial survey data. As ethanol production is a complex process, consisting of more than 100 unit operations, spreadsheet modeling would not be an effective tool to provide detail information of the energy and water consumption throughout the process. Owing to the development of the process control and administration system, nowadays the energy and water usage as well as capital investment cost in the industrial plant can be well predicted by the computer simulation. SuperPro Designer® and Aspen Plus® are two tools being used to simulate the dry grind process (McAloon et al., 2000; Kwiatkowski et al., 2006).

The McAloon model is composed of two parts: a processing simulation model and a spreadsheet analysis model (McAloon et al., 2000). The processing simulation model is implemented on the ASPEN Plus® platform to achieve the mass and energy balances, and the simulation results are then incorporated in the Microsoft Excel® spreadsheet to conduct the sensitivity analysis. Although it would be easy for users to conduct a sensitivity analysis of different feedstock prices, changes in the process model would be required to construct new modified ASPEN Plus® simulation models.

More recently, USDA developed a conventional dry grind process model to simulate a 40 million gallon capacity facility upon the SuperPro Designer® platform (Kwiatkowski et al., 2006). The results derived from this model, such as energy and water consumption as well as capital investment and operating cost, agree with the current industrial operating performance. The research showed that model simulation would be an effective approach to represent a modern ethanol facility. This conventional dry grind simulation model can be used as a baseline and would allow the users to develop and evaluate both the economic and environmental impact of the process modifications.

As for the modified dry grind ethanol process analysis, Li et al. (2010) reported that a new engineering economic spreadsheet model was developed to analyze different ethanol production methods. Unlike previous spreadsheet models, this model is mass balanced and compositionally driven. A mass balanced model is integrated in order to check of each component mass flow and to ensure the yield and composition of each product are realistic. Within this model, the compositions of coproducts and input feedstock rates are input parameters that can be determined by users. Different types of the modified dry grind ethanol process will result in different compositions of coproducts. By inputting the composition of those coproducts, it is possible for users to evaluate the economics of various modified dry grind ethanol productions. However, this model also relies on several assumptions, particularly in the areas of energy and water consumption as well as the capital investment cost.

3.3 PREVIOUS STUDIES ON THE ENERGY DEMAND

Rapid growth in ethanol production has recently received considerable attention throughout the nation. Many studies analyzing the energy balance issue began to appear in the literature since early 1990's (Keeney and Deluca, 1992; Shapouri et al., 2002; Pimentel, 2003). Those studies conducted a life cycle assessment of the energy consumption in corn based ethanol production by calculating its net energy value (NEV). NEV is defined as the energy content of ethanol minus the fossil energy used to produce ethanol (Shapouri et al., 2002). However, the findings of those life cycle assessments varied significantly.

Keeney and DeLuca (1992) reported a negative NEV, and the deficits of the results are less than 2.79 MJ per liter of ethanol (MJ/liter) (10,000 BTU/gal). Pimentel (2003) reported a significant energy deficit in the corn-to-ethanol production, with a net energy value loss of -6.17 MJ/liter (-22,119 BTU/gal). Put another way, the energy required to produce each gallon of ethanol is about 29% more than the energy content of each gallon ethanol. More recently, Pimentel and Patzek (2005) reported that there is still 28% energy loss in producing ethanol. However, in recent papers, most results showed that producing ethanol from corn can achieve a positive net energy value (Farrell et al., 2006; Shapouri et al., 2002; Shapouri et al., 2003; Shapouri and Gallagher, 2005; Wang et al., 1999).

This wide variation of energy consumption results from varied assumptions in terms of farm production, ethanol production technologies, and coproducts evaluation. Despite the detail in each of these papers, it may be difficult to understand why the disparity is so great. The energy consumption in the life cycle of the corn based ethanol production can be composed of three parts: farming, transportation, and ethanol production. For this analysis, we focus on the energy demand of ethanol production.

3.3.1 Energy Sources for an Ethanol Plant

Thermal energy and electricity are the main types of energy used in the ethanol production. Thermal energy, in the form of steam and hot air, is used in liquefaction, fermentation, and distillation. However, due to its lower efficiency, boiler steam is not always used for drying in a natural gas fired ethanol plant. Electricity is required in all stages of the ethanol production process to run motors, pumps, and other unit operations such as dewatering press and molecular sieve. Currently, most dry grind ethanol plants only generate steam onsite and purchase electricity from a utility.

Natural gas and coal are two sources typically used to generate steam. Each energy source requires a unique set of equipment to generate steam. For coal fired ethanol plants, the most common equipment type includes a fluidized-bed boiler energy system for steam generation, and a steam fired dryer for DDGS drying. In contrast, for natural gas ethanol plants, a natural gas boiler is usually utilized to generate steam and a natural gas fueled direct-fired dryer for drying DDGS (Mueller and Cuttica, 2006).

Mueller and Cuttica (2006) reported a detailed energy and economic analysis between coal fired and natural gas fired ethanol plants. The report estimated that the thermal fuel use, not including electricity, in the coal fired system is 11.2 MJ/liter (40,256 BTU/gal) compared with 9.0 MJ/liter (32,330 BTU/gal) for the natural gas fired system. The report further illustrated the reasons why coal fired systems require higher thermal energy: 1) the boiler efficiency of the coal fired system is lower than that of the natural gas fired system, which are 78% and 80%, respectively; 2) the steam fired dryer used at coal fired plants requires higher thermal energy compared to the direct fired dryers used at natural gas plants. The report also showed detailed energy flows for both natural gas and coal fired plants. However, this report did not provide any sources to verify whether the data regarding the energy consumption in each step of the process are reliable.

In 2007, the Renewable Fuels Association (RFA) conducted a survey of US ethanol production plants (Wu, 2008). A majority of dry grind ethanol facilities (86%) are fueled with natural gas. The remaining 14% are coal fired dry grind ethanol plants that supplement coal use with a range of natural gas (3-23%) as the process fuel (Wu, 2008).

3.3.2 Energy Requirement in Negative NEV Papers

Pimentel (2003) reported that the energy balance of corn based ethanol production is negative, based on a personal communication with an industrial expert. In this analysis, 10.9 MJ of coal and 0.73 kWh of electricity are required to produce one liter of denatured ethanol In more recent works (Pimentel and Patzek, 2005; Pimentel et al., 2007), the data of steam power and electricity demand of the ethanol production is from the website of Illinois Corn Growers Association. According to those papers, the process requires 10.7 MJ of steam and 1.17 kWh of electricity to produce each liter of ethanol. This result indicated that the energy demand is even higher than that in his previous report. However, based on the updated information from Illinois Corn Growers Association (2008), the results showed that the ethanol production requires 10.7 MJ of steam and 0.4 kWh of electricity in average to produce each liter of ethanol. There is a non-trivial difference on the electricity consumption as compared to the data previously used by Pimentel. What is more, the source for the energy demand of the ethanol production at the website of Illinois Corn Growers Association is over a decade older. It is questionable whether those data represent the current energy demand of ethanol production.

3.3.3 Energy Requirement in Positive NEV Papers

In 2002, USDA conducted a survey to provide a complete picture of the dry grind ethanol industry. According to the survey (Shapouri and Gallagher, 2005), dry grind ethanol plants consume 0.31 kWh of electricity to produce one liter of ethanol, ranging from 0.16 to more than 0.53 kWh. On average, the surveyed ethanol plants utilize 9.7 MJ of thermal energy to produce each liter of ethanol, ranging from 7.2 to 15.1MJ. The average of total energy use in the ethanol production is 10.8 MJ/liter (38,861 BTU/gal).

USDA’s net energy balance of corn-to-ethanol life cycle analysis was published in 2002 and 2003 (Shapouri et al. 2002; Shapouri et al. 2003). For the estimations of the energy consumption in the ethanol production, both papers are based on the USDA 2002 survey. On average, the dry grind ethanol plants used 0.29 kWh of electricity and over 10.0 MJ of thermal energy (HHV) to produce each liter of ethanol. However, these data are different from the original USDA’s survey, which reports 0.31 kWh of electricity and 9.7 MJ of thermal energy. The distinction of these two papers (Shapouri et al. 2002; 2003) is that they considered an energy loss in producing electricity and natural gas. Considering the generation efficiency, the dry grind ethanol plant consumed 13.6 MJ of primary energy to produce each liter of ethanol (Shapouri et al., 2002). However, there is no detailed description on the how these energy losses of electricity and natural gas were determined.

More recently, Shapouri and Gallagher (2005) reported that the energy output/input ratio is 1.67, indicating corn ethanol production is energy efficient. The energy consumption in the production is still based on the USDA 2002 survey. Although this paper estimated the thermal energy using a lower heating values (LHV) assumption, other data regarding the energy use in the ethanol production remains the same with previous papers. Still, there is no detailed information on the how to measure the energy losses in producing electricity and natural gas.

Farrell et al. (2006) constructed a model named EBAMM to evaluate six representative analyses of fuel ethanol. The results indicated that current corn ethanol technologies are much less petroleum-intensive than gasoline. However, this paper also points out several errors, omissions and inconsistencies in the construction of the EBAMM model, especially steam and electricity use in corn ethanol production is based on the data that is over a decade older.

Mueller (2010) reported that based on the 2008 national dry grind ethanol plant survey, the average energy consumption had been reduced to 7.18 MJ/liter of thermal energy and 0.195 kWh/liter.

3.3.4 Energy Demand Analysis

As described above, wide variations of the energy demand in the previous papers occur as a result of different data sources. The recent RFA industrial survey showed that significant improvements have been achieved to minimize the energy demand in the past several decades (Wu, 2008). The average energy demand, including electricity, of a dry grind plant was reduced from 11.1 MJ/liter (39,719 BTU/gallon) in the 2001 USDA survey to 8.7 MJ/liter (31,070 BTU/gallon) in the 2008 RFA survey, which is ranged from 4.9 to 12.3 MJ/liter (Wu, 2008). However, the industrial survey only provides the total energy consumption rate for ethanol production, but lacks the detailed operating performance. Considering the public criticisms that corn based ethanol production is energy intensive, it is important to understand the detailed energy demand by each unit operation, and thus providing the basis for the future optimization work to minimize energy demand.

Recently, a conventional dry grind ethanol process model, developed by USDA, demonstrated that simulation modeling is an effective tool to estimate the actual operating performance (Kwiatkowski et al., 2006). The results of energy demand derived from this model well represent the current industrial operating performance. Moreover, this simulation model quantifies the energy demand of each unit operation, which would facilitate the future process optimization work.

The QQ process was developed to improve the performance of corn based ethanol production (Singh et al., 1999; Wahjudi et al., 2000). Laboratory results of the QQ process demonstrate that the separation of nonfermentable materials before fermentation would improve the ethanol concentration. Therefore, our hypothesis is that this novel process would reduce the energy demand by a more efficient ethanol recovery.

However, since no existing plant has adopted the QQ process, industrial survey would not be utilized to support our hypothesis. Therefore, modeling simulation would be an approach to estimate the performance of this novel process. A new QQ process simulation model is built to quantify the energy demand of each unit operation in the QQ process. This model is further compared with the USDA model to evaluate the energy performance of these two dry grind ethanol processes.

3.4 PREVIOUS STUDIES ON THE WATER DEMAND

With the rapid growth in the ethanol industry, water availability and utilization are the key issues that must be addressed. In the life cycle of ethanol production, water is used in two major areas: farming and plant operation. Wu et al. (2009) claimed that irrigation water use for growing corn has substantial variation by state and region, ranging from 3 to 129 liters to produce each kilogram of corn. Irrigation water will dominate the total water usage in the life-cycle of ethanol production if the ethanol plant processes the corn from irrigated fields. In the life cycle analysis, the water demand for each gallon of ethanol production ranges from a net of 10-17 liters in non-irrigated corn production regions to 324 liters in irrigated corn production regions (Wu et al., 2009). However, although the water used in ethanol production is relatively small as compared to that used in the farming, significant public concerns of intensive water usage in ethanol production have been aroused with recent ethanol production growth. The major concern is that whether the increased water demand for ethanol production would adversely impact the adequate fresh water supply in the region near the ethanol facility. For this purpose, this analysis will focus on the water demand of ethanol production.

Water plays an important role in ethanol production and is generally categorized as either process water or non-process water. Process water refers to water directly mixed with corn, whereas non-process water is used for heating and cooling in the process, including cooling water and steam water. In ethanol production, process water is required for soaking, forming a corn slurry, which facilitates pumping of materials throughout the process. For the process water, dryer vapor loss would be the major loss, whereas a small fraction of loss is due to water being incorporated in the final products. Since the operating temperature changes in the various unit operations, cooling water and steam are needed to provide the optimum operating environment. The majority of cooling systems utilize a recirculating non-contact system, where the cooling water loss occurs in the cooling tower via evaporation, drift, and blowdown.

Pimentel reported that 13 liters of water are required to produce one liter of ethanol (Pimentel, 2003; Pimentel et al., 2005). It is true that large amounts of water are required to make the process slurry in corn-to-ethanol plants, however, most plants can recycle a significant portion of their process water through a combination of centrifuges, evaporation and anaerobic digestion (Aden, 2007). With the help of the process water recycling, the water demand can be significantly reduced. Shapouri and Gallagher (2005) reported that ethanol plants used more than 15 liters of water to produce each liter of ethanol in the 1980. However, based on the USDA 2002 survey, the average water usage had been reduced to 4.7 liter of water per liter of ethanol (liter/liter), ranging from 1 to 11 liter/liter (Figure 3.1).

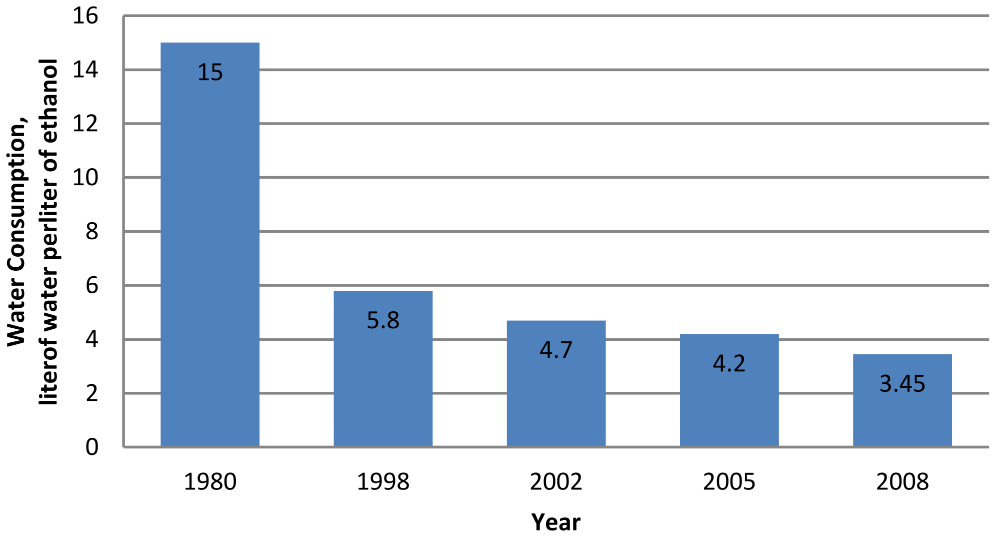

Figure 3.1. Average consumptive water usage in the existing dry grind ethanol plants (Data source: Shapouri and Gallagher, 2005; Keeney and Muller, 2006; Wu, 2008).

Keeney and Muller (2006)reported that average water use of ethanol plants located in Minnesota has declined from 5.8 liter/liter in 1998 to 4.2 liter/liter in 2005, indicating that the plants are achieving greater efficiency over time. This report also provided several recommendations on how to reduce the water consumption in ethanol production: 1) use municipal wastewater as a source of water input; 2) locate the ethanol plant close to livestock facilities in order to sell the wet distillers grains without drying; 3) place a greater economic value on water to promote water conservation in the ethanol industry.

Recently, Wu (2008) reported that based on the latest ethanol plant survey, currently dry grind ethanol plants consume an average of 3.45 liters of fresh water to produce each liter of ethanol, ranging from 2.65 to 4.9 liter/liter. Newly built plants tend to require less water, because of the improved equipment and energy efficient design.

