

**ECONOMIC AND TECHNICAL
ANALYSIS OF ETHANOL DRY
MILLING:
MODEL DESCRIPTION**

by

Rhys T. Dale and Wallace E. Tyner

Staff Paper # 06-04

April 2006

Agricultural Economics Department

Purdue University

Purdue University is committed to the policy that all persons shall have equal access to its programs and employment without regard to race, color, creed, religion, national origin, sex, age, marital status, disability, public assistance status, veteran status, or sexual orientation.

ECONOMIC AND TECHNICAL ANALYSIS OF ETHANOL DRY MILLING: MODEL DESCRIPTION

by
Rhys T. Dale
Wallace E. Tyner
Depart. of Agricultural Economics, Purdue University
West Lafayette, IN 47907-1145
wtyner@purdue.edu
Staff Paper # 06-04
April 24, 2006

Abstract

Ethanol, the common name for ethyl alcohol, is fuel grade alcohol that is predominately produced through the fermentation of simple carbohydrates by yeasts. In the United States, the carbohydrate feedstock most commonly used in the commercial production of ethanol is yellow dent corn (YDC). The use of ethanol in combustion engines emits less greenhouse gasses than its petroleum equivalent, and it is widely hoped that the increased substitution of petroleum by ethanol will reduce US dependence on imported oil and decrease greenhouse gas emissions. Production of ethanol within the United States is expected to double, from 3.4 billion gallons in 2004, to about seven billion gallons in the next five years.

Two processes currently being utilized to produce ethanol from YDC are dry milling and wet milling. The wet mill process is more versatile than the dry mill process in that it produces a greater variety of products; starch, corn syrup, ethanol, Splenda, etc., which allows for the wet mill to better react to market conditions. However, the costs of construction and operation of a wet mill are much greater than those of a dry mill. If ethanol is the target product, then it can be produced at a lower cost and more efficiently in a dry mill plant than in a wet mill plant, under current economic conditions. Of the more than 70 US ethanol plants currently in production, only a few are of the wet mill variety.

A descriptive engineering spreadsheet model (DM model) was developed to model the dry mill ethanol production process. This model was created to better understand the economics of the ethanol dry mill production process and how the profitability of dry mill plants is affected under different conditions. It was also developed to determine the economic and environmental costs and benefits of utilizing new and different technologies in the dry mill process. Specifically, this model was constructed to conduct an economic analysis for novel processes of obtaining greater alcohol yields in the dry mill process by conducting a secondary fermentation of sugars converted from lignocellulosics found in the dry mill co-product, distiller's grains. This research is being conducted at Purdue University, Michigan State, Iowa State, USDA, and NCAUR under a grant from the US Department of Energy.

The DM model is more technically precise, and more transparent, than other models of the dry mill process that have been constructed for similar purposes. The Tiffany and Eidman model (TE model) uses broad generalities of the dry mill process, based on the current state of

production, to approximate the sensitivities of the process to changes in variables. The TE model parameters were well researched, but the model suffers from several drawbacks. The main limitations of this model are that the results are very sensitive to the input values chosen by the user. Unlike the DM model, complex manipulations, such as determining the effect of new technologies would require accurate parameter estimates using the TE model. The McAloon model [11].uses highly technical engineering software (ASPEN) that acts essentially as a “black box” in the dry mill production process. This very exact model does not allow for a more general examination of the dry mill process. Changes in the production process would necessitate precise engineering plans.

Similar to the TE and McAloon models, the DM model is a spreadsheet model, but unlike the McAloon model it is completely self-contained. The DM model is a feed backward model, input requirements (corn, enzymes, chemicals, utilities, etc) are calculated based on the user entered values for annual production and process parameters. The mass flow rates, in pounds per hour were then calculated and used in estimating the size, in dimension or power, of each major piece of equipment. The cost associated with each piece of major equipment was then calculated as an exponential function of its corresponding size.

Total capital costs associated with a dry mill plant were then estimated using the percentage of equipment costs method [13]. It was found that the DM model estimates of the total capital costs associated with medium to large dry mill plants (those with the capacity to produce between 10 and 100 million gallons of ethanol a year) were within 5% of total fixed costs estimated by BBI [2]. Operating costs were compared with the 2002 USDA survey results and also found to be very close [15].

A companion document, “Economic and Technical Analysis of Dry Milling: Model User’s Manual,” staff paper no 06-05, explains how the model is used to conduct analysis of dry milling alternatives.

Keywords: Ethanol, DDGS, Dry Milling, Biochemical Process Engineering, Economic Modeling, Financing, Fermentation Process Modeling

Copyright © by Rhys T. Dale and Wallace E. Tyner. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies. This research was funded by the U.S. Department of Energy, DOE Grant #DE-FG36-04G014220.

Table of Contents

Abstract	i
I. Introduction	1
Ethanol as a Transport Fuel	1
Environmental Impacts of Ethanol	2
Governmental Policy Effects	2
II. The Ethanol Production Process	4
Yellow Dent Corn as a Substrate in Ethanol Production	4
Major Ethanol Producing Processes: Wet and Dry Milling	5
Dry Mill Process	6
Grain Handling and Milling	6
Liquefaction and Saccharification	7
Fermentation	8
Separation through Distillation	11
Recovery of Anhydrous from Hydrous Ethanol	13
Recovery of DDGS from Thin Stillage	14
III. Construction of The DM Model	15
Mass Flow Rates	15
Flow Rates: Hourly Pounds in Dry Weight	18
Energy Balance	22
Electrical Energy Flow Rates	22
Thermal Energy Flow Rates	23
Equipment Size Estimation	25
Volumetric Sizing of Tanks and Reactors	25
Hourly Energy Requirement (hp) Sizing of the Mill and Centrifuge	26
Distillation System Sizing	27
Equipment Costs	28
Cost Estimation by Scale	28
Cost Estimation of the Distillation System	30
Treatment of Equipment Cost Inflation	30
Total Plant Cost Estimation and Financing	32
Model Validity	35
References	38

List of Figures

Figure 1 Dry Mill Process Flow Diagram.....	6
Figure 2 Glucose, Alcohol, CO ₂ , Cell Mass Levels During Fermentation (16 hours)	10
Figure 3 Equilibrium Relationship between Alcohol / Water Concentrations	11
Figure 4 Continuous Feed Distillation Column System / Hourly Flow Rates.....	12
Figure 5 Diagram of the Trays that Constitute the Distillation Column.....	13
Figure 6 Cost Correlation Functions: Stainless Steel Tanks.....	30
Figure 7 Adjusted Consumer Price Index (CPI) vs. Marshal Swift Index (MSI).....	32
Figure 8 Fixed Capital Investment Estimates DM Model and BBI.....	36

List of Tables

Table 1 Yellow Dent Corn Kernel % Composition	4
Table 2 Cost Correlation Table / Example: Stainless Steel Tanks	29
Table 3 Comparison of Price Indices: CPI vs. MSI.....	31
Table 4 Dry Mill Capital Cost Estimate using FCI Method for a 40 MGY Plant	33
Table 5 Capital Cost Estimates: DM Model and BBI.....	36
Table 6 Comparison of DM Results and USDA Survey	37

I. Introduction

Ethyl alcohol, alternatively known as ethanol or grain neutral spirits when used as a fuel or beverage, is a colorless, combustible chemical that has been used as a transport fuel since the invention of the combustion engine. Humans have intentionally fermented ethanol as a beverage since the beginning of civilization due to its intoxicating effects¹, antibacterial properties, preservation characteristics, and high energy content to weight ratio. The concentration of ethanol through fractional distillation techniques have been practiced since the 1st century AD.

In 1978 only a few million gallons of ethanol were commercially produced in the US, 26 years later that number climbed to 3.6 billion gallons². By 2011 it is expected that the gallons of ethanol produced will be double that of 2004. The increased production of ethanol has been spurred by environmental, economic, and national security concerns, as well as lobbying by the industry and agricultural interests. The utilization of ethanol and its substitution for gasoline is hailed as having advantages in each of these areas, but not without some degree of controversy. Detractors claim that ethanol production requires a greater fossil energy investment than it returns; hence, increasing the use and depletion of non-renewable resources. Opponents also claim that the ethanol industry is a clandestine government mandated transfer to the Corn Belt.

The renewable production³ of ethanol involves the fermentation of simple carbohydrates into an alcohol solution and the purification of the alcohol. The simple sugars used in this process are currently collected by the harvesting and conversion of agricultural products such as sugar cane in Brazil, corn in the US, and eucalyptus in Russia. These crops have value as feed stuffs for either livestock or human consumption, creating competition for their use. Research⁴ is being conducted on the feasibility of commercial production of ethanol using lignocellulosic materials⁵ as a fermentable substrate, which have limited value as human or livestock feed.

Ethanol as a Transport Fuel

The primary value of ethanol is as a liquid fuel in transportation. Ethanol's physical characteristics allow it to be pressurized and ignited in a combustion engine to produce work. Ethanol can be used independently or mixed with gasoline in combustion engines making it a direct substitute for gasoline. When used as an independent fuel the level of alcohol purity (95.6%) made possible through fractional distillation is great enough for combustion in a specifically designed engine, but it can not be mixed with gasoline or separation occurs. Ethanol degrades certain types of rubber and plastic, necessitating modifications of engines designed to run on gasoline if it is to be used independently. Ethanol also has a higher oxygen content/octane rating (106) than gasoline⁶ (87), requiring changes in the compression ratio and spark timing of a gasoline engine as well as larger carburetor jets if it is to be used instead of gasoline [15].

¹ All contemporary alcoholic beverages contain ethanol. Spirits such as gin, vodka, and grain alcohol are beverages in which ethanol has been concentrated through distillation.

² 3.4 billion were consumed in the US and 200 million gallons were exported.

³ As opposed to the non-renewable production of ethanol that is derived from fossil fuels.

⁴ There are currently two commercial cellulosic ethanol plants nearing operation.

⁵ Cellulose is the most common organic compound. It lends structure to plants and is not readily digestible as an energy source to animals. However, cellulose is digestible by certain micro organisms which are symbionts with other organisms such as termites and ruminants.

⁶ In terms of energy efficiency about 2/3 of a gallon of gasoline contains the same amount of energy as one gallon of ethanol.

Commonly ethanol is purified beyond its azeotropic level and mixed with gasoline. The product is sometimes called gasohol, and the percentage of ethanol contained is made known to consumers by its label; E5 signifies a 5% ethanol blend. Mixing ethanol with gasoline is done to increase octane ratings, decrease gasoline usage, and decrease net CO₂ emissions. At 1 – 25% ethanol percentages, no modifications are needed for most cars to utilize this fuel. Many light trucks, minivans, and SUV's produced in the US since 1996 can utilize mixes that are up to 85% ethanol. These vehicles are called flexible fuel vehicles (flex fuel) and are equipped with sensors that automatically adjust engine specifications to the fuel that is being used.

Additional interest in ethanol as a transport fuel arises from its potential use in hydrogen fuel cell technology. While ethanol is already being utilized as an alternative or additive to gasoline, it is as yet undetermined whether it will prove to be useful in hydrogen fuel cells.

Environmental Impacts of Ethanol

Ethanol has long been recognized as a clean burning alternative to gasoline. The only emission from the fermentation and combustion of Ethanol is CO₂. CO₂ has been implicated in global climate change, but there are several points that are worth noting. Firstly, CO₂ that is emitted during the fermentation process can easily be captured and sequestered. Secondly, and most importantly, the combustion of ethanol is not a net producer of atmospheric green house gas. The CO₂ emissions from burning ethanol have been previously sequestered by the plants used to produce the ethanol. On the other hand, use of fossil fuels releases CO₂ that has long been sequestered in the earth.

While the combustion of ethanol does not increase atmospheric CO₂, fossil fuels, which do, are commonly used in the production process. Some researchers [14] claim that decreased emissions from ethanol that displaces gasoline are less than the increased emissions from ethanol production. This debate hinges on how much fossil fuel is necessary in ethanol production. Ethanol is also used as an oxygenate in gasoline as an alternative to lead and MTBE, which are both associated with environmental damage and detrimental health effects [15].

The fermentation process and the drying of distiller's dried grains with solubles (DDGS), has been associated with emissions of VOC's⁷ into the atmosphere. To counter this problem many ethanol plants have installed scrubbers on their stacks or installed thermal oxidizers [2].

Governmental Policy Effects

In 1978 congress passed the National Energy Act which exempted gasoline mixed with 10% ethanol from 5.4 cents of the gasoline excise tax. Thus, the effective subsidy per gallon of ethanol was 54 cents per gallon. This legislation was enacted primarily because of the detrimental effect that 1970's oil crisis had on the United States economy. It was recognized that the US economy had grown too dependent upon oil exported from a small number of politically unstable countries and their collective decisions in OPEC. In 1980 half of the states in the US exempted ethanol from a portion of their excise taxes as well. This caused interest in, and the

⁷ VOC's is an acronym for 'volatile organic compounds'. The drying of DDGS should only release H₂O into the atmosphere but they are the dryers are generally run at higher than optimal temperatures which causes the DDGS to carbonize.

production of, ethanol to increase dramatically. In 1978 10 million gallons of ethanol were produced. Two years later 175 million gallons were produced, and in 2004 3.4 billion gallons were produced.

Today, ethanol is subsidized at the federal level at 51 cents per gallon until 2007 [7]. Additionally, three income tax credits are available for bio-mass ethanol: the alcohol mixtures credit, pure alcohol fuel credit, and the small ethanol producer's credit. The alcohol mixtures credit and pure alcohol fuel credit are available to the fuel blender and retailer respectively. The small ethanol producer's credit is redeemable for up to 15 million gallons annually for 10 cents a gallon by producers who make less than 30 million gallons a year [7].

Federal incentives have been very important in the growth and development of the ethanol industry. They have allowed the industry to develop technologies and efficiencies that would not be possible under market conditions, and the ethanol industry is now able to support itself in a more open market with oil above \$60 per barrel.

Environmental and health regulations have also increased the use of ethanol since 1980. The Clean Air Act Amendments of 1990 required that the oxygen content of gasoline be increased in areas plagued with high ozone levels [15]. RFG is gasoline mixed with an oxygenate that lowers emissions of ozone producing compounds and other pollutants. Oxygenates cause combustion of fuel to be more complete decreasing emissions of some pollutants. The most common oxygenates are ethanol and MTBE. MTBE was historically the preferred oxygenate in most areas because it was less expensive than ethanol.

MTBE is methyl-tertiary-butyl ether, which can be produced from methanol and isobutylene [4]. It has been used since the late 1970's when lead was outlawed as a fuel additive. In 1995 very high levels of MTBE were found in water wells in California and later were found to be a contaminant in drinking water across the US. Its presence in drinking water is reason for concern, as it has been found to be a carcinogen if ingested in large quantities. Health concerns about MTBE have led many states in the US to enact legislation against its use as a fuel additive. California and New York are two large fuel consuming states that have outlawed MTBE. Currently, ethanol is the only other viable alternative as a fuel oxygenate in these states. However, the 2005 energy act eliminated the oxygenate requirement.

The remainder of this paper is comprised a discussion of the dry mill ethanol production process, and an explanation of the construction of the DM model. There is a separate user's manual for the model.

II. The Ethanol Production Process

The production of alcohol is the conversion of radiant solar energy into concentrated liquid form. Photosynthetic plants convert solar radiation into chemical energy through metabolic pathways. Simple carbohydrates that the plant produces can be utilized for: metabolism, structure, growth, and repair, or stored as more complex carbohydrates for future use. The most abundant storage glucan is starch. Starch is comprised of long chains of glucose with two different linkages. Ethyl alcohol is produced through the fermentation of simple carbohydrates into alcohol which can be dehydrated, or concentrated, through the distillation processes. The mass production of ethanol involves two major steps: growing and harvesting of a carbohydrate feedstock and the conversion of this feedstock into an economically viable and useful fuel. The DM model and this paper focus on the latter of these steps; however, an understanding of the former is important.

Yellow Dent Corn as a Substrate in Ethanol Production

In the United States, the most widely used feedstock for commercial ethanol production is corn. Corn is a native species of the Americas and is one of the most important and efficient producers of starch in North America. Yellow dent corn (YDC) is a hybrid of southern gourd seeds and northern flint corn varieties and is by far the most widely planted corn breed in the US Corn Belt [3].

The kernel is comprised of endosperm, germ, aleurone, and a pericarp. The pericarp is the seed coat that covers the kernel and generally comprises less than 2% of the dry weight of the kernel. The aleuron tissue is a layer of single cells that lies just below the pericarp. The endosperm makes up a majority of the kernel and serves as an energy source for the growing embryo. It contains a high concentration of starch and makes up 80 – 85% of the dry weight of a kernel [18]. The germ, or embryo, is a dormant young corn plant which initiates plant growth under specific conditions of temperature, moisture and light. The germ makes up between 8 – 10% of the dry weight of the kernel and contains protein, oil, as well as starch [18].

Table 1 shows the average composition of the different components for common Midwestern grown hybrids of YDC.

Table 1 Yellow Dent Corn Kernel % Composition

Composition of Yellow Dent Corn Kernel by Percentage						
<i>(Watson, 1994)</i>						
<i>Corn:</i>	<i>Dry Weight</i>	<i>Starch</i>	<i>Fat</i>	<i>Protein</i>	<i>Ash</i>	<i>Sugar</i>
Whole Kernel	100%	73.4%	4.4%	9.1%	1.4%	1.9%
Endosperm	82.9%	87.6%	0.8%	8.0%	0.3%	0.6%
Germ	11.1%	8.3%	33.2%	18.4%	10.5%	10.8%
Pericarp	6.0%	7.3%	1.0%	3.7%	0.8%	0.3%

Source: American Association of Cereal Chemists [18].

In the US Corn Belt, corn is planted in the spring and harvested in the fall, at which point it is dried and stored. Due to modern developments in agricultural mechanization and technology, including genetic engineering, better farm management, and more effective pesticides and fertilizer, corn production has increased in an exponential fashion over the last century. This has decreased the amount of effort, in terms of labor hours and energy, it takes to collect vast amounts of starch feedstock in the US, increasing the supply and decreasing the price of the starch feedstock that is available for conversion into ethanol.

Dried YDC can be cheaply shipped across the country to feed lots or to corn processing plants. Processing plants convert the YDC into a higher value product, such as corn syrup or ethanol. To minimize corn transportation costs, a majority of corn processing and ethanol production takes place in the Corn Belt, where a majority of the corn is grown. Iowa is the state with the greatest annual corn and ethanol production per unit of land area.

Major Ethanol Producing Processes: Wet and Dry Milling

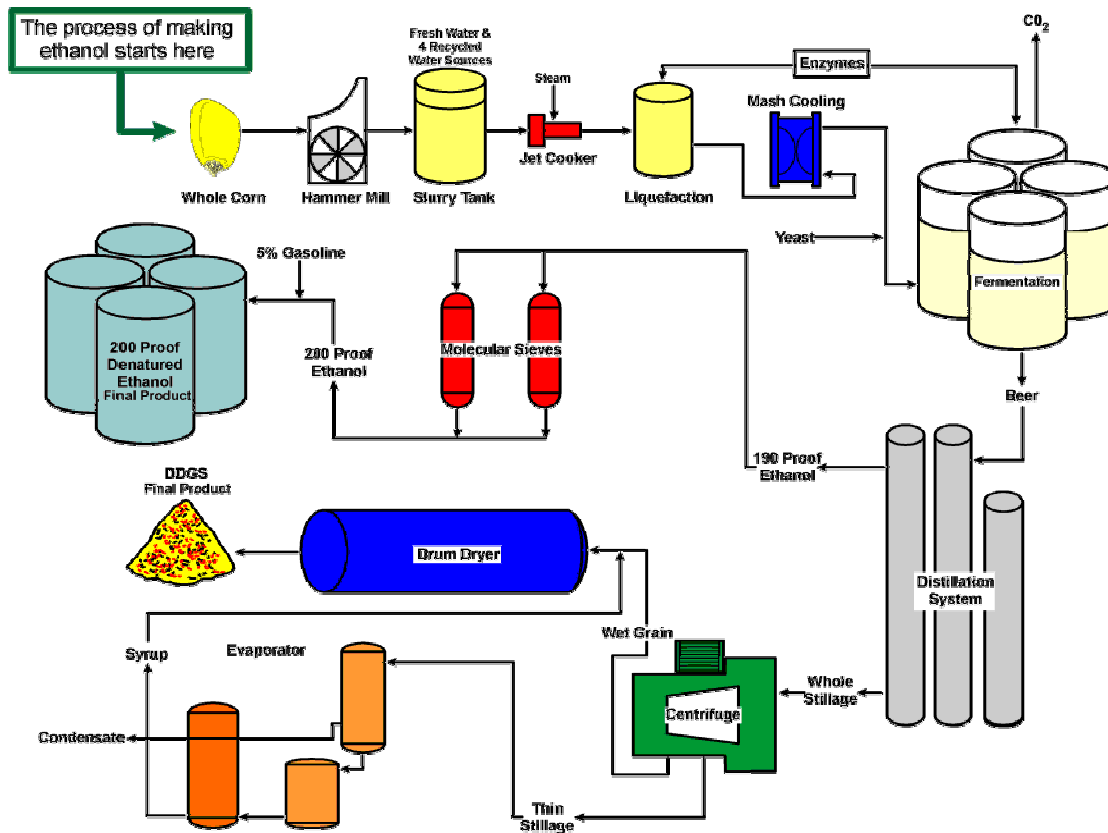
The two major processes for converting yellow dent corn into ethanol in the US are called wet milling and dry milling, both of which use corn as a feedstock to produce ethanol. Major differences between the two processes lie in the methods of glucose extraction utilized and the co-products that are produced.

In the wet milling process, the corn kernel is steeped in hot water before the germ, which is high in protein, oil, and zines, is mechanically separated from the endosperm, which is high in starch content [9]. The wet milling process is more flexible in production options and can produce corn sweeteners, starch, oil, and other products as well as ethanol and CO₂. High protein animal feeds, corn gluten feed/meal, are co-products of the wet milling process. The flexible products of the wet mill allow better reaction to changes in market conditions for corn products than in the dry milling process. Dry mill plants produce ethanol as a primary product and a high protein / caloric animal feed (DDGS) and CO₂ as co-products. Wet mills are slightly less efficient in ethanol production and require greater capital investment. The wet mill process does enjoy advantages in ethanol production over the dry mill process, including the ability to recycle yeast cells from batch to batch and lower water usage per gallon of ethanol produced.

This paper will only consider ethanol produced in the dry mill process. This is because nearly all⁸ current US ethanol production capacity, and all planned expansion in capacity, utilizes this process. The dry mill process does not separate the endosperm, germ, or bran of the corn kernel prior to fermentation as in the wet mill process. In the dry mill process the entire kernel is ground, enzymatically treated, fermented, and sent to the distillation column prior to product and co-product recovery. Figure 1 is a flow diagram provided by the Renewable Fuels Association (RFA), of the dry mill process [15].

⁸ There are currently only 4 wet mill ethanol plants in production.

Figure 1 Dry Mill Process Flow Diagram



Source: Renewable Fuels Association [15]

Dry Mill Process

The dry mill process, as described earlier and shown in Figure 1, consists of four major steps: grain handling and milling, liquefaction and saccharification, fermentation, and co-product recovery. Grain handling and milling is the step in which the corn is brought into the plant and ground to promote better starch to glucose conversion. Liquefaction and saccharification is where the starch is converted into glucose. Fermentation is the process of yeast converting glucose into ethanol. Co-product recovery is the step in which the alcohol and corn by-products are purified and made market ready.

Grain Handling and Milling

In the dry mill process, dried corn kernels are brought into the plant on trucks or rail where it must pass through quality control. In quality control the corn is examined for quality of kernel, kernel content, and moisture levels. If the shipment passes quality control, it is moved into plant storage silos using grain handling equipment such as bucket elevators. When corn is needed in the production process it is cleaned of debris en route from the storage bins to the mill. Blowers, screens, and magnets are sometimes used in the cleaning process. The whole corn kernels are crushed into a coarse grind meal still containing all components of the kernel (germ, endosperm, and pericarp). Milling in dry mills is usually accomplished through use of a hammer mill. A hammer mill is an enclosed grinding area with a centrally located axis from which free

hanging tines (hammers) are driven by an electrical motor. The hammers swing and crush the kernels as they enter the grinding area and particles are reduced until the kernel pieces are small enough to exit through a screen. The milling increases the surface area of the corn, exposing starch and allowing more efficient hydrolysis to occur. After the corn is milled, it is ready for liquefaction and sent to the slurry tank.