Typically, the water losses in the different ethanol plants vary with the evaporation rate in the cooling tower, and the percentage of water vapor captured in the DDGS dryer (Wu et al., 2009). Further, based on the USDA dry grind process model, assuming a temperature drop of 20˚F for the cooling tower, no recapture of dryer vapor loss, and a boiler makeup water rate of 5 percent, Wu et al. (2009) proposed a breakdown of water usage in the dry grind ethanol production as shown in Figure 3.2. The result shows that cooling water and dryer vapor loss account for the major water loss in the corn-to-ethanol production.

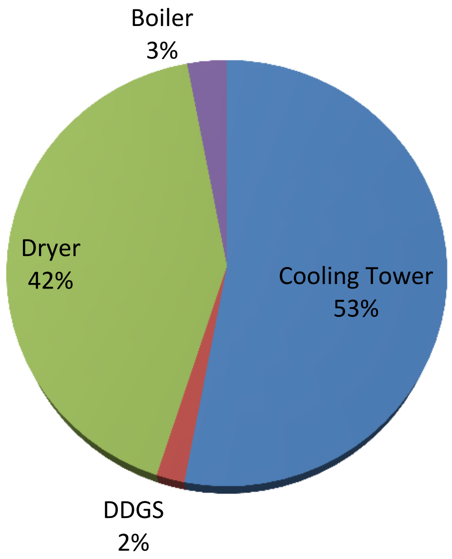

Figure 3.2. The breakdown of water usage in the dry grind ethanol production (Wu et al., 2009).

3.5 PREVIOUS STUDIES ON THE ECONOMIC ANALYSIS

Corn based ethanol production has increased exponentially in the last two decades from 227 million liters (60 million gallons) in the mid 1970s to 34 billion liters (9 billion gallons) in 2008 (Renewable Fuels Association, 2009). However, recent fluctuations in petroleum, ethanol, and corn prices have driven several large producers of ethanol into bankruptcy, mergers, and acquisition. Despite these economic challenges, corn based ethanol still remains the most viable biofuel available on the market today and is projected to produce 57 billion liters (15 billion gallons) by 2022 (EPA, 2009). Therefore, it is critical to understand what are the important factors affecting the economic performance of corn based ethanol production. Based on previous economic studies, there are four major factors associated with the economic performance of corn based ethanol production, including capital investment costs, operating costs, ethanol prices, and ethanol yield rate. These major factors will be considered below.

3.5.1 Capital Investment Costs

The capital investment is the total amount of money needed to supply the plants and manufacturing facilities plus the amount of money required as working capital for operation of the facilities (Peters et al., 2003). There are few papers discussing the sensitivity of profit with regard to capital investment costs mainly because the typical design of a standard plant has not changed much over the past few years. According to Eidman (2007), due to the high cost of stainless steel, copper and concrete, the fixed capital investment costs have increased to $0.4 per liter of output in 2006 from $0.26 in 2003 for a 120 MGY dry grind ethanol plant.

Gallagher et al. (2005) proposed that capital costs typically increase less than proportionately with plant capacity in the dry grind ethanol industry. Therefore, larger plant capacity will have an advantage with respect to fixed capital investment costs. However, capital costs of an ethanol plant increases more rapidly than the average of all processing plants, where the power factors are 0.836 and 0.6, respectively (Gallagher et al., 2005). More specifically, Eidman (2007) estimated that the capital investment cost would be $0.33 per liter for a 151 MLY (40 MGY) dry grind ethanol plant, compared with $0.26 per liter for a 379 MLY (100 MGY) plant.

3.5.2 Operating Costs

During recent years, the dry grind ethanol production has attained a significant improvement in the processing efficiency. McAloon et al. (2000) reported that the production cost per liter had decreased to \$0.23 in 2000 from \$0.65 in 1978. Energy saving technologies and higher ethanol yield per bushel are the two factors reducing the production cost (McAloon et al., 2000). There are several other factors associated with the production cost discussed below.

The single greatest cost in the dry grind ethanol production is the feedstock corn cost, which accounts for more than half of the total production cost. Corn prices vary from year to year, and the variations have been especially drastic in recent years. McAloon et al. (2000) reported that when corn prices are \$0.076 per kg (\$1.94 per bushel), the feedstock cost accounts for \$0.18 of each liter ethanol produced. The total production costs of the same facility are \$0.23 per liter for a 25 MGY ethanol plant. Since DDGS prices follow corn prices, when analyzing the production costs, the feedstock cost of the dry grind process is often computed on a “net cost” basis, which is offset by the revenue gained from the sales of DDGS. Wyman (1996) reported when corn is \$0.12 per kg (\$2.94 per bushel), the gross feedstock cost accounts \$0.23 per anhydrous liter (\$0.87 per anhydrous gallon), and the net feedstock cost is reduced to \$0.12 per anhydrous liter (\$0.45 per anhydrous gallon). Kwiatkowski et al. (2006) reported that the cost of producing ethanol increased from \$0.24 to \$0.36 per liter while the price of corn increased from \$0.07 to \$0.13 per kg; however, this analysis did not consider that DDGS price would fluctuate with changes in corn price. Eidman (2007) conducted a sensitivity analysis of corn price, and the results showed that if DDGS price remains \$0.08 per kg (\$71.43 per ton), every \$0.04 per kg (\$1 per bushel) increase of corn price would result in a \$0.094 per liter (\$0.356 per gallon) increase of the net ethanol production cost. However, the markets suggest the price of DDGS follows corn price. Assuming the price of DDGS increases at approximately 92% of the increase in the corn price, Tiffany and Eidman (2003) proposed the net ethanol production cost increases \$0.07 per liter (\$0.26 per gallon) at each \$0.04 per kg (\$1 per bushel) increase of corn price. More recently, Li et al. (2010) developed a model to estimate the price of DDGS based on corn price, protein and NDF content of DDGS, and this model will enhance the research on the net production cost analysis.

Utility costs are another important factor associated with the operating costs. In a dry grind ethanol plant, energy is utilized in two forms, thermal energy and electric power. Thermal energy is of greater importance because it dominates the total energy consumption in ethanol production. Most of the previous studies assume natural gas is the source providing thermal energy. For example, Eidman (2007) proposed that a dry grind ethanol plant requires 8,983 BTU of natural gas to produce one liter of ethanol, hence a $1 change in the price of natural gas will result in a production cost change of $0.009 per liter ($0.034 per gallon). However, the amount of energy consumption in the ethanol production varies in the previous papers, as discussed in Chapter 3.3.

3.5.3 Ethanol Prices

Ethanol is the most valuable product in the dry grind process. Tiffany and Eidman (2003) claimed, for a 151 MLY (40 MGY) dry grind ethanol plant, an additional revenue of $480,000 per year can be returned by each $0.003 per liter ($0.01 per gallon) increase of the fuel ethanol price. Based on the energy content equivalence, Tyner and Taheripour (2007) claimed that the ethanol price should be 70% of the wholesale gasoline price. Despite its low energy density, ethanol has an additive value as a result of the higher oxygen and octane content. Historically, the ethanol price was higher than the wholesale price of gasoline by an average of $0.09 per liter ($0.35 per gallon) from 2002 to 2004, when the ethanol supplies could not fulfill the demand (Eidman, 2007). Industry representatives suggest the ethanol price should be $0.053 to $0.066 per liter ($0.20 to 0.25 per gallon) higher than wholesale price of gasoline when ethanol supplies meet the demand (Eidman, 2007).

Over in the medium term, the price of gasoline can be predicted from the price of crude oil. Tyner and Taheripour (2007) claimed an econometric relationship for gasoline prices where wholesale gasoline price ($/gal) = 0.1076 + 0.031270*crude oil price ($/barrel). Estimated from national data for the period from January 2000 to 2006, Eidman (2007) concluded that wholesale gasoline price ($/gal) = 0.037 + 0.030*crude oil price ($/barrel). Assuming the ethanol price is $0.05 per liter ($0.20 per gallon) higher than the wholesale price of gasoline, by using Eidman's relationship equation, the price of ethanol should increase $0.08 per liter ($0.3 per gallon) as the price of crude oil increases $10 per barrel.

3.5.4 Ethanol Yield Rate

The amount of ethanol yield by each bushel of corn processed is the most important factor for plant managers. Currently, one kg of corn generates 0.41 liter of anhydrous ethanol

(Tiffany and Eidman, 2003). Recently, many researchers have investigated the improvement of the ethanol yield efficiency. Developing high starch concentration corns and producing more effective enzymes and better yeast strains are some of the examples. Tiffany and Eidman (2003) proposed that as the ethanol yield rate increased by 0.015 liter per kg (0.1 gallon per bushel), a 151 MLY (40 MGY) ethanol plant would improve its profits by $801,550 per year.

CHAPTER 4: METHODOLOGY

4.1 PROCESS MODEL DEVELOPMENT

As described above, the USDA SuperPro Designer® simulation model is a proven tool to predict actual operating performance for a modern ethanol facility using conventional dry grind ethanol process. Due to its promising laboratory results, the QQ process was selected for consideration in this analysis. A QQ process model was developed based on the information from the USDA model as well as laboratory experimental results. The process model was developed in the SuperPro Designer® platform to evaluate its mass and energy balance. The user may now select a feedstock input rate and the model quantifies the volume, composition, and other physical characteristics of the process streams for each unit operation. In addition, the user may select the unit operation requirements, such as residence time, working temperature, and operation efficiency. This information becomes the basis for sizing the equipment, estimate the energy and water demands, and subsequently provide cost and benefit analysis for the QQ process.

Due to the germ and fiber removal at the front end, the QQ process improves its processing capacity relative to the conventional dry grind process. The conventional dry grind model developed by USDA is designed to process 1.1 million kg of corn per day (43,800 bu/day) (Kwiatkowski et al., 2006). To compare both processes consistently, a QQ process model is designed to process 1.3 million kg of corn per day (52,500 bu/day), without increasing the size of the equipment used in the conventional dry grind process. The QQ ethanol plant operates 24h/day and 350 days per year, with time set aside for maintenance and repairs.

The QQ process consists of six major sub-systems, including grain cleaning, germ and fiber recovery, liquefaction and saccharification, fermentation, distillation, and DDGS recovery. The simplified flow sheet is given in Figure 4.1. Each unit operation in the model is identified a number ID based on each one of the six sections and the type operation. For example, 103BC identifies the belt conveyer in the grain cleaning section (100’s for grain cleaning section), and 313HX represents the heat exchanger in the liquefaction and saccharification section (300’s for liquefaction and saccharification section). Table 4.1 gives an overview of some of the key unit operations in the QQ process model.

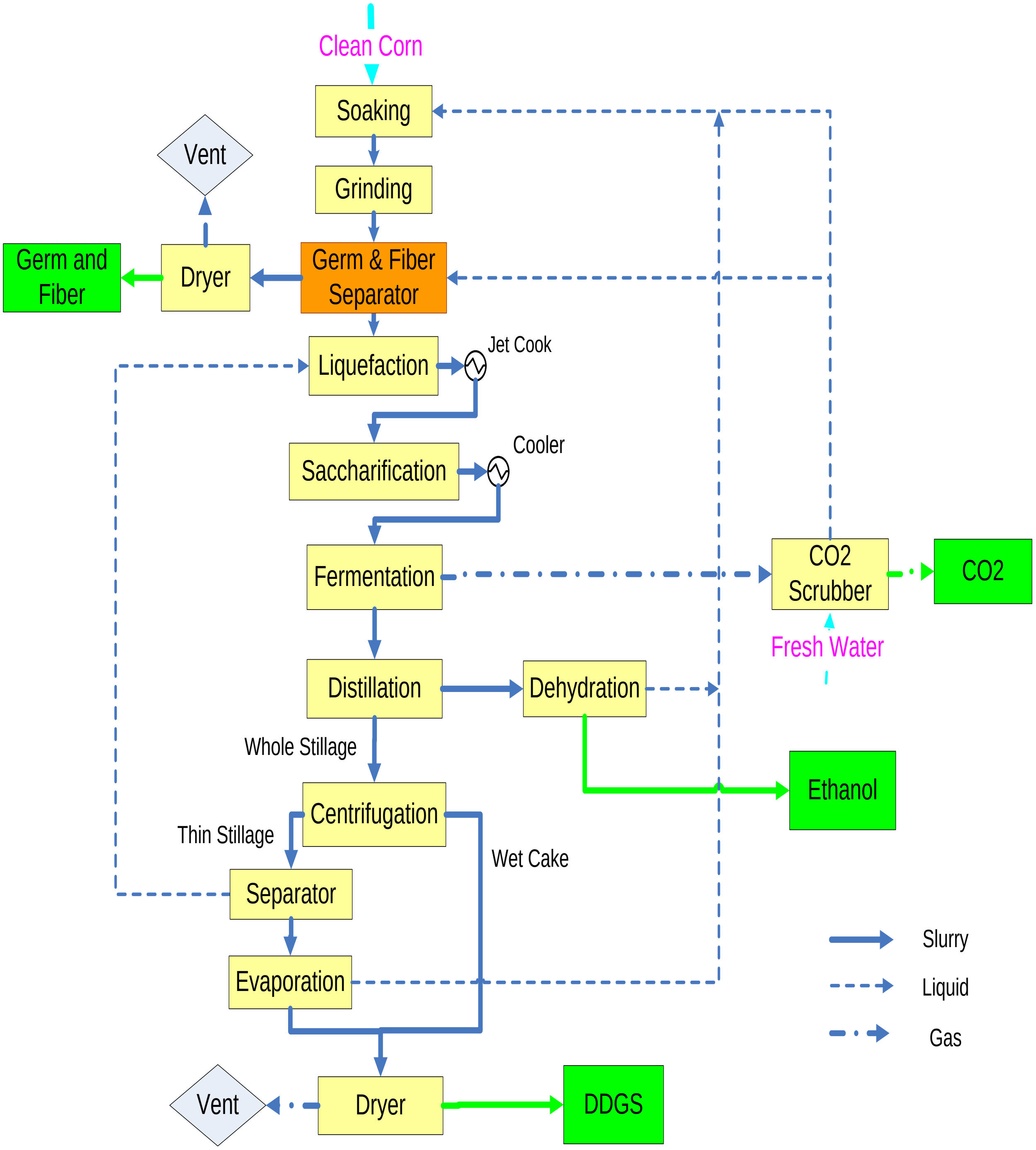

Figure 4.1. Simplified flow sheet of the QQ process.

Table 4.1. Overview of selected QQ process equipment.

Unit ID	Name	Description
102 SL	Corn storage	72 hr Residence time
104 U	Grain cleaner	0.3% Removed as trash to downstream
201V	Soaking tank	8 hr Residence time
214 PFF	Dewatering press	0.46 kW/m^2 Specific power
		Output dryness: 50% moisture content
217 FBDR	Fluid-bed dryer	Natural gas direct fired: 0.06 kg/kg evaporated[1]
		0.04 kW/(kg/h) Specific power
303 V	Slurring mix tank	0.25 hr Residence time
306 HX	Liquefaction heater	87.8 ℃ Exit temperature
307 V	Liquefaction tank	0.9 hr Residence time
		0.6 kW/m^3 Specific power[1]
310 HX	Jet cooker	110 ℃ Exit Temperature
318 V	Saccharification tank	20 min Residence time
		0.036 kW/m^3 Specific power[1]
403 HX	Cooler	32.3 ℃ Exit temperature
406 FR	Fermentor	60 hr Residence time
		0.028 kW/m^3 Specific power[1]
408 V	Degasser	0.05 hr Residence time
409 C	Condenser	98.154% ethanol condensation ratio
		1.2% CO_2 condensation ratio
505 MS	Molecular sieves	99.7% ethanol in outlet
		14 kW operating power[1]
512 V	Anhydrous ethanol day tank	100 hr Residence time
515 V	Denaturant ethanol day tank	156 hr Residence time
604 SC	Stillage centrifuge	30% (w/w) solids in underflow
609 E	Thin stillage evaporator	Four-effect evaporator
		35% solids in syrup
615 D	DDGS dryer	Natural gas direct fired: 0.06 kg/kg evaporated[1]
616 TO	Thermal oxidizer	234 kW heat duty[1]

1. Kwiatkowski et al., 2006

4.1.1 Corn Composition

An understanding of composition of corn is vital for conducting sustainability analysis of the QQ process. The corn kernel is a seed that has four easily separable parts: tip cap, pericarp, endosperm, and germ (Watson, 1987). The benefits of the QQ process are ultimately determined by the amount of the germ and fiber recovered at the front end, and how this recovery affects the following operations in terms of ethanol yield rate, utility demand, as well as the compositions of coproducts. Dry basis is usually used in the mass balance analysis because the amount of dry matter does not change in the system while the amount of water may. Assuming 14.5% moisture content, 1 bushel of corn (56 lb) will have 47.88 lb of dry material.

In the QQ process, the tip cap is always separated together with the pericarp. Thus, to simplify the model, corn kernel is divided into three parts: pericarp + tip cap, endosperm and germ. Starch, oil, neutral detergent fiber (NDF), protein, sugars, and ash are major constituents making up the corn kernel. To better illustrate the recovered components by the QQ process, the protein and NDF can be further divided based on their distribution in the each part of the corn kernel. Table 4.2 and 4.3 show the fractions as measured by lb/bu and percent dry basis (Unpublished data, Eckhoff).

Table 4.2. Compositional components in the different corn fractions (lb/bu).

	Corn	Endosperm	Germ	Pericarp+Tipcap
	47.88	39.78	5.30	2.80
Protein	4.55	3.24	1.15	0.16
-Insoluble germ protein	0.45	-	0.45	-
-Insoluble nongerm protein	3.04	2.98	-	0.06
-Soluble protein	1.06	0.26	0.71	0.10
NDF	4.55	1.32	0.82	2.41
-Cellular fiber	1.32	1.32	-	-
-Coarse fiber	2.41	-	-	2.41
-Germ fiber	0.82	-	0.82	-
Starch	34.71	34.12	0.42	0.17
Sugar	1.20	0.35	0.83	0.02
Oil	2.01	0.28	1.70	0.03
Other	0.34	0.31	0.01	0.02
Ash	0.53	0.11	0.54	0.02

Table 4.3. Compositional components in the different corn fractions (percent db).

	Corn	Endosperm	Germ	Pericarp+Tipcap
	47.88	39.78	5.30	2.80
Protein	9.50%	8.14%	21.73%	5.68%
-Insoluble germ protein	0.93%	-	8.41%	-
-Insoluble nongerm protein	6.36%	7.50%	-	2.16%
-Soluble protein	2.21%	0.64%	13.32%	3.51%
NDF	9.50%	3.32%	15.46%	85.97%
-Cellular fiber	2.76%	3.32%	-	-
-Coarse fiber	5.04%	-	-	85.97%
-Germ fiber	1.71%	-	15.46%	-
Starch	72.50%	85.78%	8.00%	5.94%
Sugar	2.50%	0.87%	15.66%	0.77%
Oil	4.20%	0.71%	32.12%	1.00%
Other	0.70%	0.78%	0.19%	0.71%
Ash	1.10%	0.28%	10.16%	0.72%

Fermentable components in the corn kernel are the key for ethanol production. Starch and sugars are the two primary fermentable components. Due to the limited amount of sugars in the corn kernel, starch is the most valuable resource in the corn kernel for an ethanol facility. Starch accounts for 72.5% of the total dry matter of the corn kernel and is primarily located in the endosperm.

The fiber fraction can be divided into three distinct parts. The fiber found in the germ meal, germ fiber, is not separable and accounts for approximately 18% of the fiber in the kernel. Approximately 53% of the corn fiber is classified as coarse fiber in our work, located in the pericarp and tipcap, with the remaining 29% as endosperm cellular fiber.

Traditionally, corn proteins are classified into four types based on their solubility: albumins, globulins, zein, and glutelins (Watson, 1987). To simplify our model, protein is classified based on the solubility as well as on the location, including insoluble germ protein, insoluble nongerm protein, and soluble protein. Insoluble germ protein is limited in the germ fraction, while insoluble nongerm protein is mainly from the endosperm with a small fraction from the pericarp and tipcap. Approximately 70% of soluble protein is from the germ fraction.

4.1.2 Grain Cleaning

Corn is shipped in bulk to the ethanol plants by truck, hopper car, and barge. Using a belt conveyer, corn is placed in a storage bin (102 SL) sized to hold corn for three days of operation. Prior to soaking, a grain cleaner (104 U), represented by the two-way component splitter in this model, is applied to separate foreign materials and broken kernels, which account for 0.3% of total flow rate as debris in the bottom product (Kwiatkowski et al., 2006). Those foreign materials and broken kernels are removed to prevent unnecessary viscosity increase during the process and maintaining the quality of the products.

4.1.3 Germ and Fiber Recovery

The germ and fiber recovery sub-system is the key innovation in the QQ process, which is adopted from the wet milling systems (Figure 4.2). Soaking is the critical step in the QQ process, which affects the consequent germ and fiber recovery performance. The soaking step increases the moisture content of the grain, softens the kernels to facilitate the germ and fiber separation, and preserves the integrity of the germ during grinding. The soaking tank (201 V) in the model is sized for 8 hr residence time to make sure the corn has been well soaked. The moisture content of the slurry will increase from 14.5 to 57.4% during soaking. To minimize the water and energy use, the soaking water in this model is sourced by recycling three streams consisting of the downstream of the CO_2 scrubber, the downstream of the stripper distillation tank, and the condensed water vapor from the thin stillage evaporator. The temperature of this soaking water input is approximately 68˚C, which provides the necessary heat to meet the soaking requirements at 55˚C. Therefore, no external heaters are required to equip with the soaking tank. The design of this soaking water input reduces both water and heating demands.

After soaking, the corn slurry is then sent to the coarse grinding mills (ID: 202 GR) to lightly break up the corn kernel, and thus germ and fiber can be separated from the slurry by hydrocyclones. The separation system, based on the density difference, consists of two stages of hydrocyclones and three stages of wash screens. In this model, the wash screen is represented by a two-way component splitter. The diluted slurry from the mills is pumped to hydrocyclones, where the lighter parts, germ and fiber, are floated off the top. The purity of the germ and fiber fraction is determined by the top flow ratio of the first hydrocyclone (Table 2.5). All of the separated germ and fiber parts leave in the top flow of the first hydrocyclone and are routed to the washing system; a starchy slurry leaves in the underflow and proceeds to the second hydrocyclone. The second hydrocyclone is designed to minimize the germ and fiber loss in the starchy slurry by recycling its top flow back to the grinding tank. The top flow ratio of the second hydrocyclone determines the amount of germ and fiber that is recycled to the grind tank (Table 4.4). The extent of the separation is derived from the laboratory experimental results (Li et al., 2010), and it can be easily adjusted based on other experimental data.

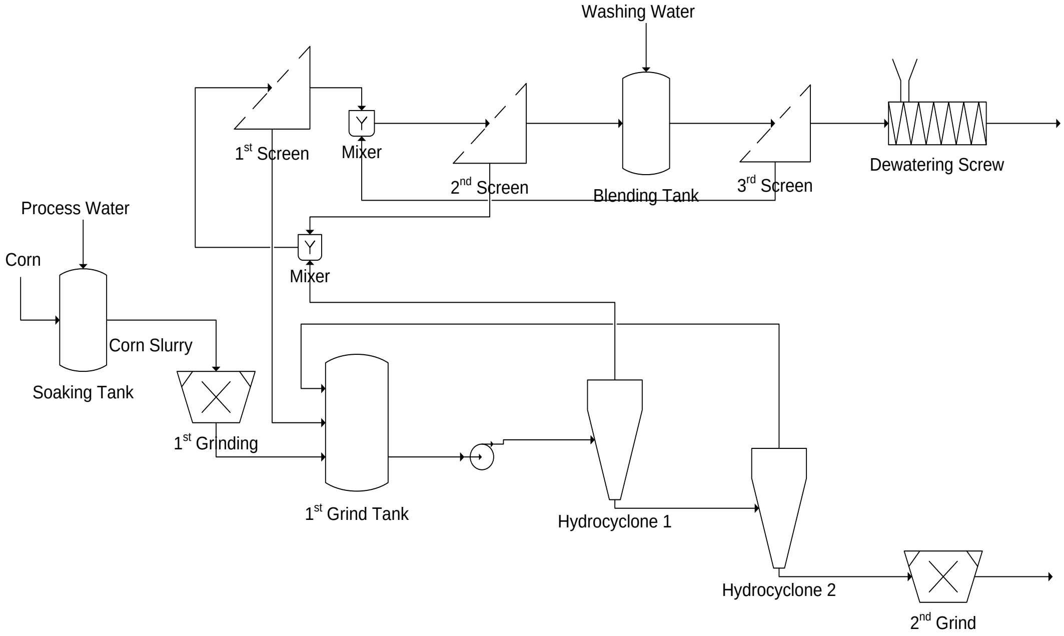

Figure 4.2. The germ and fiber recovery sub-system in the QQ Process.

The washing system consists of three gravity screens, aiming to wash the loose starch and protein from the germ and fiber parts. Water is acquired from CO_2 scrubber downstream and is recycled to the last stage of washing. The washing water runs in a counter current fashion and finally leaves in the underflow of the first screen with the free starch and protein. The detailed information of separation ratios of the wash screens are shown in Table 4.4, and are based on industrial data and a mass balance of the process.

After washing, the germ and fiber are then dewatered in the screw press (ID: 214 PFF), which is represented by a plate and frame filter in this model, to an average of 50% moisture content. Germ and fiber are further dried and separated via a fluid bed dryer (ID: 217 FBDR) to 3% and 10% moisture content, respectively. The outlet stream of germ and fiber are produced at a rate of 4,228 and 3,871 kg/h, respectively. The germ is to be sold for extraction to produce corn crude oil.

Table 4.4. Operation information of germ and fiber recovery system (% (w/w) solids in the upflow).

	Hydrocyclone system			First wash		Second wash		Third wash	
	Ratio, 1st hydrocyclone (%)	Ratio, 2nd hydrocyclone (%)	Output (lb/bu)	Ratio (%)	Output (lb/bu)	Ratio (%)	Output (lb/bu)	Ratio (%)	Output (lb/bu)
Ashes	42	25	0.361	58	0.289	60	0.207	73	0.151
Cellular Fiber	30	30	0.509	95	0.498	97	0.488	99	0.484
Coarse Fiber	83	85	2.454	95	2.401	97	2.352	99	2.330
Germ Fiber	73	75	0.784	95	0.767	97	0.751	99	0.745
Insoluble Germ Protein	83	82	0.451	95	0.441	97	0.432	99	0.428
Insoluble Nongerm Protein	30	11	1.378	50	1.206	40	0.689	25	0.172
Oil	85	86	2.062	95	2.017	97	1.976	99	1.958
Other	7	10	0.026	90	0.026	90	0.026	95	0.053
Soluble Protein	35	28	0.572	62	0.458	70	0.389	75	0.292
Starch	15	10	6.660	39	3.848	40	2.138	30	0.642
Sugars	31	35	0.740	50	0.618	40	0.331	37	0.122

After the germ and fiber separation, the starch concentration of the slurry increases to 27.9%. Because of the washing water input, the moisture content of the slurry improves to 66.7%, compared with 57% before the germ and fiber separation. The corn slurry is then fed into a fine grinder to get a desired particle size aiming at improving the performance of cooking hydration and subsequent enzymatic conversion to ethanol.

4.1.4 Liquefaction and Saccharification

The process of hydrolyzing starch to fermentable sugars (dextrins) uses a combination of heat and enzymes (Power, 2003). First, starch granules are hydrated in aqueous suspension, but they do not swell without heat. Therefore, a heater is set before the liquefaction tank to increase the slurry temperature to 88 ℃, providing the heat to separate the granules, rupture hydrogen bonds, and permit water to hydrate the starch molecule. However, this swelling process, called gelatinization, increases the viscosity of the mash, making it difficult to pump. Thus, before the gelatinization, Alpha-amylase is added at 0.082% dry basis of corn input (Kwiatkowski et al., 2006). Alpha-amylase is an enzyme that converts starch to dextrose, and thus reduces the viscosity of the solution. Lime and ammonia are also added in the tank to keep the slurry at pH

6.5. The slurry is then mixed with “backset”, a recycled stream from the liquid portion of thin stillage. In addition to the water conservation, the backset provides critical nutrients for yeast propagation during fermentation and some heat to reduce the energy consumption. Liquefaction is initially held in the liquefaction tank (ID: 307 V) for 60 min at 88 ℃ with agitation, and then cooked at 110 ℃ for 15 min by using a jet cooker (Kwiatkowski et al., 2006). After the jet cooker heating, the slurry needs to be cooled down to meet the operational requirements of the following saccharification operation. To recover the extra heat of the outlet of the jet cooker, a heat exchanger is designed to use preheat the slurry before going to the jet cooker. After the liquefaction step, starch has been broken down into dextrins as the reaction products.

Further conversion of dextrins to glucose is referred to saccharification. Glucoamylase is added at 0.11% (db) of corn to help to generate glucose (Kwiatkowski et al., 2006). To ensure a proper working environment for glucoamylase, a heat exchanger is set before the saccharification tank to cool the slurry down to 60 ℃ and sulfuric acid is added to lower the pH to 4.5. The slurry is held in the saccharification tank (ID: 318V) for 5 hr, and approximately 98% starch is converted into glucose (4.1). Glucoamylase continues to be active during fermentation if there are any unhydrolyzed dextrins remaining. Following the saccharification reaction, the stream is transferred to a heat exchanger with the heat being recovered by other streams in the process, and cooled by a cooler to 32 ℃ prior to fermentation.

$$\text{Starch} + \text{Water} \rightarrow \text{Glucose (98\% reaction efficiency)} \tag{4.1}$$

4.1.5 Fermentation

Fermentation is a conversion step where glucose is converted into ethanol and carbon dioxide with yeast. Urea is added at the rate of 0.3% (wet basis) of corn input to provide a nitrogen source for the yeast propagation. The fermentation (ID: 406 FR) simulated in this process is continuous, and the residence time is set at 60 hr. The very simple expression for fermentation shows that glucose yields almost the same amount of ethanol and carbon dioxide. In this model, 91.9% of total glucose is assumed to be converted to produce ethanol and carbon dioxide (4.2). Following Eq. (4.2), 3.28% of initial glucose is consumed for the yeast propagation, and carbon dioxide is produced by the yeast metabolism (4.3). The remaining 4.82% glucose is not involved in the conversion and is left to the DDGS. The extent of conversation is based on industrial data and research data, and the current ethanol concentration of the output is 15% (w/w). However, the reaction efficiency can be easily modified by users to meet their preferences. In addition, the chemical changes associated with fermentation of glucose to ethanol release heat energy of 515 Btu/lb of ethanol (Grethlein and Nelson, 1992). Ethanol coupled with high temperature is toxic to the yeast, which will affect the ethanol yield. Thus, cooling water is continuously provided to maintain the fermentation working temperature at 32 ℃.

$$\text{Glucose} \rightarrow 0.511\ \text{Ethanol} + 0.489\ CO_2 \quad (91.9\%\ \text{reaction efficiency}) \qquad (4.2)$$

$$0.88\ \text{Glucose} + 0.12\ \text{Urea} \rightarrow 0.742\ \text{Yeast Dry Matter} + 0.258\ CO_2 \quad (40.5\%\ \text{reaction efficiency}) \qquad (4.3)$$

98.5% of carbon dioxide and 2.25% of ethanol are emitted in the venting stream and transferred to the CO_2 scrubber. To recover the emitted ethanol, fresh process water is fed in the CO_2 scrubber and is then recycled to the soaking tank. This is the only fresh process water input in the system and is fed at a rate of 23,832 kg/h, which is 0.43 kg per kg of corn processed.

The beer after the fermentation is preheated via two heat exchangers, recovering the heat from the inlet stream of saccharification tank and the outlet stream of the first distillation column. The beer is then sent through a degasser, which is represented by a flash (ID: 408 V) in this model, to recover the residual carbon dioxide. Some ethanol and water are also purged to the vapor stream from the degasser. The vapor stream including CO_2, ethanol, and water vapor are processed to a condenser (ID: 409 C). The majority of ethanol and water in the vapor stream are condensed and then mixed with the liquid stream from the degasser for distillation.

4.1.6 Ethanol Recovery

The ethanol recovery sub-system considered here is designed to produce anhydrous ethanol from the beer for the use as fuel ethanol. As the azeotrope point of ethanol-water mixture is 95.6% of ethanol by volume, normal fractional distillation cannot produce anhydrous ethanol. In this analysis, the ethanol recovery sub-system consists of three distillation columns and a molecular sieve dehydrator that is used to accomplish the final dehydration step (Figure 4.3).