Liquefaction and Saccharification

In the liquefaction step the starch content of the corn kernel is readied for conversion and then broken down into smaller glucose units. Few species of yeast, and no commercial yeasts, can readily ferment starch into alcohol. Starch must be broken down into smaller fermentable units: glucose (DP-1)⁹, disaccharides (DP-2) and trisaccharides (DP-3). The measure of the hydrolysis¹⁰ of starch is termed dextrose equivalent (DE). A complete hydrolysis of starch to dextrose would be a 100-DE product¹¹ [12]. The conversion of starch into smaller units can be accomplished through use of acid (acid hydrolysis) or enzyme¹² (enzymatic hydrolysis).

Acid hydrolysis is a random cleaving of the alpha-1, 4 and alpha-1,6 linkages in starch over time [1]. Acids are used to catalyze the cleavage of the covalent bond with water. Other reactions occur, since acid is not a specific catalyst, but the primary reaction is as follows:



Enzymatic hydrolysis is a more common way in which starch molecules are cleaved into smaller subunits by decreasing the activation energy of the reaction [15]. Enzymatic hydrolysis uses specific enzymes, bacterial or fungal, because non-target reactions are far less common than in acid hydrolysis. This specificity of reaction increases the target conversion efficiency rate. In the liquefaction and saccharification two different enzymes, alpha-amylase and gluco-amylase are utilized to hydrolyze starch into fermentable sugars. Alpha amylases are endozymes¹³ that cleave alpha-1, 4 linkage hydrolyzing starch solutions into dextrin solutions. The optimal temperature for this reaction is between 130 – 150° F, with an optimal pH of 5.0 – 7.0 (dependent upon the enzyme used). Gluco-amylase is a mix of several different kinds of enzymes including: alpha-amylases, cellulases, and proteases. Gluco-amylases are exoamylolytic¹⁴ cleaving alpha- 1,4 and alpha- 1,6 linkages. Gluco-amylases activate a dextrose hydrolyzate (96% dextrose) before reversion occurs, leaving disaccharides. The reaction is the same as in acid hydrolysis but a higher DE level (increased concentration of fermentable sugars) is almost always achieved:



The DM model and this work assume an enzymatic rather than acid hydrolysis approach as it is by far a more popular method in the ethanol production process.

⁹ DP refers to the degree of polymerization, the number of dextrose units in a saccharide.

¹⁰ Hydrolysis is the cleaving of a molecule (starch) into two (dextrose) with the addition of a H₂O molecule.

¹¹ $DP = [(20,000/DE) - 18] / 162$

¹² An enzyme is a protein that catalyzes, or reduces the activation energy of, a chemical reaction

¹³ Edozymes are enzymes that cause hydrolysis to occur randomly.

¹⁴ Exoamylolytic enzymes cleave molecules in a stepwise manner.

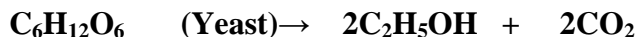
The milled grain from the hammer mill enters the slurry tank where water is added. The hydrated feed stock is termed 'slurry' which is generally comprised of between 20 and 40% solids (crushed corn) by weight. The water added to the grain is either fresh or recycled from other stages of the production process in which dehydration has occurred. Recycled water used to produce the slurry is called backset and can make up between 0 and 100 % of the water used. Commonly, 20 – 40 % of the water input is backset¹⁵. Backset water generally comes from the distillation of alcohol in the form of thin stillage. The water balance of a dry mill plant is very important because of the relatively large amount of water used in the production a gallon of ethanol and the expense associated with the treatment and disposal of used water¹⁶. In 2002 the water necessary to produce one gallon of ethanol ranged between .75 and 11 gallons with an average of 4.7 gallons [15]. State of the art water treatment utilizes anaerobic digesters that can remove 95% of organic compounds. This increases the rate of water recycled and produces methane that can be utilized as a fuel in production.

Alpha amylase is added to the slurry at levels between .05 - .1 % of dry corn weight and held at elevated temperatures for 60 – 90 minutes. The slurry is then cooked by a jet cooker to help gelatinize the solution (increasing viscosity), which increases the speed and efficiency of hydrolysis. This mixture is held in a high pressure hold tube. Steam is forced into the hold tube which pressurizes the heated slurry for 15 to 20 minutes. The slurry is now a dextrin solution, termed 'mash' which is cooled and pumped from the hold tube and prepared for saccharification.

Saccharification is the stage in which dextrin molecules are cleaved into smaller fermentable gluco-units (DP-1, DP-2, and DP-3) through addition of gluco-amylase. Saccharification can be carried out in a separate designated tank, the saccharification tank, or in the same vessel where fermentation takes place. The process of saccharification and fermentation occurring at the same time in the same vessel is known as simultaneous saccharification and fermentation (SSF¹⁷). In SSF the yeast can not metabolize gluco-units until the dextrans have been cleaved.

Fermentation

The fermentation of glucose into alcohol is carried out by yeasts which are a form of fungi (mycota). Yeasts used in the fermentation of commercial alcohol have been selected, or engineered, to possess certain favorable characteristics that are economically beneficial in the fermentation process. Contemporary commercial yeast strains metabolize glucose, disaccharides, and trisaccharides for cell growth, repair, reproduction, and alcohol production. Alcohol production is the targeted reaction in commercial dry mill ethanol facilities and is represented in the following equation:



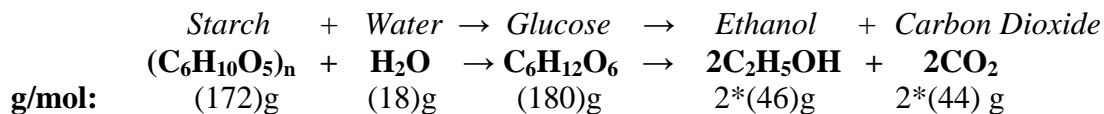
A sufficiently large yeast colony can completely convert glucose into alcohol over a period of 10 – 70 hours at temperatures between 90 – 100 degrees F. As is shown in the chemical reaction above, the fermentation process produces an equal amount (2 moles) of CO₂

¹⁵ As the percentage of backset in slurry water increases so do toxins that are harmful to yeast cells.

¹⁶ Some plants utilize anaerobic digesters that use microorganisms to clean backset water. This decreases the need for fresh water in the dry mill process.

¹⁷ Not to be confused with solid state fermentation which is also sometimes referred to as SSF.

and alcohol [8]. The theoretical yield of ethanol per pound of starch is found stoichiometrically. The atomic weights of C = 12, O = 16, and H = 1 are used to calculate the molecular mass of the substrates, intermediary products, and products:



Under ideal circumstances .511 (92 / 180) pounds of ethanol and .489 (88 / 180) pounds of carbon dioxide are expected to be produced per pound of glucose fermented (.529 pounds ethanol and .511 pounds carbon dioxide per pound of starch fermented). These are theoretical yields and represent the maximum possible yields which are never actually achieved in fermentations. Lower achieved yields are due to yeast cell growth / metabolism, less than optimal conditions, error, and for other reasons [8]. Total conversion rates in commercial ethanol production are generally between 75 and 85% of the theoretical yields.

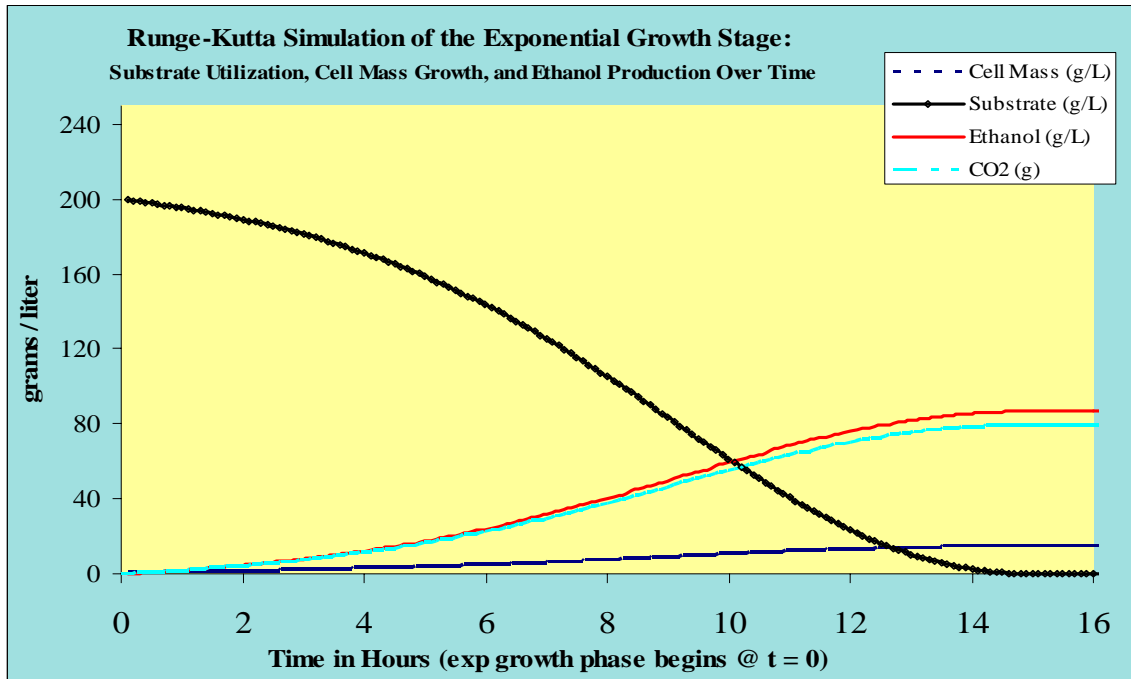
In dry mills the average batch fermentation is finished after 52 hours [15]. The rate of alcohol production occurs slowly during the initial stages of fermentation known as the lag phase. During this phase yeast cells mature and propagate so that an increase in cell mass is observed under aerobic conditions. The rate of alcohol production increases during the exponential growth stage under microanaerobic conditions. The rate of alcohol production tapers off as glucose levels become relatively scarce. Figure 2 shows the relationship between alcohol production, cell mass, carbon dioxide emissions and substrate utilization over 16 hours for a batch fermentation using Runge-Kutta simulation.

High alcohol concentrations can be lethal to yeast cells. Some types of yeast used in commercial alcohol production can tolerate alcohol concentration from 12% (by volume) up to nearly 18%. Through utilization of new technologies targeting greater alcohol tolerance in yeast, the average alcohol percentage in beer has increased in the last several years from 12% to 16%¹⁸. The increase in the alcohol percentage in beer has allowed dry mill capacity to increase while using less energy in the dehydration of ethanol and co-products.

Simple carbohydrates used in metabolic pathways are not the only requirement for yeast cell survival. Nitrogen, calcium, and other micro-nutrients need to be included in the feed medium to ensure proper yeast health [8]. Corn steep liquor, a co-product in the wet mill process, is a good nutrient source for yeast and is commonly used in ethanol facilities. Lacticide, SO₂, and other antibiotics need to be added to the feed medium as well to ensure that ‘volunteer’ fungi and bacteria do not grow in the feed medium and utilize the glucose for ‘selfish reasons’ producing lactic acid and other non-target chemicals.

¹⁸ Personal communication with Dr. Ingledoo.

Figure 2 Glucose, Alcohol, CO₂, Cell Mass Levels During Fermentation (16 hours)



Source: N. Mosier and M. Ladisch [reprinted with permission]

In the dry mill process, mash flows into the fermentation vessels. Mash may be either a dextrin solution from the liquefaction tank for SSF, or a glucose solution from the saccharification tank. The fermentation period is the most time intensive step in the dry mill process. The time involved with this process necessitates relatively large tanks. Commonly, four fermentation vessels are utilized. In order to maintain quality cells and high rates of fermentation, the yeast microbes require nutrients (nitrogen, calcium, etc.) which are supplied by the corn protein and stillage water or added to the fermentation vessel.

Fermentation can either be carried out in batches or in a continuous fashion. Batch fermentation refers to the process in which the fermentation is allowed to complete in a single fermentation vessel. In the continuous fermentation process, which is utilized in 20% of dry mills, the beer is cycled continuously, in a step-wise fashion, through different fermentation vessels.

During fermentation CO₂ and ethanol are produced. The CO₂ produced is captured upon degasification and can be sold¹⁹ as a by-product or released into the atmosphere. The ethanol that was converted from glucose is contained in an aqueous solution known as ‘beer’. Beer is a 12% – 18% ethyl alcohol²⁰ solution also containing any remaining unfermented solids: oil, proteins, cellulose, etc. The recovery of ethanol and co-products begins with the beer being sent to a distillation system. In the distillation process alcohol is separated from the rest of the beer through a set of step wise vaporizations and condensations. The beer less the alcohol extracted

¹⁹ Beverage companies provide a large market for the CO₂, and it is common practice for these companies to purchase the necessary equipment for CO₂ capture and storage in an ethanol plant in return for a favorable contract on the CO₂.