The complete normal fractional distillation system consists of a sequence of three columns, including a beer column (ID: 501 C) to pre-condense the ethanol concentration, a rectifier column (ID: 504 C) to concentrate the mixture close to the azeotrope point, and a stripping column (ID: 508 C) to minimize the ethanol loss. In the distillation system, reflux ratio is an important factor for estimating heating and cooling requirement as well as the number of stages in the column. The specific design parameters, such as reflux ratio (fraction of minimum reflux ratio (R / R_{min})), pressure, stage efficiency, and ethanol recovery ratio in the distillate, are based on the USDA dry grind model (Kwiatkowski et al., 2006). Table 4.5 shows input data, specific design parameters, and output data for the design of this distillation sub-system.

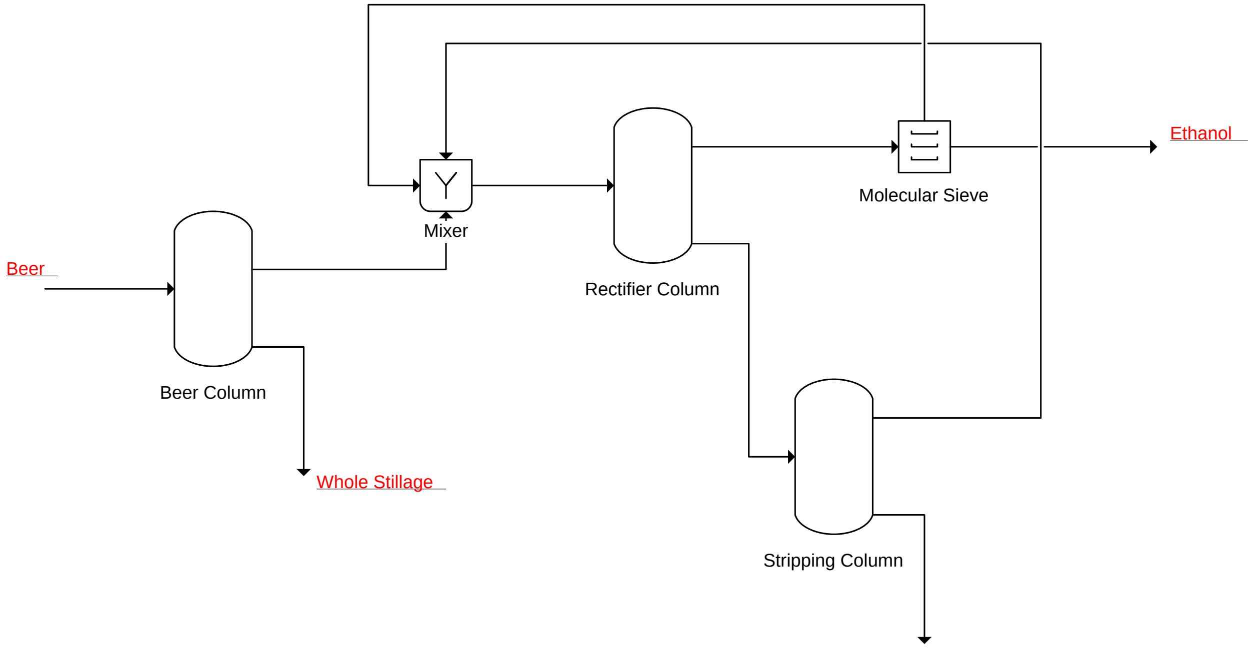

Figure 4.3. The distillation sub-system in the QQ process.

Table 4.5. Specific design parameters and operating data of the distillation sub-system.

	Beer Column	Rectifier Column	Stripping Column
R / R_{min}	1.212	1.263	1.25
Pressure (bar)	1.03	1.03	1.03
Stage efficiency	36.4%	40%	40%
Ethanol recovery ratio	99.7%	99.44%	99%
Ethanol concentration in the feed (m/m)	14.99%	59.46%	0.92%
Ethanol concentration in the distillate (m/m)	60.82%	92.72%	7.42%

The first step in the ethanol recovery is the beer column, which captures 99.7% of the ethanol produced from the fermentation. The beer is fed to the column near the middle point whereas the steam is fed at the bottom. The volatile materials such as ethanol and water are recovered from the downward-flowing beer by the rising hot vapor. Some water vapor are then condensed and refluxed back to the column by the use of cooling water. After the beer column, the ethanol concentration improves to 60.82%. The stillage from the bottom of the beer column contains some residual glucose and all the non-fermentable materials such as proteins, oil, fibers, and yeast dry matter, and it is transferred to the whole stillage tank for the DDGS processing.

Rectifier and stripper are the two columns utilized to further recover ethanol from the beer. Over 99% of the ethanol goes over the upper outlet of the rectifier as distillate. The bottom stream containing some ethanol is fed to the stripper to remove additional water. The upper stream from the stripper contains most of the residual ethanol and is recycled and combined with the beer column distillate as a feed input of the rectifier to minimize the ethanol loss. The rectifier distillate contains primary ethanol which is purified close to 180 °proof in this model.

Molecular sieve dehydrator (ID: 505 MS), represented by a two-way splitter in this model, is utilized to purify the ethanol stream to 99.7% (Kwiatkowski et al., 2006). This dewatered ethanol is produced at the rate of 17,771 kg/h in this model and stored in the ethanol daily tank (ID: 512 V) which is sized for 100 hr residence time. As anhydrous ethanol is not directly used for fuel ethanol, it is further mixed with denaturant, which is fed at 2% of ethanol output rate, to generate the final product. The denatured ethanol is stored in the product tank (ID: 515 V) with the capacity of 156 hr residence time.

4.1.7 DDGS Processing

Whole stillage leaving the distillation is hot and contains approximately 12% solids. Due to its natural rich in protein and other nutrients, whole stillage is susceptible to bacterial growth and will decompose rapidly. Thus, a drying process is needed to provide a valuable distillery coproduct (DDGS) with a long shelf life and lowered storage and transportation volume requirements.

The temperature of the whole stillage from the distillation tank is at 115 ℃. In order to minimize energy consumption, this hot whole stillage is linked to a heat exchanger that preheats the beer that is about to enter the beer column. Further, the whole stillage is sent to a centrifuge to remove the water by recovering the coarse particles as the bottom flow; approximately 75% of the water present in the whole stillage is removed to the top liquid portion. The liquid stream from the centrifuge, known as the thin stillage, contains 1% total solids. Approximately one fourth of the thin stillage, used as backset, is fed back to the liquefaction tank (Kwiatkowski et al., 2006). The remaining thin stillage is concentrated in the evaporator to yield syrup at 35% solids. A four-effect evaporator is designed in this model, and it reuses the overhead vapors from the rectifier instead of steam to provide heating for the evaporation, which provides considerable steam savings.

To minimize the process water demand, the outgoing vapor from the evaporator is condensed by the cooling water. After the condensation, the recovered vapor is further mixed with the bottom stream from the stripper column and water from CO_2 scrubber. The mixed stream has more than 99.9% water concentration with minor CO_2 and ethanol, and it can be reused as process water. 30% of this combined water stream is recycled to the germ and fiber washing step, while remaining 70% is fed back to the soaking tank.

The solid stream from centrifugation, known as wet cake, is mixed with syrup and sent to the rotary dryer. A direct gas fired rotating drum dryer is utilized to dry the stream from 70% to 9%. 0.06 kg gas is required to evaporate each kg of water in this model, which equalizes the energy use of 1,350 Btu per pound of water evaporated (Meredith, 2003). The top flow of the dryer that is rich in volatile organic compounds (VOC) is processed via the thermal oxidization to control air pollution. DDGS is produced at the rate of 9,831 kg/h in this model.

4.2 METHODOLOGY OF ENERGY DEMAND ANALYSIS

Extracting the process stream data is the most crucial step for the thermodynamic analysis. The stream data related to the heating demand includes the specific heat capacity of raw materials, temperature and flow rates of each processing stream, as well as the residence time of each unit operation. A simple equation (4.4) is showed to calculate the stream heat load:

$$\Delta H = c_P * m * (T_{p,i} - T_{p,i-1}) \tag{4.4}$$

Where

ΔH is the stream heat load (kJ/h);

c_P is the specific heat capacity (kJ / (kg K));

m is the mass flowrate (kg/h);

T is the temperature of stream (K).

With the aid of simulation software (SuperPro Designer®), the model calculates the specific heat of each stream based on its composition. In the corn-to-ethanol production, corn is the single major dry matter input. Therefore, to facilitate the comparison of these two dry grind models on a consistent level, the specific heat capacity of each corn component in the QQ model is based on the USDA model (Kwiatkowski et al., 2006). In addition, the QQ process model further quantifies the heating duty of each unit operation based on its operating information, such as temperature and flowrate. Table 4.6 shows the temperature and moisture content of several major streams in the QQ process.

As temperature varies in the process, external utilities are needed to provide the heating or cooling to the system to meet each unit operation requirement. Steam and natural gas are two utilities used to provide heating, whereas cooling water is utilized for cooling. Cooling water demand will be detailed in the water demand analysis. Electricity is another energy source used to run the pumps and certain equipment, such as dewatering press, molecular sieve, and agitation tank.

Table 4.6. Temperature and water content requirements in the QQ process.

Process Step	Moisture Content	Temperature
Corn input	14.50%	25 ℃
After soaking	57.37%	58.1 ℃
After separation	66.71%	60.6 ℃
Mix with backup thin stillage	70.32%	64.4 ℃
Liquefaction	70.32%	88.4 ℃
Jet cook	70.32%	110 ℃
After saccharification	67.58%	60 ℃
After fermentation	77.37%	32.2 ℃
Whole stillage	89.82%	86 ℃
Thin stillage	99.00%	86 ℃
Wet cake	70.23%	86 ℃
DDGS	9.00%	70 ℃

As described above, steam, natural gas, and electricity are the utilities required for the QQ process. The steam is used to provide heat to certain unit operations such as the distillation and heaters. Considering the energy conservation, natural gas is utilized in the direct gas fired dryer drum to dry germ, fiber, and DDGS. Based on the USDA model, the mass-to-energy factor of steam and natural gas are 487.41 kcal/kg and 12,163 kcal/kg, respectively (Kwiatkowski et al., 2006). The simulation model quantifies the heat load of each unit operation based on its operating information. As energy demand is usually reported in terms of the amount of energy used to produce each gallon of ethanol, a detailed energy usage can be provided for evaluation based on the heat load as well as the ethanol output rate. Further, to compare the two dry grind processes on a consistent level, we modified the conventional dry grind process model developed by USDA to have the same composition of corn as used in the QQ process.

4.3 METHODOLOGY OF WATER DEMAND ANALYSIS

Based on the previous research, the water demand of ethanol production is reported in terms of the amount of water used for each gallon of ethanol produced (liter/liter). Therefore, the water demand is not only related to the quantity of water used in the production but also associated with the ethanol yield rate. For the process water demand analysis, the simulation model is used to quantify the process water usage based on the feedstock input rate and the moisture content requirement of each processing stream. In the QQ process model design, the water vapor loss from the thin stillage evaporator and distillation system have been recaptured and recycled as a source of process water input. A molecular sieve is used for the ethanol dehydration to minimize the water loss. However, to avoid the additional capital and operating cost, the dryer vapor is not recaptured in this model.

Cooling water and steam water are two types of non-process water in ethanol production. As steam is purchased as a utility, not generated at the site in this model, steam water is not considered in this water demand analysis. Based on the previous studies, steam water only accounts for less than 3 percent of total water demand (Wu et al., 2009). Therefore, the exclusion of steam demand would not have a considerable impact on the total water demand analysis.

The cooling water system in this QQ process is of the recirculating non-contact type, where the cooling water loss mainly occurs in the cooling tower via evaporation, blowdown, and drift. Blowdown and drift water are removed to control dissolved solids concentration in the cooling water system. In a well-operated recirculating cooling system, blowdown and drift water loss accounts for only a small portion of the cooling water usage (Asano et al., 2007). To simplify the analysis, the cooling water demand is based on the evaporation rate of the cooling water. The rate of evaporation can be predicted by assuming the latent heat of vaporization is the driving force for the cooling. Approximately 2,300 kJ of heat is lost to evaporate 1 kg of water. About 4.2 kJ of heat is released to cool 1 kg of water by 1˚C. Therefore, a simplified mass and heat balance equation can be expressed as follows (4.5):

$$2300 * Qe = 4.2 * Qc * \Delta T. \tag{4.5}$$

Where

Qe is the evaporation rate (kg/h);

Qc is the circulation rate (kg/h);

ΔT is the temperature change (˚C).

Based on the cooling requirement in each unit operation, the simulation model quantifies the circulation flowrate of the cooling water. In the QQ process model, the supply and return temperature of cooling water are designed to be 15 and 26˚C, respectively. Based on the equation above, the evaporation rate would be 2% of the circulation rate. Without considering the blowdown and drift loss in this analysis, the makeup cooling water usage consists of 2% of the circulation flowrate.

To compare the water demand between the QQ process and the conventional dry grind process consistently, we modified the USDA's dry grind process model to have the same composition of corn used in the QQ process. Further, modifications were made to keep the same supply and return temperature of cooling water as in the QQ process. The flowrate of the process water input in the QQ process is designed to maintain similar moisture content in the process streams as in the conventional dry grind processes.

4.4 COST MODEL DEVELOPMENT

A cost model was developed on the SuperPro Designer® platform to evaluate the economic performance of the QQ process. Capital investment costs and operating costs are the vital parts of this cost model. Capital investment costs are estimated based on the purchased costs of each piece of operating equipment, whereas operating costs are composed of feedstock, utility, and other plant related costs. The data used in the model were obtained from the previous USDA's wet milling and dry grind ethanol models and laboratory experimental results (Kwiatkowski et al., 2006; Ramirez et al., 2008). Since no QQ ethanol plants has been in operation in the United States at this time, this model will provide an understanding of the economic performance of the QQ process at the commercial scale.

The QQ ethanol plant operates 24hr/day and 350 days per year, with some time set aside for maintenance and repairs. Since it can recover approximately 24% of the whole kernel at the front end, QQ process can operate at 24% extra capacities without modifying existing equipment in the conventional dry grind process. In order to facilitate comparison with the USDA's dry grind ethanol model with the corn input at 1,115 metric ton/day (43,800 bu/day) (Kwiatkowski et al., 2006), this QQ ethanol model is designed at a capacity of processing corn at 1,336 metric ton/day (52,500 bu/day).

4.4.1 Capital Investment Assumptions

Capital investment is composed of fixed capital investment, working capital, and start-up costs (Peters et al., 2003). The fixed capital investment is the sum of the direct costs and the indirect costs. The onsite costs and the offsite costs are the two categories of the direct costs.

The onsite costs correspond to installed equipment, which include the purchased equipment, installation, piping, instrumentation and control, as well as electrical equipment and material. The QQ ethanol facility utilizes belt conveyers and pumps to transport the solid and liquid streams short distances, respectively. Hammer mills are utilized to break the structure of the corn kernel. Receiver tanks and vertical on-legs tanks are used to store various process streams. Hydrocyclones, centrifuges, and screens are used for separation. Heaters, coolers and heat exchangers are installed to maintain and recover heat within the process. Evaporators, presses, and filters are used to remove water in the process. A fluid bed dryer is utilized to dry and separate germ and fiber streams, while a rotary dryer is applied to dry the DDGS stream. A wet air oxidizer is installed to reduce air pollution. The costs of these equipment are based on the SuperPro Designer® equipment cost estimating parameters as well as USDA dry grind and wet milling models (Kwiatkowski et al., 2006; Ramirez et al., 2008).

The offsite costs refer to the steam plant, cooling towers, and other facilities built in separate locations. Indirect costs are expenses not directly associated with material and labor of the installation. Engineering expense and construction expense are two types of indirect costs, accounting for 10% and 18% of direct costs, respectively, while working capital and startup capital costs are set at 15% and 10% of fixed costs, respectively (Table 4.7) (Douglas, 1988).

Based on the cost estimation factors used by Douglas (1988), the total capital investment cost would be four times the total equipment purchase costs (Table 4.7). Within this model, the purchase cost of each piece of equipment is estimated by its capacity. The changes of equipment capacity will change its purchase cost via the use of cost to capacity scaling factors. Thus, this model will facilitate the sensitivity analysis of the plant capacity.

Table 4.7. Total capital investment costs (Douglas, 1988).

	Factor of purchased equipment cost
Onsite costs:	
- Purchased equipment	100%
- Purchased equipment installation	40%
- Piping	30%
- Instrumentation and control	10%
- Electrical equipment and material	15%
Total onsite costs	195%
Offsite costs:	
- Building	40%
- Yard improvement	15%
Total offsite costs	55%
Total Direct costs:	250%
- Engineering	25%
- Construction	45%
Total indirect costs:	70%
Fixed capital costs:	320%
Working capital costs:	48%
Startup capital costs:	32%
Total capital investment costs:	400%

4.4.2 Operating Cost Assumptions

Operating costs of an ethanol plant consist of raw materials, utility, labor, and facility dependent costs. The volume of raw materials is an input value provided by the user. The utilities required by the process are then calculated by the model simulation. The unit costs of the raw materials and utilities are the input values incorporated into the model which can be easily modified as market conditions change.

A breakdown of the unit cost of raw materials used in the QQ process is given in Table 4.8. The feedstock (corn) cost accounts for the majority of total operating cost, although the unit cost of corn varies over time. The prices of commodities, such as corn, ethanol, and DDGS, utilized in this model are based on the market prices as observed in April 2009. Urea is utilized to provide the source of nitrogen for the yeast propagation and its cost is based on Li et al. (2010). The costs of enzymes and yeast as well as process water are based on the USDA's dry grind ethanol model (Kwiatkowski et al., 2006).

Natural gas, steam, electricity and cooling water are the utilities required by the QQ ethanol plant (Table 4.8). The utility demand by the each piece of equipment is based on process flowrates estimated by the model. The unit cost of these utilities can be easily changed to suit the users' preference. The natural gas and electricity prices are based on the market prices as observed in April 2009, while the steam is assumed to be purchased at 1.25 times the natural gas price, at $5 per MMBtu. The unit cost of make-up cooling water is assumed to be the same as the process water in this analysis. Recall that the cooling water demand calculated by the model is a recirculation rate, not a make-up cooling water rate. A make-up rate of 2% is assumed in this model to calculate the cooling water expenditures.

Table 4.8. Unit cost of raw materials and utilities.

	Unit Cost
Raw Materials:	
-Corn	$0.165/kg[1] ($4.2/Bu)
-Alpha amylase	$2.25/kg[2]
-Glucoamylase	$2.25/kg[2]
-Yeast	$1.86/kg[2]
-Urea	$0.31/kg[3]
-Succinic acid	$0.11/kg[2]
-Process water	$0.00035/liter[2]
-Denaturant	$0.475/kg[3]
Utilities:	
-Natural Gas	$4 per MMBtu[1]
-Steam	$5 per MMBtu[4]
-Electricity	$0.078/kWh[1]
-Cooling Water	$0.00035/liter[2]

1. Market prices as observed in April 2009; 2. Kwiatkowski et al., 2006;
3. Li et al., 2010; 4. Purchased at 1.25 times the natural gas cost

Facility dependent costs include maintenance cost, insurance, local taxes, and other factory expenses. Maintenance costs are assumed at 3% of direct fixed capital costs, while insurance, local taxes and other factory expenses are 0.15%, 0.15%, and 0.1%, respectively. Depreciation and amortized loan payments are also associated with the facility dependent costs. The QQ plant considered here is assumed to be constructed without any external loans, and thus no amortized loan payments are needed. The plant has a 10 year lifetime with zero salvage value at the end. The annual depreciation costs are calculated by utilizing the straight-line method.

Ten operators and one supervisor are assumed to work full time in this QQ ethanol facility. The unit labor costs of an operator and a supervisor are at an all-inclusive rate of $69/h and $105/h, respectively.

4.4.3 Product Value Assumptions

In the QQ process, ethanol, DDGS, germ, and fiber are the four marketed products, whereas CO_2 is assumed to be purged to the atmosphere (Table 4.9). The prices of ethanol and DDGS in this analysis are based on the market prices in April 2009, which are \$0.45 per liter (\$1.72 per gallon) and \$143 per metric ton (\$130 per ton), respectively. Taylor et al. (2001) reported that the benefits of germ separation are highly sensitive to the prices of crude corn oil. As there is no oil extraction designed in the QQ process, the value of germ fraction is calculated as the value of the oil and protein in the germ minus the cost of extracting the oil. The market prices of crude corn oil were \$0.81 per kg (\$0.37 per lb) in April 2009. As corn oil content is 43.13% in the germ fraction, the value of corn oil is \$0.35 per kg of germ fraction. Taylor et al. (2001) claimed that the value of protein is \$0.04 per kg of germ whereas the oil extraction cost is approximately \$0.02 per kg of germ. Therefore, the value of germ fraction in this model is \$0.37 per kg. The price of fiber is set at \$0.08 per kg based on a ratio of DDGS prices.

Table 4.9. Unit value of products as of April 2009.

Products	Unit revenue
Ethanol	\$0.45/liter
DDGS	\$143/metric ton
Germ	\$0.37/kg
Fiber	\$0.08/kg

4.4.4 Economic analysis

A baseline situation has been selected for the preceding energy and water analysis. No external loans are provided to build the facilities. Therefore, the annual cash flow is determined by the sum of the income after tax as well as depreciation. The analysis does not consider the impacts of inflation during the lifetime of the facility, thus it would be considered in real terms. The payback period for the QQ facility is determined as a ratio of total capital investment cost to annual cash flow.

Two additional economic scenarios are considered as well. First, an ownership group is presumed to provide 100% of the capital requirement. As investors, these individuals are presumed to collect dividends rated at 12% of the original equity invested. Dividends are subtracted from the cash flow calculation described above. Second, building from the investor scenario, those investors are presumed to provide 40% of the initial capital required, thus the remaining funds are to be acquired via loan. The interest rate of the loan is assumed to be 10%, with payments amortized over the period of 15 years. Amortized loan payments are presumed to be part of operating costs for the facility, thus impacting the net profit. The payback period is determined as a ratio of the investor equity to annual cash flow.

A Seven-column Table is built to determine the effect of ethanol and corn prices on the return on investment (ROI) performance of the QQ ethanol plant. The method to build a Seven-column Table and to calculate the ROI can be found in Ting (1998). The ROI is calculated over the lifetime of the QQ ethanol plant. For this sensitivity analysis, corn prices are ranged from \$0.12 to \$0.21/kg with a step of \$0.03/kg, while ethanol prices are between \$0.35 and \$0.6/liter with a step of \$0.05/kg. Based on the corn and ethanol prices, the corresponding ROI performance is predicted.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 MATERIAL ANALYSIS

5.1.1 Mass Balance Analysis

Dry matter yields are preferred in the mass-balance analysis in ethanol production, because they do not change with the different amount of water used by different process designs. In the QQ process, corn is the primary feedstock input. Urea is fed into the process at the rate of 0.3% (wet basis) of corn input to provide nitrogen for yeast propagation. The quantity of enzyme and yeast are not traced in this mass-balance analysis due to their limited input rates. Ethanol, CO_2, germ, fiber, and DDGS are the major outputs in the QQ process. Among them, CO_2 is the only anhydrous product. Germ, fiber, and DDGS are produced at 10% moisture content, while anhydrous ethanol is mixed with 2% denaturant to meet fuel ethanol requirements. However, the dry weights of those products are used in the dry matter analysis. The results of the dry matter analyses are converted to pounds per bushel (lb/bu) as illustrated in Figure 5.1.

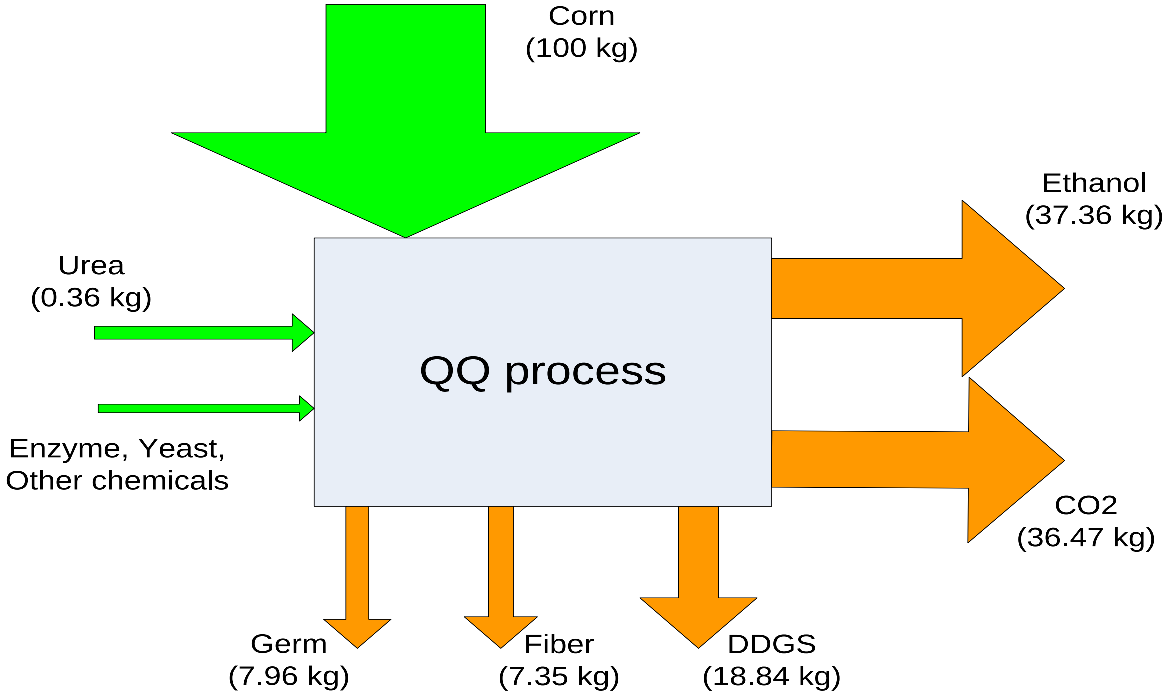

Figure 5.1. The breakdown of Input-Output mass balance in the QQ process.

Regarding the dry matter input, 100 kg of corn dry matter is fed into the process with 0.36 kgof urea. The total output of the QQ process is produced at the rate of107.98 kg per 100 kg corn dry matter input. The difference between the input and output dry matter is due to saccharification where some process water is reacted with starch to produce glucose. Approximately 7.49 kg of process water are required for the saccharification unit operation for 100 kg corn dry matter input.

Ethanol and CO_2 are two major products, each accounting for approximately one third of the total output. The remaining third of the dry matter makes up the coproducts, such as germ, fiber, and DDGS. Among these products, ethanol yield rate is the most important factor for an ethanol facility. Ethanol is produced at a rate of 0.405 liter/kg (37.36 kg ethanol per 100 kg corn dry matter input) in the QQ process.

Comparing the dry grind and the QQ processes, the results showed that the conventional dry grind process achieves a higher ethanol yield at a rate of 0.414 liter/kg (2.78 gal/bu), compared to 0.405 liter/kg (2.72 gal/bu) for the QQ process. The lower ethanol yield rate in the QQ process is due to starch losses in the germ and fiber recovery process.

5.1.2 Coproduct Composition Analysis

Germ, fiber, and DDGS are the three major coproducts in the QQ process that can be marketed and offset operating costs. As these products are used for food processing or animal feed, their values are largely dependent on their nutritional compositions.

Germ and fiber are recovered by the two-stage hydrocyclones after the first grind. The purity of germ and fiber is controlled by the overflow ratio of the first hydrocyclone. Based on the ratio set in this model, approximately 95% of pericarp fiber and 90% of germ are separated from the corn slurry. After dewatering to 50% moisture content in the press, the lighter germ fraction is separated from the heavier fiber fraction in a fluid bed dryer by density difference. Both germ and fiber fraction are dried to 10% moisture content. The germ fraction contains 43% oil (db) and can be further used for oil extraction, whereas the fiber fraction is composed of 70% NDF (db). In addition, a small amount of starch and sugars attached to the germ and pericarp is also recovered. Specifically, starch accounts for 8% of germ fraction and 10% of fiber fraction, respectively. After germ and fiber recovery, all nonfermantable materials and some unconverted starch and sugar remain in DDGS. Detailed compositions of germ, fiber, and DDGS streams are shown in Table 5.1.

Table 5.1. The composition of coproducts in the QQ process.

	Germ	**Fiber**	**DDGS**
Oil	43.13%	8.89%	0.56%
Protein	15.44%	8.62%	45.89%
NDF	28.71%	69.96%	17.06%
Starch	7.58%	10.02%	7.41%
Sugar	2.41%	0.87%	20.33%
Ash	2.56%	1.19%	4.28%
Other	0.18%	0.46%	4.48%

Because of the germ and pericarp recovery at the front end, the oil and fiber content of DDGS are reduced in the QQ process, improving the quality of DDGS. The NDF content of DDGS is reduced to 17%, whereas the protein content is increased to 46% (Table 5.1).

Figure 5.2 illustrates the composition comparison of DDGS produced between the conventional dry grind and the QQ process. Due to the germ and fiber pre-fractionation, the QQ process produces DDGS with higher protein and lower fiber content, and thus making it a potentially amenable feed for non-ruminant animals. The expanding market of the improved DDGS would potentially alleviate concerns of the "food versus fuel" debate by the public. In addition, the improved nutritional characteristic of DDGS demands a premium price, thus further improving the economics of the ethanol facility.

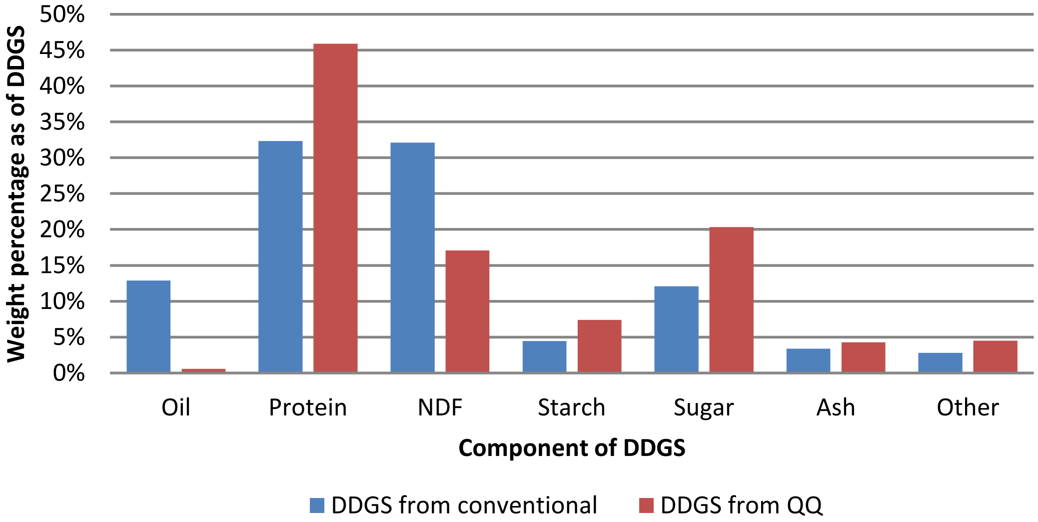

Figure 5.2. Comparison of the composition of DDGS in the two dry grind processes.

5.1.3 Verification of Product Yield and Composition

Model verification is an essential part of the model development process to facilitate acceptance and reliable support decision making. Verification is done to ensure whether the model is programmed correctly and that mistakes have not been made in implementing the model.

Considerable experiments of the QQ process have been conducted in the laboratory scale, aimed to quantitatively measure the dry matters yields and the compositions of each coproduct (Li et al., 2010). As no ethanol facility has adopted the QQ process yet, those experimental results were used to verify the QQ process simulation model.

Figure 5.3 shows that dry matter yields by the QQ process simulation model is only 0.03 lb/bu less than the experimental data, which is equivalent of 0.06% difference. Moreover, the yield of each product in the simulation model is consistent with the experimental data and has less than a 1% difference.