²⁰ The current target percentage of alcohol in fully fermented beer by volume is 16% for most dry mills. The 2002 average was a bit over 15% [16].

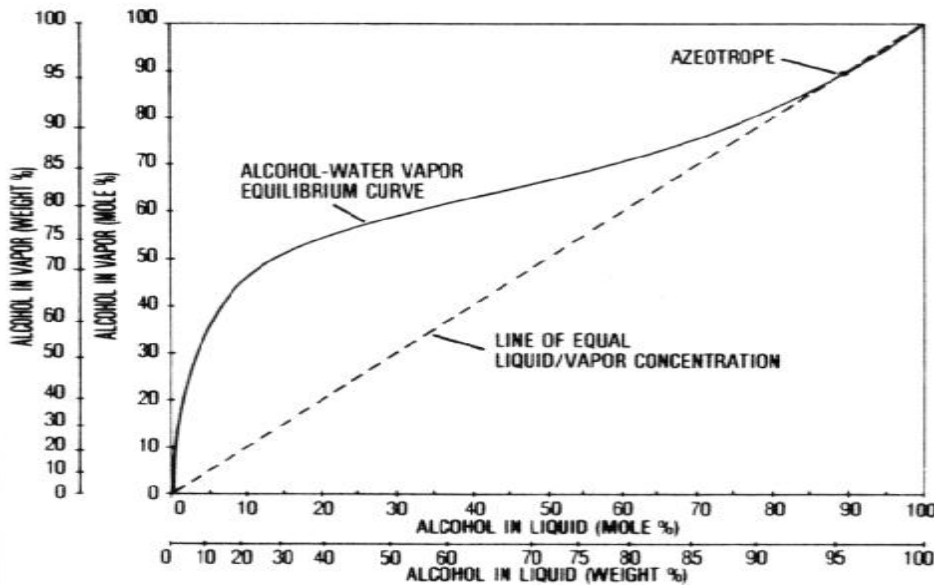
through distillation is known as whole stillage. Through use of a centrifuge, the solids in the whole stillage can be divided into two streams, soluble (thin stillage) and insoluble (wet distiller's grain or WDG). The two streams are then dehydrated and mixed to compose DDGS. DDGS is a medium protein animal feed that is an economically important co-product to the dry millers.

Separation through Distillation

Fractional distillation is a method for separating the various components of the aqueous mixture that have different boiling points through the application of heat. Pure ethyl alcohol boils at a temperature of 173 F while water boils at 212 F [19]; thus, alcohol is more volatile. Any mixture of alcohol and water will boil at a temperature within this range; the higher the alcohol content, the closer the boiling point will be to 173 F. As heat is applied to an aqueous alcohol solution, the percentage of alcohol content in the vapor will increase while the percentage of alcohol in the condensate will decrease.

Through controlled sequential evaporations, condensations, re-evaporations, and re-condensations the alcohol content in the vapor can be concentrated to even higher levels. This is only true up to a certain point, the azeotropic point, at which alcohol and water share the same vapor pressure / boiling point. At an alcohol concentration of 95.6% water and alcohol can no longer be separated by fractional distillation (Figure 3).

Figure 3 Equilibrium Relationship between Alcohol / Water Concentrations

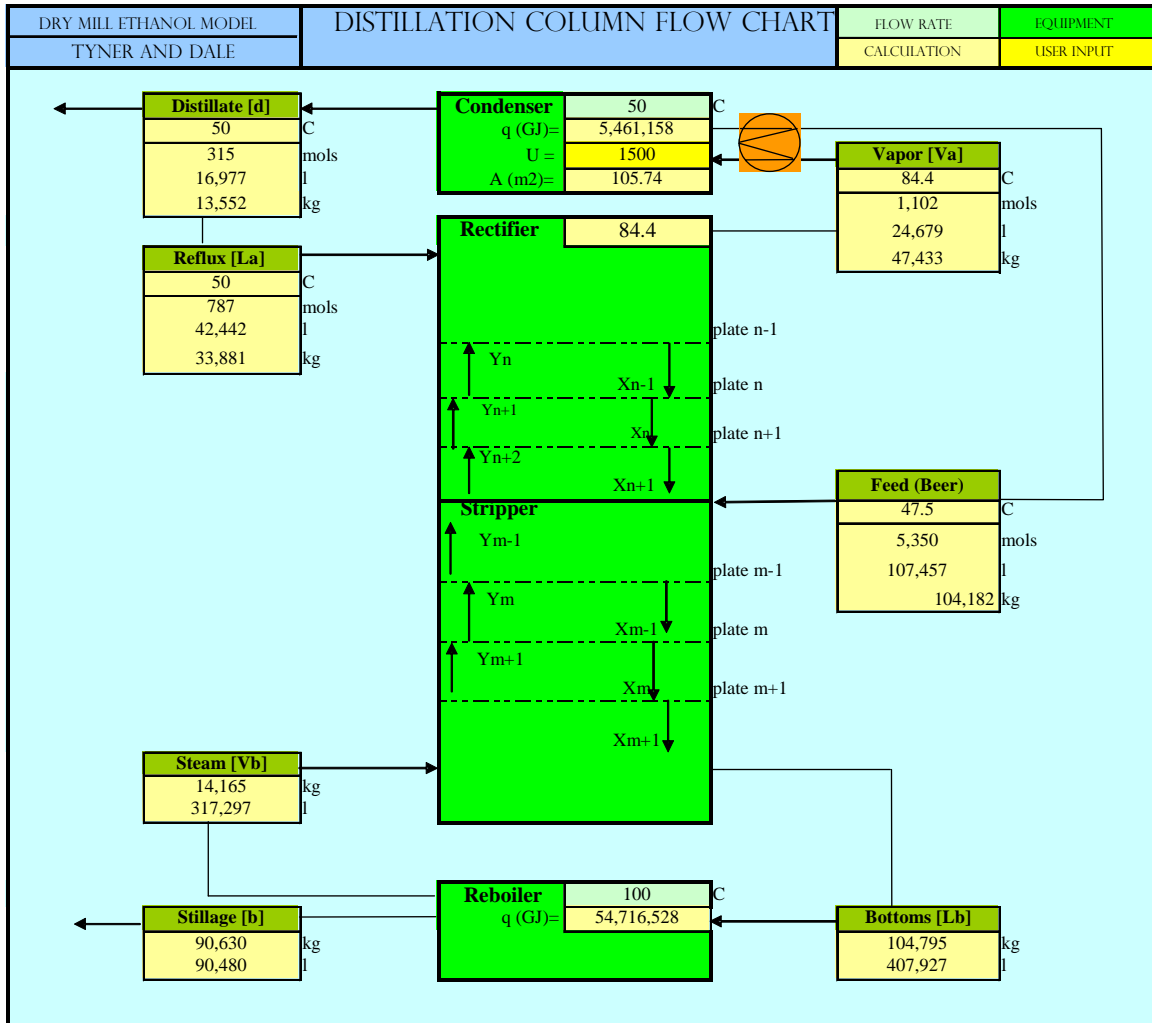


Source: Alcohol Distillation: Basic Principles [19]

There are several different types of distillation systems, but the most commonly used in commercial dry mill ethanol production, and the one modeled in this paper, is a continuous-feed distillation (trays) column system (Figure 4). This system is comprised of a number of trays that are conjoined as a column. The alcohol solution, i.e. beer, enters near the middle of the column. Trays above the feed compose the rectifying section while those below comprise the stripping

section. The rectifying section feeds into a condenser, which condenses the vapor, and below the stripping section there exists a heat source [19].

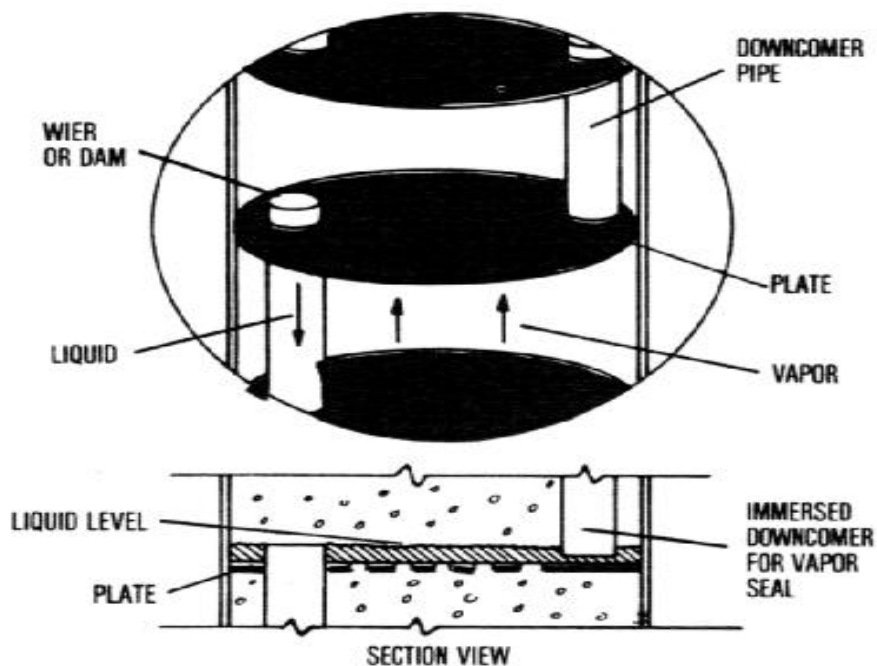
Figure 4 Continuous Feed Distillation Column System / Hourly Flow Rates



Source: DM Model Estimates

Beer from the fermentation vessels (or beer well), is heated through use of a heat exchanger and fed into the distillation column. The beer flows downwards through the trays where it is impeded by pores in the trays and rising alcohol vapors. Figure 5 shows how the trays that compose the column are configured. The tray design allow for mixing of the vapor with the beer, which allows the alcohol in the beer to better evaporate as the water condenses. The condensation of the water produces heat while the alcohol uses this heat in evaporating [19]. The alcohol content in the vapor increases as it moves up the column through the continuous disequilibrium in liquid and vapor volatilities and successive condensations and evaporations. Thus, the alcohol percentage is greatest at the top most tray and weakest at the bottom most tray. The vapor in the top tray, the purest in alcohol content, enters the condenser where it is condensed into liquid form.

Figure 5 Diagram of the Trays that Constitute the Distillation Column



Source: Alcohol Distillation: Basic Principles [19]

A portion of the condensed alcohol is re-circulated (50 – 80%) into the rectification section to control the purity of the evaporating alcohol vapor. This is termed the ‘reflux ratio’. A higher reflux ratio is associated with higher alcohol purity and greater heating requirement. Only 20 – 50 % of the vapor leaves as the purest type of ethanol, ‘hydrous ethanol’, which is sent to be further purified in molecular sieves. The water condensate in the bottom tray, which has the lowest alcohol content, is comprised mostly of water and solids, and contains some residual alcohol and soluble nutrients. This material, which flows from the bottom of the stripper column, is called ‘whole stillage’.

The two streams, whole stillage and hydrous ethanol, leaving the distillation column are not yet market ready. Hydrous ethanol is not suitable for mixing with gasoline because it does not stay in solution properly. The whole stillage contains valuable corn protein, fiber, and sugars but they are too dilute to be of much value.

Recovery of Anhydrous from Hydrous Ethanol

Further purification of the hydrous ethanol is necessary if the final intended use is as vehicle fuel. There are two processes in which higher purification can be reached; through the addition of another component or through the use of molecular sieves. The addition of a third component is an older separation technology. The idea behind this method is to add a solvent that has a higher boiling point (such as benzene or diethyl ether) to the hydrous ethanol and distilling the water from the hydrous ethanol. This step is followed by a third distillation to separate the solvent from the anhydrous ethanol. This allows alcohol to be distilled to levels of nearly 100% purity through the use of three separate distillations [19]. This method consumes more energy and is not as cost effective as the separation method using molecular sieves which has become widely used in dry mills.

Molecular sieves consist of tanks containing porous crystalline aluminosilicates (zeolites) that separate molecules based on size [19]. The hydrous ethanol from the distillation column is vaporized and flows through the porous packing of the molecular sieve. The pores are large enough for H₂O molecules to enter and become trapped but too small for the larger alcohol molecules to enter. The trapping of H₂O is increased by ionic force from the presence of cations [19]. Anhydrous ethanol flows out the sieve while the pores of the zeolite are filled with H₂O molecules. Once the zeolite packing is saturated with water the sieve must be dehydrated and recharged with cations.