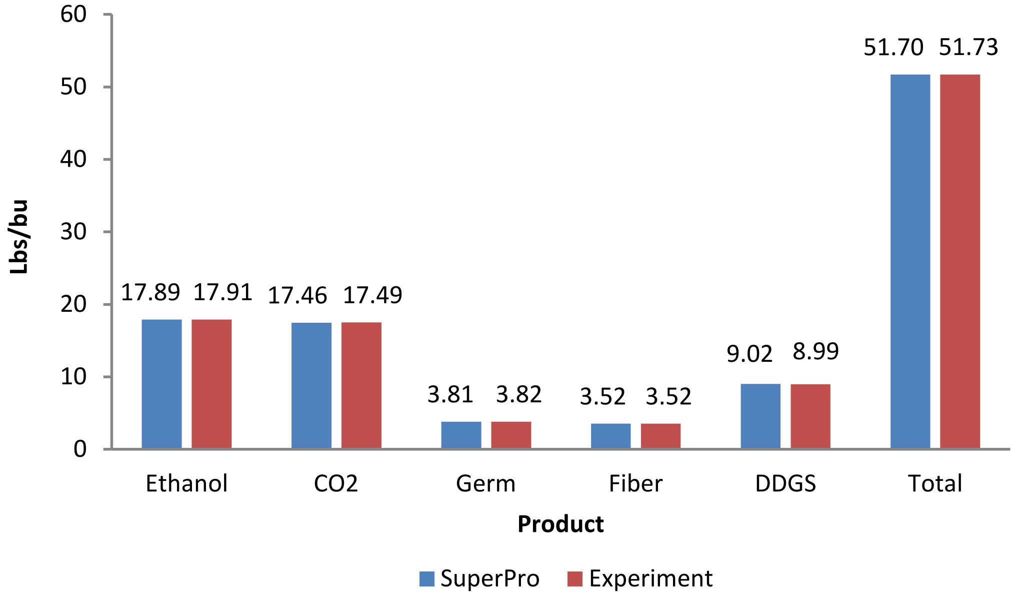

Figure 5.3. Verification of dry matter yields.

The compositions of each coproduct, such as corn germ, corn fiber, and DDGS, are also compared and shown in Figure 5.4. The results further verify that the QQ process model simulates well the experimental data.

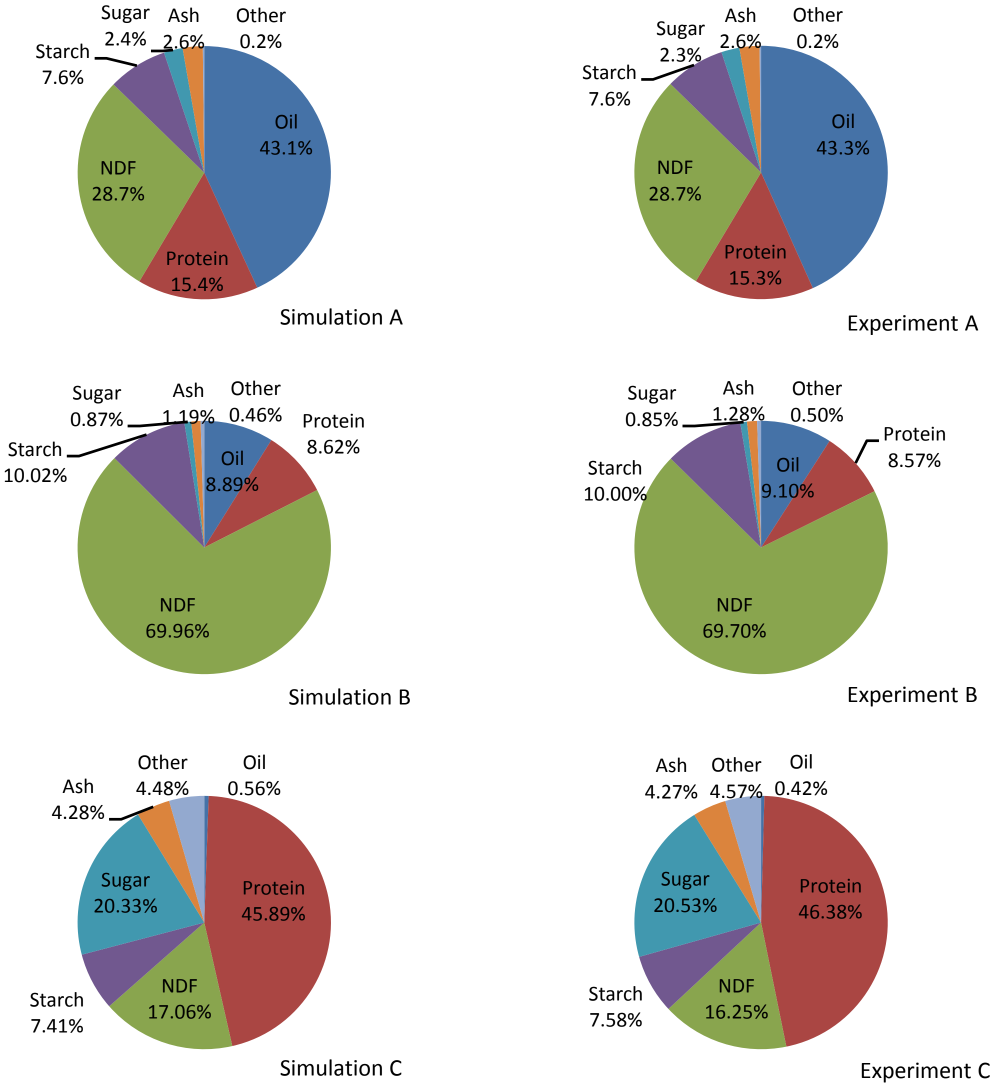

Figure 5.4. Verification of composition of each coproduct (A, B, and C represent germ, fiber, and DDGS, respectively).

5.2 ENERGY DEMAND

5.2.1 Energy Demand in the QQ Process

Based on the simulation model, the QQ process utilizes 8.7 MJ of energy to produce each liter of anhydrous ethanol (31,342 BTU/gal) (Figure 5.5). Steam is the largest energy source in the process, accounting for more than half of the total energy demand. A significant amount of steam is used to provide heat in distillation and liquefaction unit operations. Natural gas is the second largest energy source used to dry the coproducts including germ, fiber, and DDGS, which accounts for approximately 3.6 MJ per liter of ethanol (MJ/liter) (12,880 BTU/gal).

Approximately 0.17 kWh/liter (2,100 BTU/gal) of electricity are required to run pumps, motors, and certain unit operations such as molecular sieve and dewatering press.

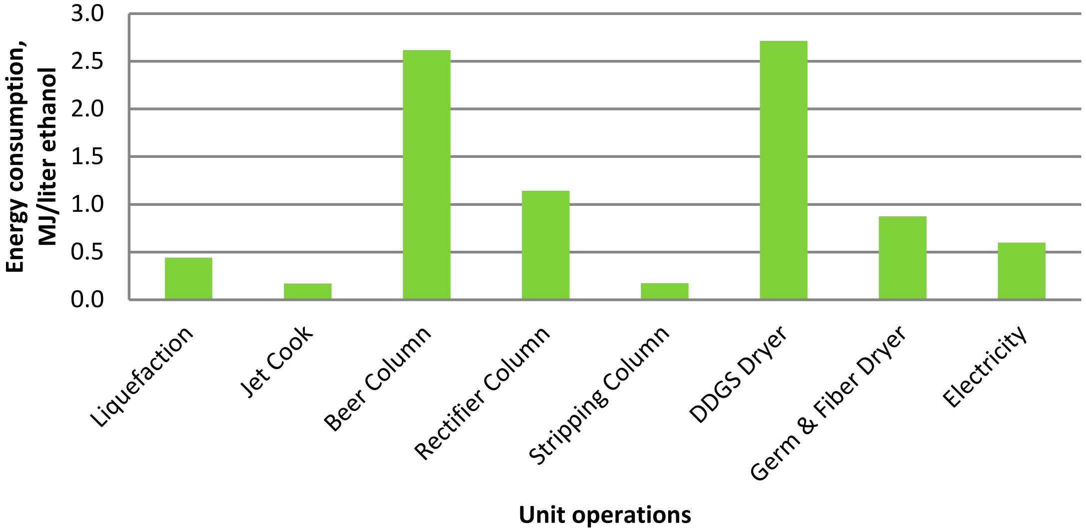

Figure 5.5. The energy consumption in the QQ process.

The distillation system that is composed of three distillation columns dominates the steam usage in the QQ ethanol process, whereas a small fraction of steam is used for liquefaction and the jet cooker. The beer distillation column is the single largest energy consumptive operation unit, where steam is used to separate the ethanol from the beer to 60% concentration. Since the whole stillage is removed from the bottom of the beer column, the inlet stream of the rectifier column has lower volume but higher ethanol concentration, relative to the inlet stream of the beer column. Therefore, the steam consumption of the rectifier column is much lower compared to that of the beer column. A small portion of steam is utilized in the stripping column to minimize the ethanol loss by recycling its upstream into the rectifier column.

Dryers, directly powered by natural gas, are the second largest energy intensive sectors in the QQ process. Both DDGS as well as germ and fiber dryers are utilized to dry the products to 10% moisture content. The natural gas demand of the DDGS dryer is three times that of the germ and fiber dryer, whereas the loading rate of the DDGS dryer is only twice of that of the germ and fiber dryer. The higher unit energy demand of the DDGS dryer results from the higher moisture content of its loading stream. The moisture content of the DDGS dryer loading stream is approximately 70%, whereas that of the germ and fiber stream is reduced to 50% via passing the dewatering press before loading to the dryer. The dewatering press, powered by electricity, utilizes mechanical force to remove water. Without the phase change of water, the dewatering press is more energy efficient to remove water than natural gas drying. However, the dewatering press can dry to no less than 50% moisture content due to the limitation of mechanical press.

5.2.2 Energy Demand Comparison between the QQ and the Conventional Process

The results demonstrated that the QQ process gains a 31.6% energy reduction, including electricity consumption, relative to the conventional dry grind ethanol process, reducing from 11.7 MJ/liter (42,081BTU/gal) to 8.7 MJ/liter (31,342 BTU/gal) (Figure 5.6). As the QQ process runs more unit operations, it requires higher electricity demand than the conventional dry grind process. However, because the total electricity demand in the QQ process does not account for a large portion of the total energy demand, the significant steam savings in the QQ process offset its higher electricity demand, reducing the total energy demand for the QQ process.

The energy savings in the beer column is the biggest contributor to the energy reduction. The QQ process reduces its steam requirement to 2.6 MJ/liter (9,391 BTU/gal), compared with 4.6 MJ/liter (16,433 BTU/gal) in the conventional dry grind process. This significant energy saving in the beer distillation column results from its higher ethanol concentration of the inlet stream in the QQ process. Due to the germ and fiber recovery at the front end, the ethanol concentration of the inlet stream of the beer column is improved to 15% (w/w) from 10.9% (w/w) in the conventional dry grind process (Table 5.2).

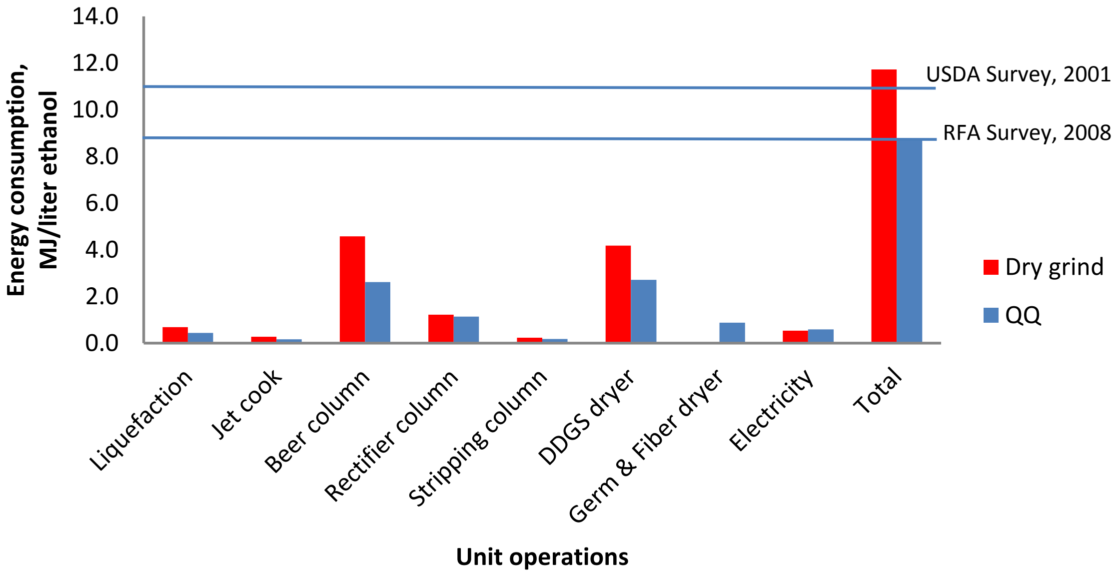

Figure 5.6. The energy consumption comparison of two dry grind processes.

As the same ethanol recovery rate is applied to both processes, the QQ process results in a higher ethanol concentration after passing the beer column. However, due to the lower loading rate (Table 5.2), the energy savings in the rectifier and stripping columns are not so significant compared to those achieved in the beer column.

Table 5.2. Operating information in the distillation system.

Process Step	QQ	Conventional Dry Grind
Beer column inlet		
-Ethanol concentration	15%	10.9%
-Loading rate (kg/h)	118,926	138,899
Rectifier column inlet		
-Ethanol concentration	59.5%	51.4%
-loading rate (kg/h)	35,865	35,335
Stripper column inlet		
-Ethanol concentration	0.9%	0.6%
-Loading rate (kg/h)	12,992	15,327

In addition, due to the germ and fiber recovery at the front end of the QQ process, no heating energy is required to heat those materials during the liquefaction and jet cooker unit operation. Based on the simulation results, approximately 0.4 MJ/liter (1,300 BTU/gal) of energy savings can be achieved by the QQ process without heating the germ and fiber fractions.

The QQ process demands less energy for the DDGS dryer, which corresponds to its lower loading rate of DDGS stream. This lower loading rate is due to the germ and fiber recovery at the front end of the QQ process. Those recovered germ and fiber streams are also required to be dried to 10% moisture content, the same as that of DDGS. However, the use of the dewatering press in the germ and fiber recovery system reduces the moisture content of the loading stream to the germ and fiber dryer, which reduces the energy demands of the dryers in the QQ process by approximately 0.6 MJ/liter (2,100 BTU/gal) (Figure 5.6).

Compared to the previous studies, the energy demand of the simulated conventional dry grind process is higher than that of both the USDA 2001 survey (Shapouri and Gallagher, 2005) and 2008 RFA industrial survey (Wu, 2008). The lower energy demand by the surveys is because not every ethanol plant provides DDGS as a coproduct. Due to the high cost of drying, some plants produce wet distillers grains with solubles rather than DDGS, which provides significant energy savings.

The energy demand of the simulated QQ process is relatively low compared to the results by Rodriguez et al. (2010), which are 8.7 MJ/ liter (31,342 BTU/gal) and 8.8 MJ/liter (31,782 BTU/gal). The energy demand of the QQ process by the spreadsheet model (Rodriguez et al. 2010) is predicted based on the energy demand of the conventional dry grind process (Shapouri and Gallagher, 2005) and further considered the energy savings in the distillation system due to its higher ethanol concentration relative to the conventional dry grind process. The QQ process simulation model provides a detailed analysis of energy demand in each unit operation, not limiting to the distillation system only.

5.3 WATER DEMAND

Based on the assumptions, the total water demand of the QQ process is 3.49 liter of water per liter of ethanol (liter/liter), excluding the water from corn itself. The fresh process water and cooling water account for 1.06 and 2.43 liter/liter, respectively.

5.3.1 Water Demand in the QQ Process

5.3.1.1 Process Water Consumption

The detailed input-output flowrate of process water is shown in Figure 5.7. There is only one fresh process water input point in the process. The process water is the water directly added to ground corn to make the slurry. To achieve a similar moisture content in the processing stream as in the conventional dry grind process, the process water demand is 1.06 liter/liter in the QQ process. The fresh process water is fed into the CO_2 scrubber tank at the rate of 1.06 liter/liter. After recovering the emitted ethanol in the CO_2 scrubber, this process water is routed back to the soaking tank. In addition, corn is assumed to enter the system with 14.5% moisture content. The water within the corn kernel provides 0.36 liter/liter of water to the system.