The final step before ethanol is market ready is denaturation. Denaturant, is a chemical that is added to the anhydrous ethanol to make it unconsumable for humans. This must be done in order to avoid large Bureau of Alcohol, Tobacco, and Firearms bond payments. The most common denaturant added is gasoline at levels of nearly 5% by volume. The anhydrous ethanol and denaturant mixture is now called ‘anhydrous denatured ethanol’. At this point it is ready to be shipped and ultimately blended with a higher percentage of gasoline.

Recovery of DDGS from Thin Stillage

The whole stillage from the bottom of the distillation column contains the spent grains after fermentation. The spent grains are comprised of everything that was not converted into alcohol or CO₂, the proteins, fiber, lignocellulosics, ash, and unfermented sugars. A portion of the whole stillage that leaves the distillation column is used as backset in the hydration of slurry and the remaining portion is sent to be centrifuged into two streams: insoluble solids (wet distiller’s grains) and soluble solids (thin stillage).

Thin stillage leaving the centrifuge contains any water soluble components. This includes any soluble gluco units that were not fermented and soluble proteins. The thin stillage from the centrifuge is passed through multiple effect evaporators²¹ that remove a majority of the water and concentrates the soluble solids into a syrup (30 – 60% solids). The syrup which is high in nutritional value is then added to the insoluble stream, WDG, and is now known as wet distiller’s grains with solubles (WDGS). The addition of the syrup to the distiller’s grains decreases the amount of waste water leaving the dry mill while increasing both the nutritional and economic value of the distiller’s grain.

WDGS can be sold to nearby animal operations for feed or dried to produce DDGS. It is necessary that the WDGS, also called ‘wet cake’ when sold in this form, be fed to the animals within a week or two of production, because it readily spoils. The selling of wet cake, or WDGS, is not nearly as common as the selling of DDGS. The drying of DDGS takes place in rotary dryers that are known as ‘drum dryers’ that require a good deal of thermal energy, almost a quarter of the thermal energy used in ethanol production. The moisture content is reduced from 60% in WDGS to levels of nearly 10% in DDGS. The DDGS are stored until they are ready to be shipped to feed yards. This feed is high in protein, calories, and is an especially useful feed for cattle and other ruminants due to its by-pass protein content.

²¹ The multiple effect evaporation system decreases the amount of energy needed in dehydration by reusing the evaporate from each effect.

III. Construction of The DM Model

The DM model is a set of spreadsheets integrating all aspects of the dry mill ethanol production process. In the first step of the model, discussed in greater detail in the next chapter, the user enters values corresponding to the production, physical, and economic parameters of a dry mill. The parameter values are used to calculate the necessary hourly flow rates of inputs and outputs at all stages in the dry mill process²². The hourly flow rates are then used to estimate the required size of major equipment used in the dry mill process, as well as to calculate annual revenues and variable input costs. The equipment size estimates are then used to approximate their associated cost using the exponential method of scale [13]. These individual equipment cost estimates are summed to determine the total capital costs associated with the dry mill plant. The total capital cost in the DM model is calculated as a function of total equipment costs. The factor that was used in capital cost estimation in the DM model was specific to evaluating the capital costs of liquid chemical plants. This method returns estimates that are reportedly within a range of +/- 20% of the actual capital costs. Working capital is calculated as a user specified percentage of first year operating costs and added to the cost estimate to return an estimate of total fixed capital investment. The total fixed capital investment value is instrumental in calculating the annual loan terms and finances for the associated dry mill plant. All of this information was then used to calculate cash flows, profit margins, internal rate of return, and net present value for the dry mill plant.

Mass Flow Rates

Ethanol plants are classified according to the number of gallons of anhydrous ethanol that they are capable of producing in one year. This classification number is the dry mill's total capacity, also referred to as its nameplate capacity. For example, if a dry mill were to run at full capacity, continuously for 365 days, and it produced 40,000,000 gallons of anhydrous ethanol, then its 'nameplate capacity' would be 40 MGY (million gallons per year).

The output of a dry mill plant is a function of inputs into the plant and corresponding conversion rates. The inputs include the amount of grain, chemicals, water, and utilities needed in the production process. In a similar fashion, the DM model is constructed in such a way that the input requirements of the plant are determined by user entered process parameters and output level. The total annual capacity value (Total Capacity)²³ is entered by the user and is the cornerstone upon which the rest of the DM model is built. The flow rate of anhydrous ethanol (Anhydrous EtOH), in gallons per hour, flowing from the molecular sieve at full capacity is found through division of total capacity by the number of hours in a year. It is the hourly flow rate of anhydrous ethanol dictated by total capacity.

$$\text{Anhydrous EtOH (gal/hour)} = \text{Total Capacity (gal)} / [24 * 365 \text{ (hours)}]$$

Less than full plant utilization may be expected and occurs for a number of reasons, including: equipment failure, human error, logistic problems, regulation, and scheduled plant maintenance. The allowance for less than full capacity utilization in the dry mill plant was

²² A stage or step is a smaller part of a process. The processes are grain handling and milling, liquefaction/sachrifaction, fermentation, and co-product recovery. A stage of a process is when the product enters a piece of equipment in a process.

²³ Variable names that are bold are direct user input values.

included as a factor in the DM model. The actual totals of anhydrous gallons of ethanol produced annually (Actual Capacity) was determined as the product of two user specified values, total capacity (**Total Capacity**) and plant capacity utilization percentage rate (**Utilization**)²⁴:

$$\text{Actual Capacity (gal)} = \text{Total Capacity (gal)} * \text{Utilization (\%)}$$

The Ethanol Plant Development Handbook advises prospective dry millers to plan on an average of 350 – 360, 24 hour, days of full capacity plant utilization [2]. This one to two week allowance of plant idleness corresponds with an annual average dry mill capacity utilization of 95 to 99 percent.

In a similar fashion, hourly flow rates are first calculated for full capacity utilization and then multiplied by capacity utilization percentage to calculate the average actual hourly flow rates. The larger, full utilization hourly flow rates are used in calculating necessary equipment size. This is of importance to ensure that equipment is of sufficient size and capability to operate at levels of necessary capacity utilization. The lesser, actual flow rates (yearly hourly average) are used to calculate both variable input costs and revenues, from actual input flow rates and output flow rates respectively. The following discussion will present full capacity flow rates- all of which can be converted into actual flow rates through the simple multiplication of the rate by the capacity utilization percentage.

The hourly flow rate of hydrous ethanol to the molecular sieves, in gallons per hour, is calculated using the hourly flow rate of anhydrous ethanol, in gallons per hour, and the alcohol percentage purity of hydrous ethanol (**Hydrous EtOH**). The alcohol purity percentage of the hydrous ethanol (distillate) is a user specified value that should be set at or barely below the azeotropic point. With these values the hourly gallons of hydrous ethanol flowing into the molecular sieves from the distillation condenser is calculated as:

$$\text{Hydrous EtOH (gal/hr)} = \text{Anhydrous EtOH (gal/hr)} / [1 - \text{Hydrous EtOH (\%)}]$$

The hourly flow rate, in gallons, of the water that is trapped by the molecular sieves (Mol Sieve H₂O) is calculated as the hourly flow of hydrous ethanol less the hourly flow of anhydrous ethanol:

$$\text{Mol Sieve H}_2\text{O (gal/hr)} = \text{Hydrous EtOH (gal/hr)} - \text{Anhydrous EtOH (gal/hr)}$$

At this juncture it is realized that all flow rates have been thus far measured in units of volume (gallons), whereas many of the intermediary products (starch and glucose), outputs (DDGS and CO₂), and inputs (grain) are solids that are more readily measured in units of mass (pounds). Conversion to a common unit is necessary to continue. It should be recognized that the conversion of volumetric units to units of mass is less laborious calculation than the contrary. For these reasons, the hourly volumetric flow rates of ethanol, mash, beer and water which were calculated in gallons were also calculated in units of mass, pounds per hour. This was accomplished by dividing their hourly flow rate, in gallons, by their respective densities (pounds per gallon). A useful anhydrous rate converted into mass is the hourly flow rate of anhydrous

²⁴ The capacity utilization percentage can be directly entered by the user or calculated from the user inputting the number of days a year (DOP) and hours a day of operation (HOP).

$$\text{CU\%} = (\text{DOP} * \text{Hop}) / (365 * 24)$$

ethanol. One gallon of ethanol weighs about 6.59 pounds. However, the user is permitted to enter a different value, if so inclined. This hourly flow rate, in gallons, is converted to an hourly flow rate, in pounds²⁵, through its subsequent multiplication by its specific density (Anhydrous Density).

$$\text{Anhydrous EtOH (lbs/hr)} = \text{Anhydrous EtOH (gal/hr)} * \text{Anhydrous Density (lbs/gal)}$$

With hourly flow rates calculated in both pounds and gallons, flow rates for solids may be calculated. The fermentation process is an important step of the dry mill process in which hourly flow rates for both solids and liquids are required. The fermentation process, as was discussed previously, can either be carried out in batches or continuously. In the DM model the fermentation process is modeled as a continuous process. This was not only done because this method lends itself more readily to modeling but also because it is more commonly used than batch fermentation in dry mills.

To obtain the required hourly flow rate of anhydrous alcohol, a specific hourly flow rate of glucose must enter the fermentation vessel. The fermentable sugars in the mash are derived from the hydrolyzed starch found in the grain. Theoretically, a gram of starch is cleaved to yield 1.11 grams²⁶ of glucose and a gram of glucose yields .51 grams of alcohol and .49 grams of CO₂ once fermentation has commenced. The theoretical required hourly flow of pounds of glucose (Theoretical Glucose), starch (Theoretical Starch), and grain (Theoretical Grain) necessary to produce the hourly pounds of flow of anhydrous alcohol can be calculated using its hourly flow rate, in pounds (Anhydrous EtOH), the starch composition percentage of the grain (**Starch/Grain**), and the theoretical conversion rates:

$$\text{Theoretical Glucose (lb/hr)} = \text{Anhydrous EtOH (lb/hr)} / .51$$

$$\text{Theoretical Starch (lb/hr)} = \text{Theoretical Glucose (lb/hr)} / 1.11$$

$$\text{Theoretical Grain (lb/hr)} = \text{Theoretical Starch (lb/hr)} / \text{Starch/Grain (\%)}$$

These rates are theoretical yields which mean that they are the maximum attainable yields, not actual yields. To account for the disparity between theoretical and actual yields, conversion efficiency percentages of theoretical (<100%) are included as user specified values in the DM model. The user can specify the conversion efficiency percentage in: liquefaction, starch to dextrin (**Dextrin/Starch**), saccharification, dextrin to glucose (**Glucose/Dextrin**), and fermentation, glucose to ethanol (**EtOH/Glucose**). The actual hourly flow rate of glucose (Glucose) in pounds per hour necessitated by the alcohol hourly flow rate is calculated by dividing the theoretical hourly flow rate by its associated conversion efficiency percentage:

$$\text{Glucose (lb/hr)} = \text{Theoretical Glucose (lb/hr)} / (\text{EtOH/Glucose (\%)})$$

²⁶ A water molecule is added to the starch molecule in hydrolysis to return a yield higher than one.

The conversion efficiency percentage of starch hydrolyzed to glucose (Glucose/Starch%), which is in practice quite high, is calculated as the product of the conversion efficiency rates for starch to dextrans and dextrans to glucose:

$$\text{Glucose/Starch (\%)} = \text{Dextrin/Starch (\%)} * \text{Glucose/Dextrin (\%)}$$

The actual hourly flow rate of starch in pounds per hour (Starch) necessary to yield the required hourly flow rate of glucose is calculated, similarly to the actual flow of glucose, as the necessary theoretical hourly flow rate over its corresponding conversion efficiency percentage:

$$\text{Starch (lb/hr)} = \text{Theoretical Starch (lb/hr)} / \text{Glucose/Starch (\%)}$$

The hourly flow rate in pounds of grain per hour (Grain) necessary to yield the actual hourly flow rate of starch is a function of the: user specified percentage of grain which is comprised of starch (**Starch/Grain**) and required actual hourly flow rate of starch:

$$\text{Grain (lb/hr)} = \text{Starch (lb/hr)} / \text{Starch/Grain (\%)}$$

Similar to the calculation of the theoretical and actual flow rates for grain requirements, the carbon dioxide hourly flow rates are calculated. The theoretical production of CO₂ (Theoretical CO₂) in fermentation is 1 pound of glucose yields .49 pounds of CO₂. Since CO₂ is a co-product of the same fermentation process that produces ethanol, the inputs are necessarily the same and the same conversion efficiency rate applies. This allows the direct substitution of the previously calculated theoretical hourly flow rate of glucose and the theoretical yield as the subsequent denominator to calculate the theoretical hourly yield of CO₂:

$$\text{Theoretical CO}_2 \text{ (lb/hr)} = \text{Theoretical Glucose (lb/hr)} * .49$$

The above calculation of the theoretical hourly yield of CO₂ is not necessary in the calculation of the actual CO₂ hourly yield (CO₂). This is because the actual hourly flow rate of glucose into the fermentation vessel has been previously calculated. The actual hourly glucose flow is divided by the theoretical percentage yield of CO₂ (49%), which calculates the theoretical hourly yield of CO₂ given the actual flow rate of glucose. This theoretical flow rate is multiplied by the fermentation conversion efficiency percentage (**EtOH/Starch**) to return the actual hourly CO₂ yield rate in pounds per hour:

$$\text{CO}_2 \text{ (lb/hr)} = [\text{Glucose (lb/hr)} / .49] * \text{EtOH/Starch (\%)}$$

Given that we now know the hourly flow of pounds of: grain input, CO₂ output, and ethanol output, it is now possible to calculate the weight of DDGS output. For this we will need to calculate flows in dry weight.

Flow Rates: Hourly Pounds in Dry Weight

The following sections utilize another type of flow rate found only in units of mass, the dry weight flow rate. The dry weight flow rates would be equivalent to the regular flow rates if absolutely no moisture was used in the dry mill production process. These hourly flow rates are indicated in the following discussion by a (dry-) preceding their variable name. Dry flow rates

are used in determining the water balance of the dry mill and model closure. When possible, dry hourly flow rates were calculated by dividing the hourly flow rate, in pounds, by the corresponding solids / moisture ratio. As an example, the user specifies the solids / moisture ratio of grain (**Grain Moisture**) that can be used, along with the hourly flow rate in pounds of grain (Grain) to calculate the hourly dry weight flow rate of grain (Dry Grain):

$$\text{Dry Grain (lb/hr)} = [\text{Grain (lb/hr)} / (1 - \text{Grain Moisture (\%)})]$$

The relative flow rate of water and grain flowing into the slurry tank determines the moisture / solids ratio of the mash. The hourly flow rate of grain (Grain) was calculated previously, and the mash moisture / solids ratio (**Mash Moisture**) is a value specified by the user. This information, in conjunction with the user specified solid / moisture ratio of the grain (**Grain Moisture**), allow the total hourly rate of water that flows into the slurry tank to be calculated. The hourly water flow rate is found by first calculating the hourly flow rate of water (H₂O Mash) to correctly hydrate the hourly dry flow rate of grain (Dry Grain) to the mash's specified solids / moisture ratio. The hourly water flow is less than the dry weight calculation because of the moisture that is contained in the grain flow. The hourly water flow rate (H₂O Mash), in pounds, is calculated as:

$$\text{H}_2\text{O Mash (lb/hr)} = [(\text{Grain} * (-\text{Grain Moisture})) / \text{Mash Moisture}] - (\text{Grain Moist} * \text{Grain})$$

The hourly flow rate of recycled water (H₂O backset) was then found by multiplying the total hourly water flow by the user specified value for the percent of water that was used as backset (**Backset**). The hourly flow rate of fresh water (H₂O Fresh) is similarly calculated:

$$\text{H}_2\text{O Backset (lb/hr)} = \text{H}_2\text{O Mash (lb/hr)} * \text{Backset (\%)}$$

$$\text{H}_2\text{O Fresh (lb/hr)} = \text{H}_2\text{O Mash (lb/hr)} * (1 - \text{Backset (\%)})$$

By the summation of the hourly flow rates of fresh water, backset water, and grain that are the components of mash, its hourly flow rate (Mash), in pounds, is calculated:

$$\text{Mash (lb/hr)} = \text{H}_2\text{O Backset (lb/hr)} + \text{H}_2\text{O Fresh (lb/hr)} + \text{Grain (lb/hr)}$$

The hourly flow rate of the mash is expressed in pounds per hour, which was converted to gallons through its division by its density in pounds per gal (Mash Density):

$$\text{Mash (gal/hr)} = \text{Mash (lb/hr)} / \text{Mash Density (lb/gal)}$$

The increase in the flow rate of mash as enzymes, chemicals, and yeast, which are added prior to fermentation are included in the mash flow rate. The hourly flow rates of each individual (a-Amylase, Chemical, and Yeast) mash additive is calculated by multiplying the hourly flow rate of starch (**a-Amylase/Starch**, **Chemical/Starch**, and **Yeast/Starch**), in pounds, by the user specified number of pounds of each that is added per pound of starch in the mash bill for each.

$$\text{a-Amylase (lb/hr)} = \text{a-Amylase/Starch (lb)} * \text{Starch (lb/hr)}$$

$$\text{Chemical (lb/hr)} = \text{Chemical/Starch (lb)} * \text{Starch (lb/hr)}$$

$$\text{Yeast (lb/hr)} = \text{Yeast/Starch (lb)} * \text{Starch (lb/hr)}$$

These hourly mash additive flow rates are summed and added to the mash flow rate prior to fermentation (Mash Final), and the evaporation of water during fermentation (Fermentation Evaporation) is calculated as a function of the physical properties of water:

$$\text{Mash Final (lb/hr)} = \text{Mash (lb/hr)} + \text{a-Amylase (lb/hr)} + \text{Chemical (lb/hr)} + \text{Yeast (lb/hr)}$$

$$\text{Fermentation Evaporation} = f(\text{Fermenters, H}_2\text{O boiling point, H}_2\text{O Density})$$

The hourly flow rate of mash prior to fermentation less the hourly yield of CO₂ that is released gives the hourly flow rate of beer, in pounds, that is pumped from the fermentation vessels and sent to the distillation column:

$$\text{Beer (lb/hr)} = \text{Mash Final (lb/hr)} - \text{Fermentation Evaporation (lb/hr)} - \text{CO}_2 \text{ (lb/hr)}$$

The flow rate of beer that enters the distillation column less the flow rate of hydrous ethanol yields the hourly flow rate of whole stillage (Whole still). The whole stillage leaves the distillation column and enters the centrifuge.

$$\text{Whole Still (lb/hr)} = \text{Beer (lb/hr)} - \text{Hydrous EtOH (lb/hr)} - \text{H}_2\text{O Backset (lb/hr)}$$

DDGS hourly flow rates are modeled somewhat differently than the other co-products, CO₂ and ethanol. The difference between DDGS and the other products is this hourly flow rate is modeled as a residual. There were three reasons for modeling the DDGS as the residual. Firstly, DDGS is a residual product. It is what is left over after the target product, ethanol, has been produced. Secondly, unlike ethanol or carbon dioxide, which both possess molecular formulas that be used to find theoretical yields, DDGS is a heterogeneous mixture of protein, unfermented gluco-units, starch molecules, and lingo-cellulosic material. Thirdly, DDGS was modeled as a residual to close the DM model. Model closure is an important factor in determining the mass, water, and energy balance. For these three independent reasons the hourly flow rate of DDGS is calculated as the dry weight flow rate of grain input less the flow rate of hydrous ethanol and CO₂ (all rates in pounds). The moisture content of DDGS is added to the dry flow rate through its division by the solids / moisture ratio:

$$\text{Mass Balance (lb/hr)} = \text{Dry Grain (lb/hr)} - \text{CO}_2 \text{ (lb/hr)} - \text{Hydrous EtOH (lb/hr)}$$

$$\text{DDGS (lb/hr)} = \text{Mass Balance} / (1 - \text{DDGS Moisture (\%)})$$

The dry weight flow rate is found as the product of the flow rate of DDGS and its moisture content (**DDGS Moisture**):

$$\text{Dry DDGS (lb/hr)} = \text{DDGS (lb/hr)} * (1 - \text{DDGS Moisture (\%)})$$

The only difference between the flow of WDGS and DDGS is their solid / moisture ratio, on average 60% and 10%, respectively. Since the only difference between WDGS and DDGS is the percentage of moisture contained in each flow, the dry flow rates must equate by definition:

$$\text{Dry DDGS (lb/hr)} = \text{Dry WDGS (lb/hr)}$$

$$\text{DDGS (lb/hr)} * (1 - \text{DDGS Solids (\%)}) = \text{WDGS (lb/hr)} * (1 - \text{WDGS Moisture (\%)})$$

The flow rate of DDGS and the moisture contents are the only values needed to calculate the WDGS hourly flow rate:

$$\text{WDGS (lb/hr)} = \text{Dry DDGS (lb/hr)} * (1 - \text{DDGS Solids (\%)}) / (1 - \text{WDGS Solids (\%)})$$

The hourly flow rate of WDGS is a combination made up by: the hourly flow rates of syrup and wet distiller's grains (WDG). Syrup created through the concentration of soluble solids by evaporation while WDG is composed of all the insoluble solids. To determine the relative proportion of the WDGS flow hourly rate that is attributable to each stream, the utilization of the physical properties of the grain input are called upon. The soluble solids that comprise the thin stillage would include any remaining glucose or dextrans, and soluble proteins:

$$\text{DGS Soluble Sugars (lb/hr)} = \text{Remaining Glucose (lb/hr)} + \text{Remaining Dextrans (lb/hr)}$$

$$\text{Dry DGS Soluble Protein (lb/hr)} = \text{Dry DDGS (lb/hr)} * \text{Soluble Protein (\%)}$$

The soluble sugar and soluble protein streams are then added to return a value for dry syrup hourly flow rate in pounds which returns syrup flow when divided by the solids percentage of syrup:

$$\text{Dry Syrup (lbs/hr)} = \text{DGS Soluble Sugars (lb/hr)} + \text{Dry DGS Soluble Protein (lb/hr)}$$

$$\text{Syrup (lbs/hr)} = \text{Dry Syrup (lb/hr)} * (1 + \text{Syrup Moisture (\%)})$$

The insoluble solids, that comprise the WDG, are unconverted starch and everything else in the corn kernel that is not soluble: insoluble protein, lignin, ash, and un-hydrolyzed starch molecules. The dry flow of WDG can be calculated by subtracting the flow of dry syrup from the flow of dry DDGS.

$$\text{Dry WDG (lb/hr)} = \text{Dry DGSS (lb/hr)} - \text{Dry Syrup (lbs/hr)}$$

Finally the hourly flow of WDG from the centrifuge to the drum dryer in pounds is calculated using its moisture content:

$$\text{WDG (lb/hr)} = \text{Dry WDG (lb/hr)} * (1 + \text{WDG Moisture (\%)})$$

The evaporation rate for the drum dryer is calculated by subtracting the hourly flow of WDGS from DDGS:

$$\text{DDGS H}_2\text{O Evaporation (lb/hr)} = \text{WDGS (lbs/hr)} - \text{DDGS (lbs/hr)}$$

In a similar fashion the evaporation of water from thin stillage to syrup is calculated as the difference of these two flows:

$$\text{Stillage H}_2\text{O Evaporation (lb/hr)} = [\text{Thin Stillage} - \text{Syrup} - \text{Backset}] \text{ (lb/hr)}$$

All necessary mass and volume hourly flows rates are calculated. It is important to remember that all flow rate calculations are first carried out assuming full capacity, for purposes of equipment size estimation. Only after full capacity flow rates have been found are the average annual flow rates calculated, for calculation of revenues and variable cost, by multiplying the full capacity utilization by a percent utilization factor, and then multiplied by the percentage of utilization to estimate variable costs and revenues. Hourly flow rates were found either in units of volume, mass, or dry weight and subsequently converted to the other units if applicable.

Energy Balance

Energy is an important and costly input in the production process of ethanol. After feedstock costs, it is the most expensive variable cost. Each gallon of ethanol produced is estimated to require between 36,000 and 48,000 Btu's of energy input in the plant [2]. This energy is utilized in two forms, thermal (steam) and electrical. Electrical energy is used to run machinery with moving parts or motors such as pumps, centrifuges, and mills. Historically, the electrical input has been 1.1 kWh with an associated cost in the range of 3 to 12 cents, per gallon of ethanol produced [15]. At electrical costs of greater than \$.06 per kWh, electrical cogeneration becomes a more appealing prospect to the plant owners.