As no dryer vapor loss is recaptured in this model, the water vapor lost during the drying coproducts dominates the process water losses, accounting for approximately 1.17 liter/liter. DDGS dryer and germ and fiber dryer account for 0.9 and 0.27 liter/liter water loss, respectively. The higher vapor loss by the DDGS dryer results from the higher flow rate and the higher moisture content of its loading stream. Moreover, the results showed that the vapor losses in the dryers are higher than the fresh process water input requirements. If those vapor losses from the dryers can be condensed and reused as the water input in the process, it would be possible to achieve close to zero fresh water usage for the corn-to-ethanol production, driven only by the water within corn kernel itself. However, the major obstacle lies on how to recapture the vapor loss economically.

Approximately 0.16 liter/liter of process water is required in the saccharification process, providing water to convert starch into glucose. Only a small fraction of process water is lost to the coproduct streams whose moisture content is approximately 10%. Because of its high dehydration efficiency, molecular sieves effectively dry the ethanol to 99.7%. The water left with ethanol is as low as 0.003 liter/liter and is not shown in Figure 5.7.

To minimize the process water usage, ethanol process has several internal approaches to water recovery. For instance, the vapor loss from the thin stillage evaporator is condensed and reused as a source of process water. Although condensing the evaporator vapor loss increases the cooling water demand, it reduces the overall water demand as a result of lower evaporation loss.

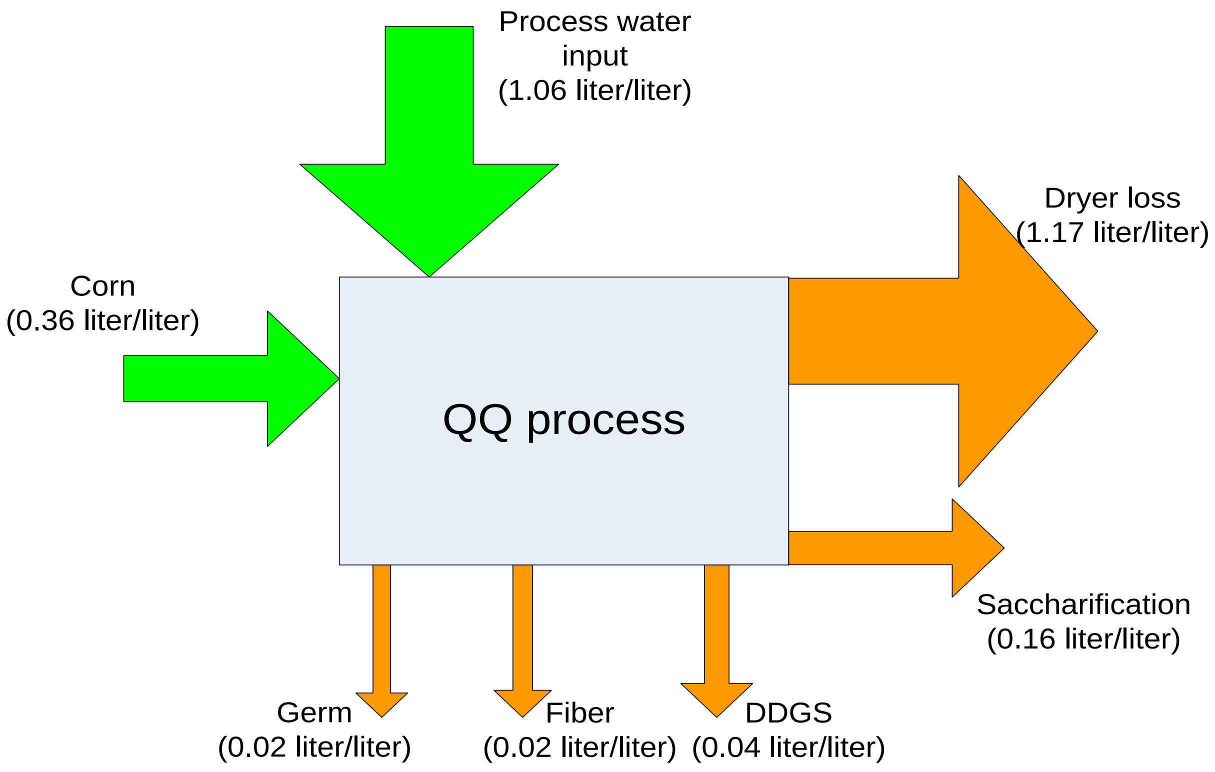

Figure 5.7. The process water input-output in the QQ process in the term of liter of water per liter of ethanol (liter/liter).

5.3.1.2 Cooling Water Consumption

Assuming the makeup rate of 2% of the cooling water recirculation rate, the cooling water usage of the QQ process is 2.44 liter/liter (Figure 5.8). The cooling water demand in the distillation system is most intensive, accounting for 1.43 liter/liter. Cooling water provided in the distillation system helps to return the overhead liquid to the column as reflux liquid in order to achieve more complete separation. The beer column distillation demands the largest cooling water usage, because of its low ethanol concentration as well as its large input volume. As the whole stillage is removed from the bottom of the beer column, the distillate proceeds to the rectifier and stripping column. This stream has a higher ethanol concentration and lower flow rate, and thus it reduces the cooling water demand for distillation.

Approximately 0.45 liter/liter of cooling water is used in the thin stillage evaporator to recapture the vapor loss. The condensed water vapor can be reused as process water, minimizing the process water demand. Due to the release of heat during the reaction in the fermentation tank, 0.41 liter/liter of cooling water is required to maintain the operating temperature constantly at 32 ℃.

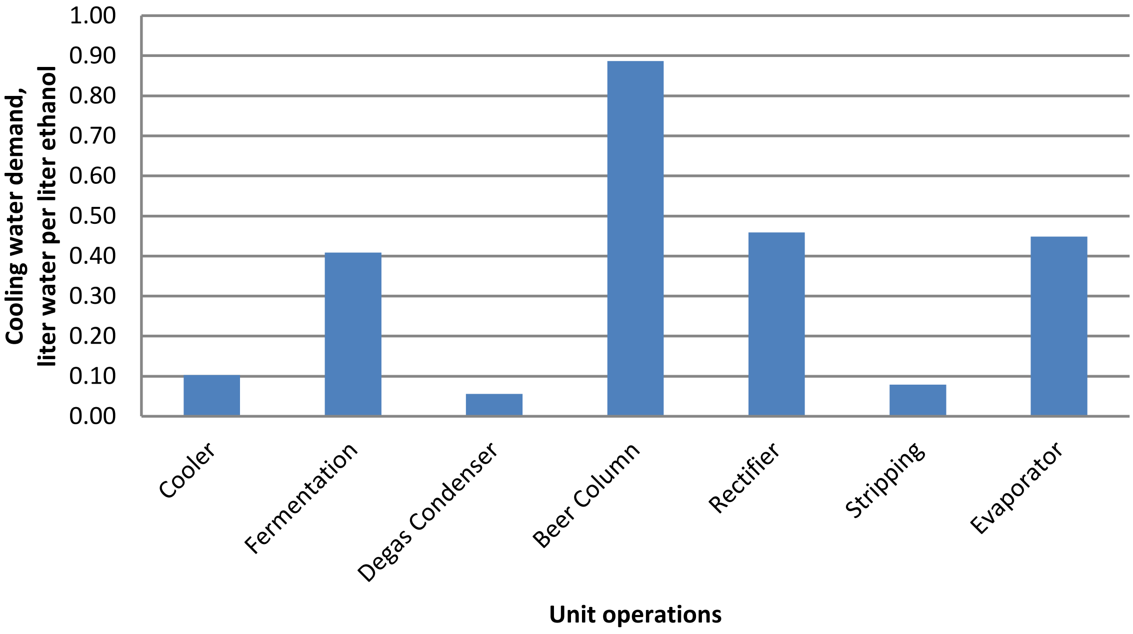

Figure 5.8. The cooling water usage in the QQ process.

5.3.2 Water Demand Comparison between the QQ and the Conventional Process

The results showed that the QQ process provides savings on the total water demand. The total water demand of QQ process is reduced to 3.49 liter/liter from 4.25 liter/liter in the conventional dry grind process. The total water consumption of the conventional dry grind process is predicted at 4.25 liter/liter by the simulation model. Compared with previous studies, this result is higher than 3.45 liter/liter by Wu (2008) based on the RFA industrial survey. The difference is due to the difference of cooling water management, especially the cooling water recirculation rate, among various ethanol plants as well as the water recycle system design.The QQ process does not require higher process water input rate relative to corn input into the process. 0.43 kg process water per kg of corn is required. The reason is that the water used for the germ and fiber washing in the QQ process are recycled and reused for the following unit operations. However, because of its lower ethanol yield, the process water demand of the QQ process is a little higher than that of the conventional dry grind process relative to ethanol produced, 1.06 versus 1.04 liter/liter, respectively.

The cooling water demand of QQ process has been reduced to 2.43 liter/liter, compared with 3.21 liter/liter in the conventional dry grind process (Figure 5.9). The savings of cooling water used for evaporator vapor recapture as well as distillation are the major contributors for the cooling water reduction in the QQ process.

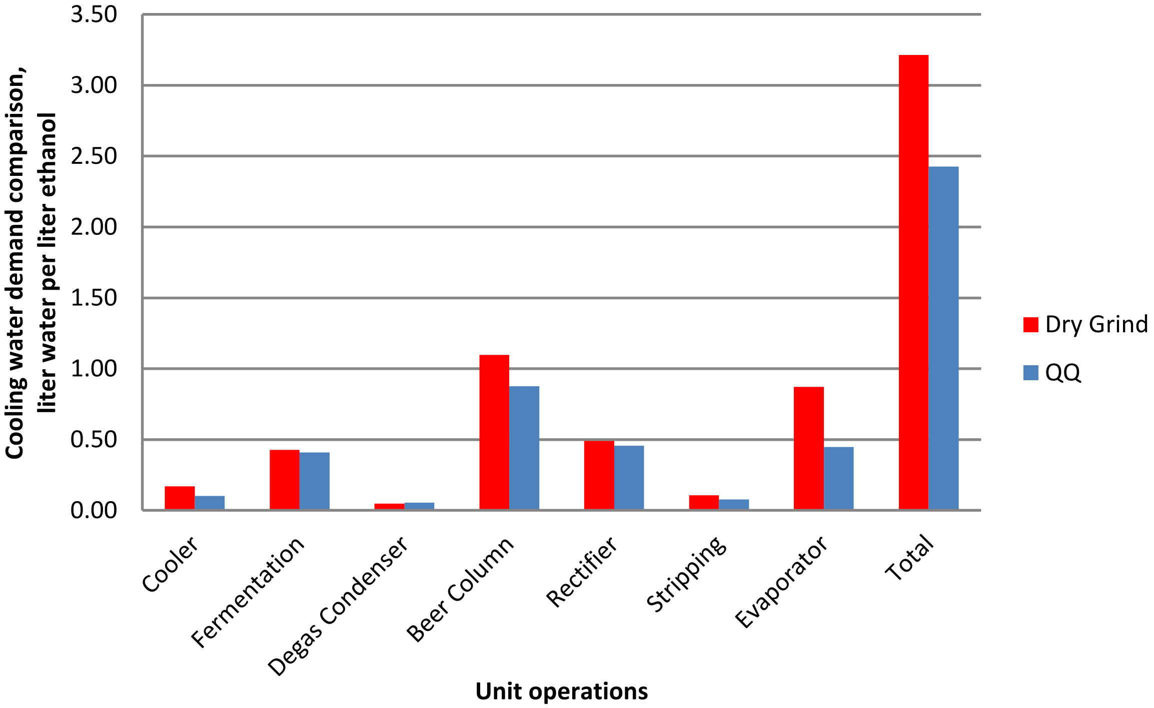

Figure 5.9. The cooling water demand comparison.

Due to the germ and fiber recovery at the front end, the amount of thin stillage loading to the evaporator in the QQ process is considerably lower than that in the conventional dry grind process. Because the cooling water demand is proportional to the vapor loss rate, the lower loading rate of evaporator in the QQ process results in a lower vapor loss. This leads to a lower cooling water demand for vapor recapture. Approximately 0.42 liter/liter savings have been achieved in the QQ process.

As germ and fiber are nonfermentable materials, the recovery of germ and fiber at the front end improves the ethanol concentration after fermentation. The higher ethanol concentration would facilitate the ethanol and water separation in the distillation system. Approximately 0.22 liter/liter of cooling water savings has been achieved in the beer column of the QQ process. Due to its lower loading rate, however, the savings in the rectifier column is lower than that in the beer column. However, the stripping column has similar cooling water demands in both processes.

To facilitate yeast propagation, a cooler is set to cool the mash down to 30˚C before feeding into the fermentation tank. The separation of germ and fiber at the front end reduces the amount of materials processed in the cooler before fermentation, thus providing 0.07 liter/liter savings of cooling water in the QQ process.

5.4 ECONOMIC ANALYSIS

5.4.1 Economic Performance in the QQ Process

5.4.1.1 Capital Investment Costs

The capital investment costs of this QQ facility have been developed from the purchased equipment costs and the details are given in Table 5.3. The total purchased equipment costs for this 189.25 million liter (50 million gallon) ethanol facility are $24.13 million. Based on the factors assumed for capital investment cost estimation, the fixed capital costs are estimated at $77.22 million. The total investment capital costs are $96.18 million including working and start-up capital cost, which is equivalent as $0.50 per liter of ethanol ($1.88 per gallon of ethanol).

Table 5.3. Total capital investment costs.

Section	US$ Million	$/liter	$/gal
Purchased equipment	24.13	0.12	0.47
Purchased equipment installation	9.65	0.05	0.19
Piping	7.24	0.04	0.14
Instrumentation and control	2.41	0.01	0.05
Electrical equipment and material	3.62	0.02	0.07
Total onsite costs	47.06	0.24	0.92
Building	9.65	0.05	0.19
Yard improvement	3.62	0.02	0.07
Total offsite costs	13.27	0.07	0.26
Total direct costs	60.33	0.31	1.18
Engineering	6.03	0.03	0.12
Construction	10.86	0.06	0.21
Total indirect costs	16.89	0.09	0.33
Fixed capital costs	77.22	0.40	1.51
Working capital costs	11.24	0.06	0.22
Startup capital costs	7.72	0.04	0.15
Total capital investment costs	96.18	0.50	1.88

5.4.1.2 Operating Costs

The annual operating costs are composed of the raw material costs, labor dependent costs, facility dependent costs, utility costs, and depreciation. As the QQ plant is assumed to be constructed without any external loans, no amortized payment is currently included in the operating cost. Based on the data used in this model, the annual operating costs of this ethanol facility are approximately $103.94 million (Table 5.4). Unit operating costs are calculated by prorating the total annual operating costs over the total annual ethanol production. Thus, the unit operating cost is approximately $0.54 per liter of ethanol ($2.03 per gallon of ethanol).

Table 5.4. Operating costs of the QQ process.

Cost Item	US$ Million/yr	%	$/liter	$/gal
Raw materials	81.16	78.09	0.42	1.59
Labor-dependent	2.10	2.02	0.01	0.04
Facility-dependent	3.51	3.38	0.02	0.07
Utilities	9.44	9.08	0.05	0.18
Depreciation	7.72	7.43	0.04	0.15
Total	103.94	100.00	0.54	2.03

The raw material costs are the primary costs of ethanol production, accounting for approximately 78% of total operating costs. Among those raw material costs, corn costs have the greatest impact on the raw material costs and require approximately $77 million each year. The costs of denaturant and enzymes are other major raw material costs in the QQ process. A breakdown of raw material cost is shown in Table 5.5.

Table 5.5. Raw material costs of the QQ process.

Raw Material Item	$/yr	%
Corn	77,083,924	94.98
Alpha-Amylase	725,760	0.89
Glucoamylase	1,064,070	1.31
Succinic acid	85,556	0.11
Yeast	234,360	0.29
Water	70,225	0.09
Urea	445,623	0.55
Denaturant	1,451,171	1.79
Total	81,160,689	100.00

The utility costs are the second major operating costs in the QQ process, consisting of natural gas, steam, electricity, and cooling water costs. The utility demand is calculated based on the operational requirement of the process. A breakdown of the utility costs of the QQ process is given in Figure 5.10. Steam costs make up the largest utility cost, accounting for 45% of total utility costs. Due to the low unit cost of the cooling water, the cooling water cost only accounts for 2% of the total utility cost.