Thermal energy is of even greater importance than electrical energy because it is used extensively in liquefaction, saccharification, distillation, and in the dehydration of DDGS. Steam, produced in boilers, is transported by pipe and used throughout the system. Natural gas is the most common fuel used to produce steam in the boilers but coal, propane, and biomass are also used. The cost of heating fuel is relatively large in the production process. In 1998, the average dry mill consumed 36,000 Btu's of thermal energy in the production of one gallon of ethanol [15]. On average, the distillation is the single system that requires the largest single share of the total thermal energy requirement (32%), but over half of the thermal energy is expended in the dehydration and recovery of DDGS (27.5% in DDGS drying and 26.4% in the evaporation of thin stillage).

Electrical Energy Flow Rates

The electrical energy flows necessary to run different types of machinery in the production process are estimated through use of an energy index. The energy index is linearly related to the total capacity of the plant. All electrical energy requirements were found in this manner excepting the distillation system. The distillation system was estimated in a different manner due to its complexity and the specific parameters that are required in its energy requirement estimation. The energy index flow rate (EI) is estimated for a plant by dividing its total capacity by an index denominator (**ElectDenom**) that is entered by the user [11].

$$\text{Energy Index} = \text{Total Capacity} / \text{Electric Denominator}$$

The energy index value is then multiplied by a coefficient estimate for each piece of machinery that uses electricity as an input. These coefficients come from *Plant Design and Economics for Chemical Engineers* [13]. The energy flow rate requirements in kilo watt hours (kWh) can be converted into Btu, HP, calories, or other energy units through simple calculation as is required. The electrical energy requirement was estimated as an hourly rate for each piece of equipment at full capacity. These individual equipment electrical flow rate requirements were then summed to estimate the total hourly electrical flow rate requirement (Sum kWh). The total actual electrical energy used was then calculated by multiplying the total hourly electrical equipment flow rate requirements by the capacity utilization percentage (**Utilization**):

$$\text{Total Actual Electrical Energy Use (kWh)} = \text{Sum kWh} * \text{Utilization (\%)}$$

Thermal Energy Flow Rates

The amount of thermal energy necessitated as steam in the dry mill process was estimated using information about the physical characteristics of the liquids (or solids) and the user specified temperature changes in each stage of the process. Thermal energy from a process consists of latent and sensible heat. The total thermal energy required, or enthalpy (H), by a process is the sum of sensible and latent heat requirements. Sensible heat is the energy when added or subtracted from a flow changes its temperature. Latent heat is the energy required to cause a phase (i.e. liquid to vapor) change in a mass:

$$\Delta \text{ Enthalpy} = \Delta \text{ Latent Heat} + \Delta \text{ Sensible Heat}$$

$$\Delta \text{ Sensible Heat (Btu)} = \Delta \text{ Temperature} * \mathbf{Cp} * \text{Mass (lbs)}$$

$$\Delta \text{ Latent Heat} = \text{Mass (lbs)} * \mathbf{Cv}$$

Where Cp is the specific heat in Btu's (water = 1, ethanol = .65) and Cv is the specific heat of vaporization (water = 1,150, ethanol = 800).

In the DM model, the thermal energy flow rate requirement for an individual process in which a temperature change occurs, is estimated by calculating both the sensible heat and latent heat. To find the sensible heat the user entered temperatures are used to calculate the temperature change: [**Temp Process – Temp Initial**] and multiplied by the mass of the flow rate and the corresponding specific heat. The amount of energy required (positive or negative), in Btu's (Btu), to change the flow rate temperature was calculated as a function of the associated hourly pounds per hour and the degree to which the temperature rises:

$$\text{Sensible Energy (Btu)} = \text{Flow (lbs/hr)} * (\mathbf{\text{Temp Process} - \text{Temp Initial (F)}}) * \mathbf{Cp}$$

Similarly the latent heat was calculated as the energy needed to result in a phase change of a flow:

$$\text{Phase Energy (Btu)} = \text{Flow (lbs/hr)} * \mathbf{Cv}$$

The values for latent and sensible heat were summed to return a value for the total thermal energy balance of each process that required or released thermal energy:

$$\text{Total Energy (Btu)} = \text{Sensible Energy (Btu)} + \text{Phase Energy (Btu)}$$

Thermal energy used for evaporation was estimated as was described above. However, in the recovery of DDGS in the dry mill process commonly multiple effect evaporators and drum dryers are used in dehydration. These pieces of equipment change the efficiency rate of evaporation of water

The use of multiple pass driers in the evaporation of thin stillage increases the energy efficiency of dehydration by a great deal. The multiple pass evaporators transfer energy from one pass to another, thereby conserving that same energy. The model incorporates this efficiency by dividing the estimated hourly Btu flow rate required to evaporate the thin stillage stream (Evaporation) by the number of passes in the evaporation system (**# of Evaporation Passes**). The number of passes is a user chosen value with a default setting of 3.

$$\text{Evaporation (Btu)} = \text{Phase (Btu)} / \# \text{ Evaporation Passes}$$

Drum dryers require more thermal energy than is required to evaporate water from WDGS. This is because the solids in the DDGS must also be heated to the same levels to remove the water. For this reason the energy required to dry WDGS is calculated as an efficiency percentage (<100%) of theoretical:

$$\text{Drying (Btu)} = \text{Phase (Btu)} * \text{Efficiency (\%)}$$

The distillation system is the single largest user of thermal energy in the production of ethanol in the dry mill process [15]. The hydrous ethanol must be raised to above its boiling point, involving a phase change, and captured as vapor and allowed to condense back into liquid form. The distillation system, once running, is fairly efficient in its retention and transfer of heat. The hourly thermal energy flow rate was estimated for the distillation system by multiplying the hourly hydrous ethanol flow rate (in gallons) by the number of Btu's required to evaporate a gallon of ethanol. This requirement was calculated as a decreasing function of the volumetric alcohol content of the beer (**EtOH Volume**) entering the distillation system and purity of the hydrous ethanol condensate:

$$\text{Distillation (Btu/gal)} = 17.8 - (52 * \text{EtOH Volume (\%)}) - (10 * (1 - \text{Hydrous EtOH (\%)}))$$

$$\text{Distillation (Btu)} = (\text{Hydrous EtOH (gal/hr)} / \text{EtOH Density (lb/gal)}) * \text{Distillation}$$

Heat exchange is important in the dry mill process for conserving energy and costs. Heat exchange is when the specific heats from two streams are crossed to heat one and cool the other. This conserves a great deal of energy in the process and usually takes place on a coil or plate heat exchanger. To simplify the model all specific heats were calculated, both positive and negative. These were then summed under the presumption that this is the theoretical minimum sensible heat required if perfect heat exchange took place. Perfect heat exchange is not possible due to less than infinite heat exchange area, fouling, and thermal leakages. To estimate sensible

heat with losses, the sum of sensible heat (Total Sensible)) is multiplied by an efficiency percentage (**HX Efficiency** <100%) that is entered by the user.

$$\text{Sum Sensible (Btu)} = \text{Total Sensible (Btu)} * \text{HX Efficiency (\%)}$$

The total thermal energy requirement flow rate (Total Btu) is calculated by summing the sensible energy required, latent energy required, and the distillation energy required:

$$\text{Sum Thermal (Btu)} = \text{Sum Sensible} + \text{Sum Latent} + \text{Distillation} + \text{Drying} + \text{Evaporation}$$

The required hourly boiler output to support the dry mill and its thermal energy requirement is calculated by multiplying the hourly total number of Btu's by 150%. The boiler size was calculated as 33% larger than necessary for several reasons. It is ill advised for any mechanism to be run at full capability for extended times; this practice increases the probability of mechanical failure. The over sizing also allows for other thermal energy needs such as space heating to be met. Another reason for over sizing is that the extra capacity may be put to use in the future if capacity expansion takes place.

$$\text{Boiler Size (Btu)} = \text{Sum Thermal (Btu)} * 1.5$$

Equipment Size Estimation

The size of the equipment needed in the ethanol production process is calculated in the DM model through use of hourly flow rates and hourly electrical and thermal requirements, all of which vary with plant capacity. In the DM model total capital costs for a given plant size are then projected using the total cost of equipment estimates. Equipment costs are estimated according to size, and, thus, good assessment of equipment size is crucially important. Equipment sizing is primarily estimated through use of the volumetric flow rates (in gallons) and the hourly energy requirements necessitated by those flow rates through equipment. The size of the distillation system is discussed separately in the costs section due to its complexity.

Volumetric Sizing of Tanks and Reactors

Tank and reactor sizing is estimated through use of total capacity flow rates (nameplate gallons working at 100% capacity) and residence time (**RTD**). The user enters the RTD for each stage of the dry mill process in minutes which is then converted into hours.²⁷ For example, the slurry tank for a 40 million gallon a year plant has an associated flow rate of 24,863 gallons of mash per hour. Given a user input value for the RTD in the tank of 90 minutes the resulting minimum necessary size of the slurry tank would be calculated as:

$$\begin{aligned} \text{Tank Size (gal)} &= \text{RTD (min)} / 60 \text{ (min)} * \text{Flow (gal/hr)} \\ &= 90 / 60 \text{ (hr)} * 24,863 \text{ (gal/hr)} \\ \text{Tank Size} &= 37,297 \text{ gallon tank} \end{aligned}$$

²⁷ Default values are included in the base spreadsheet, and these will be appropriate in most cases.

In this example, a 37,297 gallon slurry tank is calculated as the necessary volume for a 40 MGY total capacity dry mill plant if liquefaction takes 90 minutes.

Similar to the slurry tank example, the size of the high pressure hold tube, liquefaction tank, beer well, and storage tanks are estimated in gallons. The fermentation reactors are also calculated accordingly. However, fermentation vessels are calculated somewhat differently because the associated residence time is relatively long, measured in days instead of minutes, and more than one tank is utilized. The model allows the user to input the number of tanks utilized in any stage of the process. In the fermentation process the number of vessels used is generally four, which is the default value, but the user can specify any number of vessels (**FermVessels**). The necessary size of a single vessel is calculated and then divided by the number of reactors to calculate each reactor's size:

$$\text{Fermentation Vessel Size (gal)} = [(\text{Ferm RTD} / 60) * \text{Beer (lb/hr)}] / \text{Ferm Vessels}$$

The high pressure hold tube is where the mash is held at high temperatures and pressures for 10 – 20 minutes to allow further cleaving of starch molecules and the sterilization of the mash. As the name suggests, this is a tube and hence its size is a function of height, length, and diameter. No exponential function for this equipment was found in either Perry's (1998) or Peters et. al. (2003). A function was created that allowed only the diameter of the hold tube to vary with the flow rate. The resulting estimate calculated the size of the hold tube (diameter) as a function of residence time and volumetric flow rate:

$$\text{Diameter HP Tube (ft)} = [(\text{RTD}/60)*\text{flow}] / (\text{Height} * \text{Length} * \Pi)^{1/3}$$

Hourly Energy Requirement (hp) Sizing of the Grain Handling, Mill, and Centrifuge

The grain handling equipment, hammer mill, and centrifuge are three pieces of equipment whose sizes are calculated based on the amount of horse power necessitated by their output. Energy requirements were found in kilowatt hours and then converted to horse power. The hourly electrical input (EI) increases with plant capacity and was utilized in horse power size estimation [13].

Grain handling equipment sizing was calculated as a function of per minute grain weight and distance (**Distance**). The further the distance or more grain to be moved the greater the necessary handling equipment:

$$\text{Handling Equipment (kW)} = 1.6 * (\text{Grain (lb/hr)} / 3600)^{.82} * \text{Distance (ft)}$$

The hammer mill is a machine into which whole corn kernels, stored in the hopper, enter through a feed screw into the milling area. The milling area contains a gear with swinging hammers that crush the kernels into corn flour. The corn flour when fine enough exits through a screen. The necessary hourly electrical energy, in kW, necessary for a hammer mill to run is found as a function of size based on a per minute reduction percentage (**Reduction**):

$$\text{Hammer Mill Size (kW)} = 20 * (\text{Grain (lb/hr)} / 3600) * \log(\text{Reduction (\%)})$$

The necessary hourly electrical input is then converted in to horse power units using the standard conversion of 1 kW = .74 hp:

$$\text{Hammer Mill Size (hp)} = \text{Hammer Mill Size (kW)} / .74$$

The centrifuge uses cylindrical force to separate different densities of solids and liquids. In dry mill plants centrifuges are used in the separation of the whole stillage into WDG and thin stillage. Whole stillage enters the spinning centrifuge and the solids (WDG) stay in the disk while liquid (thin stillage) is forced through pores in the disk. The necessary diameter (ft) is found as a function of the hourly solids passing through:

$$\text{Centrifuge Diameter (ft)} = .0165 * (\text{Dry DDGS (lb/hr)})^{.462}$$

The horse power sizing is then calculated using the following function of diameter found in [13]:

$$\text{Centrifuge (hp)} = 74.1 * (\text{Centrifuge Diameter})^{2.1}$$

Distillation System Sizing

The size of the distillation system, including the number of trays needed, the diameter and height of the column, and the necessary thermal requirements, are all dependent upon the amount and characteristics of the input (beer) and outputs (hydrous ethanol and whole stillage) to the system. The necessary number of trays can be calculated by ‘stepping off’ the difference between alcohol and water vapor equilibrium curve as shown in Figure 5. In application, however, more trays are necessary than theory would predict. Trays come in 12”, 18”, and 24” standard sizes [2]. The optimal column height is determined by the desired alcohol content of the condensate and the percentage of alcohol in the beer feed. The necessary column diameter and area is linearly dependent upon the flow rates of the beer, alcohol, and reflux.