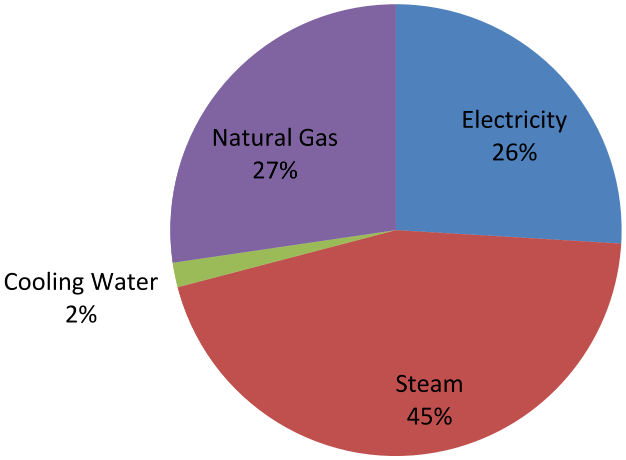

Figure 5.10. Utility costs of the QQ process as of April 2009.

5.4.1.3 Profitability Analysis

Ethanol, DDGS, fiber, and germ are four marketable products produced in the QQ process. Assuming the selling prices of these products are as of market prices in April 2009 and remain constant throughout a year, this QQ ethanol facility would gain $115.6 million annually in revenue (Table 5.6). The QQ plant would earn $0.6 for each liter of ethanol produced. Ethanol is the most important product in the QQ process, accounting for more than 76% of the total revenue. Although the yield rate of DDGS is more than twice of that of germ fraction, the unit revenue rate of germ is higher. For each liter ethanol production, the germ fraction generates $0.07 revenue as compared to $0.06 by DDGS. As corn oil is a valuable commodity in the market, the high corn oil content in the germ fraction (43.4%) makes germ a valuable product in the QQ process.

Table 5.6. Annual revenues of the QQ process, given market prices as of April 2009.

Revenue Item	US$ Million/yr	%	$/liter	$/gal
Ethanol	87.96	76.06	0.45	1.72
DDGS	11.81	10.21	0.06	0.23
Fiber	2.73	2.36	0.01	0.05
Germ	13.14	11.37	0.07	0.26
Total	115.64	100	0.60	2.26

Given a 189.25 million liter (50 million gallon) annual production, the gross profit of this QQ facility would be approximately $11.7 million. In other words, this QQ facility gains $0.06 by producing each liter of ethanol. Assuming no shareholder dividend costs, the annual cash flow is $14.74 million. The payback period of this QQ facility is approximately 6.5 years (Table 5.7).

Table 5.7. Economic performance of the QQ plant, given input costs as of April 2009.

	US$ Million/yr	$/liter	$/gal
Capital investment costs	96.18	0.50	1.88
Operating costs	103.94	0.54	2.03
Revenues	115.64	0.60	2.26
Taxable income	11.70	0.06	0.23
Taxes (40%)	4.68	0.02	0.09
Depreciation	7.72	0.04	0.15
Annual cash flow	14.74	0.08	0.29
Payback period		6.52 years	

5.4.2 ECONOMIC PERFORMANCE COMPARISON

5.4.2.1 Baseline Analysis

An economic performance comparison between the conventional dry grind plant and the QQ plant is given in Table 5.8. The comparison showed that the QQ plant required total capital investment costs of $96.2 million, which is 26% higher than that of the conventional dry grind plant. The higher capital investment costs for the QQ plant are due to the added germ and fiber recovery system.

The annual raw materials costs for the QQ plant are 20% higher than that for the conventional dry grind plant, corresponding to the increased processing capacity. However, due to its lower ethanol yield rate, the QQ plant increases its unit raw material cost by 2.2%. The difference of unit raw material cost also corresponds the ethanol yield difference, which are 0.405 liter/kg (2.72 gal/bu) and 0.414 liter/kg (2.78 gal/bu) for the QQ and conventional dry grind process, respectively.

Despite its increased processing capacity, the QQ plant demands less annual utility costs than the conventional dry grind plant. Although the QQ process requires more electricity to power additional equipment, it provides significant savings in steam demand in distillation due to the front end germ and fiber recovery. The QQ plant reduces utility costs for each gallon of ethanol production by 20.35%, which corresponds to findings in the energy demand analysis.

The QQ plant demands higher annual operation cost due to its increased processing capacity. However, the unit operation costs for these two plants are comparable, both of which are approximately 53.6 ¢/liter (203 ¢/gal). This is due to the significant utility savings of the QQ plant, which offsets its higher depreciation and raw material costs.

The coproducts provide a significant revenue boost for the QQ plant as compared to the conventional dry grind plant. DDGS is the only coproduct in the conventional plant, whereas germ, fiber, and DDGS are three coproducts produced in the QQ plant. Although the revenue of DDGS in the QQ plant is reduced because of the prefraction process, more value-added coproducts, such as germ and fiber, are produced. These factors taken together with the increased ethanol production lead the total revenue of the QQ plant to increase by almost $23 million.

Table 5.8. Economic comparison of a conventional dry grind plant and a QQ plant.

	Conventional Dry-grind Plant			QQ Plant		
	$1,000/yr	**¢/liter**	**¢/gal**	**$1,000/yr**	**¢/liter**	**¢/gal**
Fixed Capital Costs	60,283	36.52	138.23	77,222	39.89	150.97
Capital Investment	76,443	46.31	175.29	96,182	49.68	188.04
Raw materials:						
Corn	64,226	38.91	147.28	77,084	39.82	150.70
Enzymes	1,500	0.91	3.44	1,790	0.92	3.50
Yeasts	190	0.12	0.44	234	0.12	0.46
Other chemicals	474	0.29	1.09	532	0.27	1.04
Process water	63	0.04	0.14	70	0.04	0.14
Denaturant	1,237	0.75	2.84	1,451	0.75	2.84
Subtotal	**67,690**	**41.01**	**155.22**	**81,161**	**41.92**	**158.67**
Utilities:						
Electricity	1,989	1.21	4.56	2,450	1.27	4.79
Natural gas	2,555	1.55	5.86	2,579	1.33	5.04
Steam	5,521	3.34	12.66	4,247	2.19	8.30
Cooling water	181	0.11	0.42	166	0.09	0.32
Subtotal	**10,246**	**6.21**	**23.49**	**9,442**	**4.88**	**18.46**
Labor dependent	2,059	1.25	4.72	2,099	1.08	4.10
Facility dependent	2,743	1.66	6.29	3,514	1.82	6.87
Depreciation	6,028	3.65	13.82	7,722	3.99	15.10
Operating Costs	**88,767**	**53.78**	**203.55**	**103,938**	**53.69**	**203.20**
Products:						
Ethanol	74,991	45.43	171.96	87,956	45.43	171.96
DDGS	17,632	10.68	40.43	11,809	6.10	23.09
Corn germ	-		-	13,141	6.79	25.69
Corn fiber	-		-	2,732	1.41	5.34
Revenues	**92,623**	**56.11**	**212.39**	**115,638**	**59.73**	**226.07**
Gross Profit (A)	3,856	2.34	8.84	11,700	6.04	22.87
Taxes (40%) (B)	1,543	0.93	3.54	4,680	2.42	9.15
Depreciation (C)	6,028	3.65	13.82	7,722	3.99	15.10
Annual Cash Flow (A-B+C)	**8,341**	**5.05**	**19.13**	**14,742**	**7.61**	**28.82**
Payback Period (Years)		**9.16**			**6.52**	

Assuming no external loans are required for both ethanol plants, the QQ plant achieves the higher annual cash flow. Despite its higher capital investment cost, the payback period of the QQ plant is reduced to 6.5 years, compared to 9.2 years for the conventional dry grind plant. Increased processing capacity, more value-added coproducts, and lower unit utility costs are three major factors to improve the economic performance of the QQ plant, despite the fact that there is a lower ethanol yield rate.

The prefractionation process reduces the fiber content of DDGS, making it possible as the nonruminant feed. The increased nutritional quality of DDGS might demand premium prices, as considered by Li et al., 2010 and Rodriguez et al., 2010, and potentially improve the revenues of the QQ plant. However, this factor is not considered in the preceding economic analyses, thus these analyses should be considered conservative.

5.4.2.2 Scenario Analysis

Table 5.9 outlines the results from two additional economic scenarios beyond the baseline considered. These results suggest that the QQ facility will fare considerably better in both scenarios. Cash flow is reduced when investor dividends must be paid with amortized loan payments. Especially cash flow is negative for a wholly investor owned dry grind facility. The impact of seeking outside funding is particularly attractive in the case of the QQ facility, where the payback period is competitive with the baseline case—6.9 years as compared to 6.52.

Table 5.9. Economic comparison of the dry grind and the QQ plants under with investor ownership and loan requirements.

Scenario	**12% dividends**				**12% dividends + 40% equity**			
	Dry grind		QQ		Dry grind		QQ	
	$1,000/yr	¢/liter	$1,000/yr	¢/liter	$1,000/yr	¢/liter	$1,000/yr	¢/liter
Capital investment costs	76,443	46.31	96,182	49.68	76,443	46.31	96,182	49.68
Equity	76,443	46.31	96,182	49.68	30,577	18.52	38,473	19.87
Principle	-	-	-	-	45,866	27.79	57,709	29.81
Amortized payments	-	-	-	-	6,030	3.65	7,587	3.92
Operating costs	88,767	53.78	103,938	53.69	94,797	57.43	111,525	57.60
Revenues	92,623	56.11	115,638	59.73	92,623	56.11	115,638	59.73
Gross profit (A)	3,856	2.34	11,700	6.04	-2,174	-1.32	4,113	2.12
Taxes (40%) (B)	1,543	0.94	4,680	2.42	-	-	1.645	0.85
Depreciation (C)	6,028	3.65	7,722	3.99	6,028	3.65	7,722	3.99
Dividends (D)	9,173	5.56	11,542	5.96	3,669	2.22	4,617	2.38
Annual cash flow (A-B+C-D)	-832	-0.50	3,200	1.65	185	0.11	5,573	2.88
Payback period (Years)	-		30.06		165.65		6.90	

5.4.2.3 Sensitivity Analysis

Figure 5.11 shows the effect of corn and ethanol prices on the return on investment (ROI) performance over the lifetime of the QQ ethanol plant. The results show that the QQ ethanol plant can achieve higher ROI when ethanol prices are high and corn prices are low. A ROI of 64.05% is predicted when corn prices are $0.12/kg and ethanol prices are $0.6/liter. When corn prices are $0.21/kg, the QQ ethanol plant can achieve a positive ROI over the lifetime only when ethanol prices are over $0.55/liter.

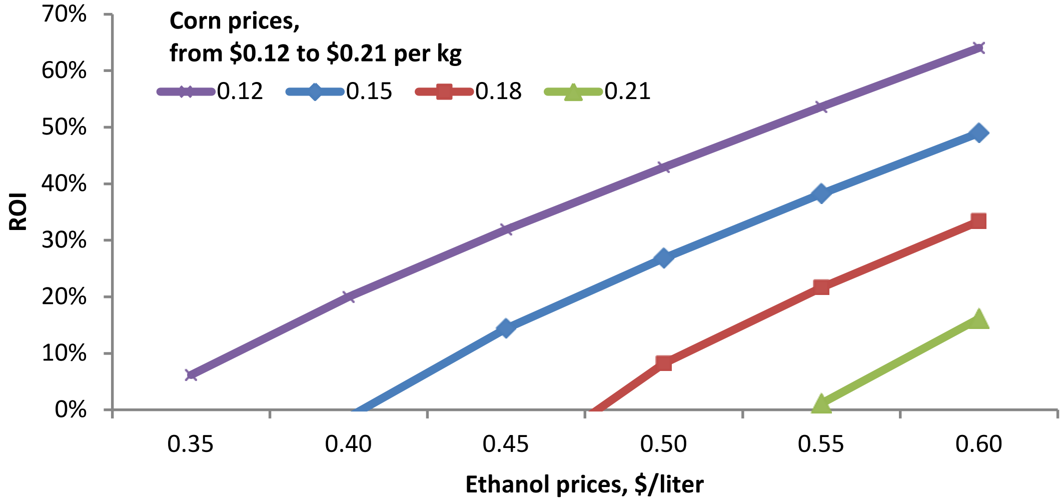

Figure 5.11. Effect of corn and ethanol prices on the ROI of the QQ ethanol plant.

CHAPTER 6: CONCLUSION

A process and cost model was developed for simulating an ethanol facility, with a capacity to process 1.3 million kg per day of corn, using the QQ process. This model was used as a tool to identify and compare energy consumption, water demand, and economic performance of the conventional dry grind and the QQ processes. The result shows that the germ and fiber recovery at the front end improves the processing capacity of a conventional dry grind ethanol facility by approximately 24%.

Our comparison shows that despite the fact that more electricity is required to power additional equipment in the QQ process, significant savings of steam demand by distillation and liquefaction steps reduce the total energy consumption by more than 32%. The energy savings are achieved by a higher ethanol concentration emerging from the distillation system and the reduced heating demand in liquefaction process due to germ and fiber removal at the front end.

The total water demands in the QQ process are 3.49 liter of water per liter of ethanol (liter/liter), compared to 4.25 liter/liter in the conventional dry grind process. Process water and cooling water are two parts of the water demands in the QQ process, which are 1.06 liter/liter and 2.43 liter/liter, respectively. Although the QQ process incorporates the wet milling front end, the water recycle loop permits the process water demands to be similar to the conventional dry grind process. The significant savings of cooling water demands result from the higher ethanol concentration after fermentation in the QQ process.

The QQ process produces more value-added coproducts, such as corn germ, corn fiber, and DDGS, but has a lower ethanol yield rate at 0.405 liter/kg (2.72 gal/bu), as compared to 0.414 liter/kg (2.78 gal/bu) in the conventional dry grind process. The lower ethanol yield in the QQ process is due to starch losses during germ and fiber recovery at the front end. However, the fiber recovery at the front end reduces the fiber content of DDGS, expanding its use as a non-ruminant feed. The oil-rich germ fraction can be further processed by corn oil extraction. These value-added coproducts provide a viable and flexible source of feed, alleviating “food versus fuel” concerns generated by the increased corn-to-ethanol production.

In addition, a detailed cost and benefit analysis of the QQ process is also provided, based on the market prices as observed in April 2009. The result shows that despite its higher capital investment cost, the QQ process reduces the payback period to 6.5 years, compared to 9.2 years for the conventional dry grind process. Increased ethanol production, more value-added coproducts, as well as significant reduced utility costs are three major contributors improving the economic performance of the QQ process.

To summarize, the reduced energy and water demand and the improved economic performance suggest that the QQ process provides a more sustainable technology than the conventional dry grind process. This work lays the foundation for the similar studies on the sustainability performance of other modified dry grind ethanol processes. This simulation technology can be used as a tool to provide decision support for the selection of sustainable biofuel production technology.

CHAPTER 7: FUTURE WORK

Previous research demonstrated that the design of process integration is critical to the energy and water consumption in the ethanol production. Our central hypothesis has been that fractionation technologies will have an impact on the water usage as well as the energy consumption. We propose the following specific aims:

Specific Aim #1: Design heat exchanger networks in the corn-to-ethanol process via pinch analysis. Our working hypothesis is that heat exchanger networks can improve the efficiency of energy use and water conservation.

Specific Aim #2: Determine the impact of the corn quality and variety on the energy, water and economic performance of an ethanol plant. Our working hypothesis is that the composition of corn has an effect on the ethanol yield efficiency as well as the quality of coproducts.

Specific Aim #3: Identify strategies to dynamically control and optimize the conversion process for energy consumption and water utilization. Our working hypothesis is that a better understanding of the processing stream properties and technology impacts can provide the needed insight into managing water and energy consumption in the facility.

It is our expectation that the interrelationships between energy, water, and economics will be limiting factors in future. We anticipate that novel fractionation technology will reduce the energy and water consumption, and further enhance economics of dry grind ethanol production. These studies are innovative in their focus on the energy and water consumption in the corn-to-ethanol processes with various technologies. The proposed work can provide a transformative approach for process optimization leading towards environmental sustainability and economic viability in the corn-to-ethanol process. In addition, this approach will serve as a baseline for future process optimization, not the least of which includes future expansion to other bioenergy feedstocks and an energy independent future for the United States.

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