The first step in estimating the distillation systems size is to find the number of theoretical plates needed (N) for the column as a function of the percent recovery of the vapor (X1) and condensate (X2), relative volatility (A_{ab}), the reflux ratio (R), and the molecular fraction of alcohol (Xf):

$$N = \log (\mathbf{X1} * \mathbf{X2} / \mathbf{X3} * \mathbf{X4}) / \log [A_{ab} / (1 + 1 / \mathbf{R} * \mathbf{Xf})^5]$$

By assuming that the log of the percent alcohol in the vapor (95.6%) and percent of alcohol in the condensate (4.4 %) equals 4.6:

$$N = 4.6 / \log [A_{ab} / (1 + 1 / \mathbf{R} * \mathbf{Xf})^5] = 40$$

The number of actual trays N_{act} is always greater than theoretical, and the rectifier has generally twice the number of trays as the stripper:

$$N_{act} = 2 * N = 80$$

$$N_{rec} = 2 * N_{act} / 3 \approx 50$$

$$N_{strip} = N_{act} / 3 \approx 30$$

The minimum reflux ratio (R_{\min}) is a function of the alcohol content in the beer and relative volatility and actual reflux ratio (R_{act}) is greater than the minimum :

$$R_{\min} = 1 / X_f (A_{\text{ab}} - 1)$$

$$R_{\text{act}} = 1.5 * R_{\min}$$

With this information we can find the diameter of the column (D) which is:

$$D = A * V^{.5}$$

Where A is a constant and V is the evaporation rate which is the hourly flow rate of hydrous ethanol figured in the flow rates:

$$A = [4 / (\Pi * C * (da / dw - 1))]^{.5} = .87$$

$$V = (\text{Hydrous EtOH})^{.5}$$

Taken together this means that the diameter of the column in ethanol plants equals:

$$D = .87 * (\text{HGEtOH})^{.5}$$

The diameter of the column is only a function of capacity. Since column height is a function of the percentage alcohol of beer and hydrous ethanol, and there is virtually no variation in these variables across plants, the column height should be constant across plants. The most common tray height is the 24" size and so that will be used as an example to find column height:

$$\text{Column Height} = \text{Tray Height} * N$$

$$\text{Column Height} = 24'' * 80 = 160'$$

The resulting estimate of distillation system size for a dry mill plant using 24" trays is a total column height of 160', a rectifier of 100', a stripper of 60', with a diameter that is a function of plant capacity.

Equipment Costs

Equipment costs are the basis for total capital cost estimation in this model. An important point of analysis in this model is that parameters can be changed to examine their effect on the production process output. Equipment cost estimation as a function of capacity was utilized when possible and similar techniques used when not possible. The distillation system is an example of equipment that could not be predicted in this manner.

Cost Estimation by Scale

Peters, Timmerhaus, and West present the cost estimation by capacity, developed by Guthrie, in their book *Plant Design and Economics for Chemical Engineers* [13]. This method utilizes historical prices of different sized equipment to assign non-linear cost functions to equipment. As the necessary equipment size increases, so too does its cost, but these costs

increase at a decreasing rate. This may be attributed to the greater bargaining power of buyers of larger equipment and the non-linear relationship between surface area and volume.

In their book, *Plant Design and Economics for Chemical Engineers*, Peters et. al. present a method of cost estimation based on equipment size and cost correlation. The cost correlation tables are equipment ‘cost functions’ of size. The cost of any given piece of equipment is estimated as a function of its size (volume, surface area, height, length, or energy requirement), function, and material. The tables describe the piece of equipment and its specifications, the size range within which the estimate is correct, the estimated cost coefficient, the associated exponent, and an error range. The cost correlation table for stainless steel tanks, for example, is presented in Table 2. The first four columns are the coefficient numbers and the last two columns show how the coefficients are used.

Table 2 Cost Correlation Table / Example: Stainless Steel Tanks

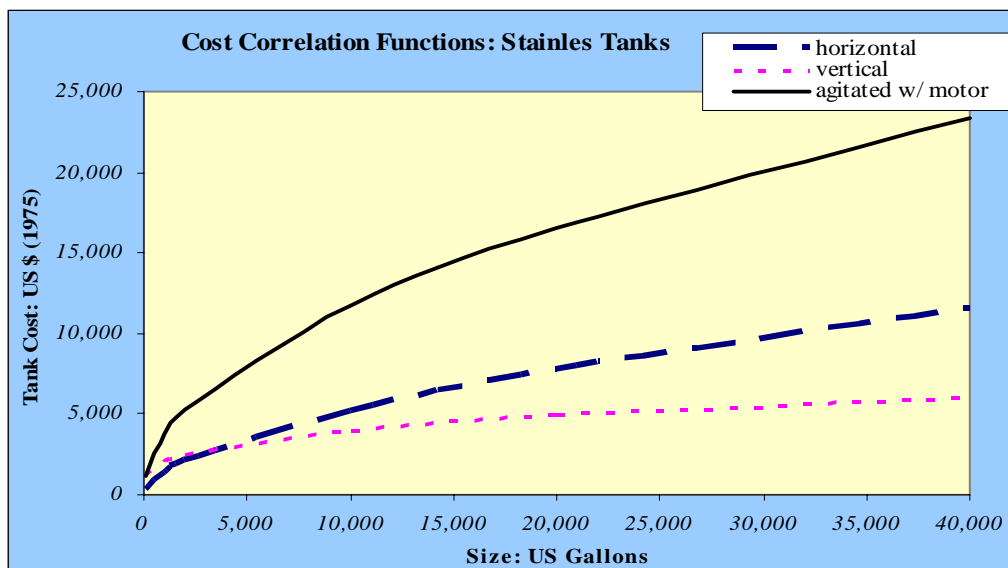
Exponential Cost Correlation Table:						
Peters, Timmerhaus, and West (2003)						
	Size	Cost	Exponent	Error	Cost Example: 2,000 gal Tank	
Tank Type:	US gal	1975 US \$			Formula	1975 US \$
horizontal: c/s	1,000	1,400	0.57	20%	$1,400 \times (2,000/1,000)^{(.57)}$	\$2,078
vertical: c/s	100	1,000	0.3	20%	$1,000 \times (2,000 / 100) ^ (.3)$	\$2,456
agitated: c/s: w/ motor	1,000	3,700	0.5	20%	$3,700 \times (2,000 / 1,000) ^ (.5)$	\$5,233

Source: *Plant Design and Economics for Chemical Engineers* [13].

For each type of tank there is a size, cost, and exponent value in Table 2. To obtain a cost estimate for a tank, size in gallons is divided by the size coefficient and taken to the corresponding exponent coefficient. The cost of a N,000 gallon horizontal tank in 1975 US dollars would be equal to $\$1,400 \times (N,000 / 1,000)^{.57}$.

The relationship between equipment cost estimation and its size can better be seen through graphical representation. Figure 6 shows the same relationship between size and cost estimates for the three different tanks as in Table 2. As the volume of a tank increases, so does the cost of a tank. The non-linear relationship between volume and surface area is the reason that price is seen to increase at a decreasing rate with respect to volume.

Figure 6 Cost Correlation Functions: Stainless Steel Tanks



Source: *Plant Design and Economics for Chemical Engineers* [13]

Using the associated cost function for each piece of equipment, all major equipment costs were estimated as a function of necessary full capacity size. For a given annual capacity in a dry mill, first, the flow rates are estimated, then, the corresponding equipment sizes for these flows were calculate, and finally, the associated costs for each piece of equipment was estimated using cost / size correlation functions. The distillation equipment was estimated in a similar manner but in a more piecemeal fashion since no correlation table was found for the system as a whole.

Cost Estimation of the Distillation System

Once the size of the distillation system is projected, there are two ways in which the cost may be predicted. The first method of cost estimation utilized cost correlation tables for all individual parts of the system. The cost of the column can be calculated since its height and diameter were estimated earlier. Cost correlation tables may also be used to estimate the cost of the trays, as the number of trays and their size are known. In this manner the column, rectifier, and stripper costs may be estimated. Another way in which to estimate the cost of the distillation system is presented by Didier and Perez in “Short Cut Method for Cost Estimation in Distillation” (2003). This method estimates a cost function for distillation systems based on the physical properties of the mixed solution, the number of trays, and the necessary column diameter.

Treatment of Equipment Cost Inflation

The cost correlation tables used in cost estimation were published in the mid-1970's. To allow for equipment inflation over the last 30 years the Marshall-Swift index was used [5]. The Marshall-Swift index was designed to be used in conjunction with cost correlation tables and is published monthly in *Process Engineering*. The index number starts in 1950 with a value equal to 100. Table 3 shows the comparative values of the consumer price index (CPI) and the Marshall-Swift index (MSI) for the 1987 – 2002 time period. The CPI is used a general indicator of changes in price levels for consumers over time, whereas the MSI is an indicator of the price

changes for installed industrial chemical equipment over time. The adjusted CPI is a monotonic transformation to equate the initial index numbers.

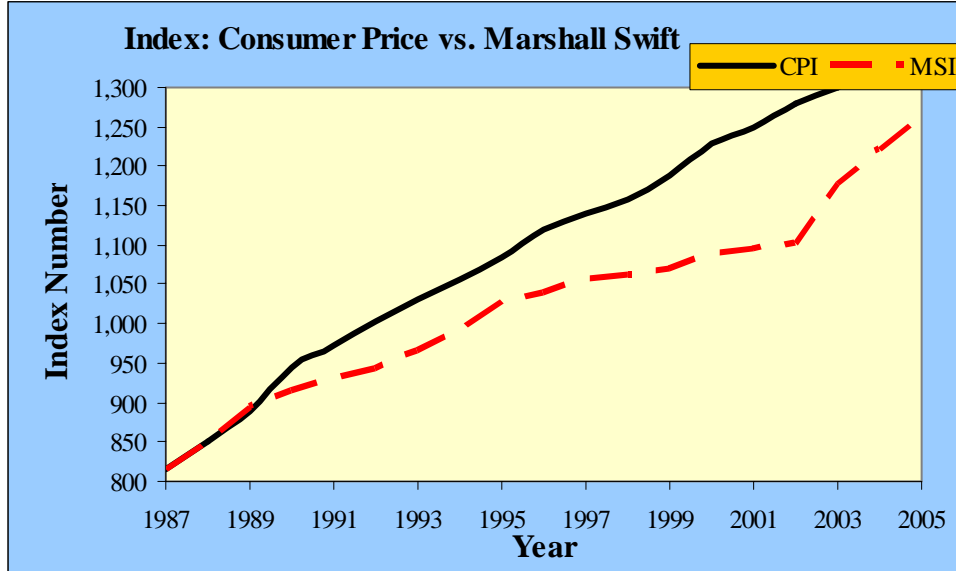
Figure 7 shows the relationship between the CPI and the MSI in graphical form and it becomes apparent that there are large differences between the CPI and MSI. The largest difference is that CPI increased more over this time period, a 36% increase in CPI compared to a 26% increase in MSI. The difference between CPI and MSI shows that economy wide changes in price levels was greater than price level changes in industrial equipment and warrants the use of the MSI as an indicator of equipment inflationary rate.

Table 3 Comparison of Price Indices: CPI vs. MSI

Comparison of Price Indices			
MSI (Chemical Engineering) CPI (BLS)			
Year	Marshall Swift Index Installed Equipment (1926 = 100)	Consumer Price Index All Goods (1982 - 1984 = 0)	Adjusted CPI All Goods
1987	814.0	115.6	814.0
1988	852.0	120.7	849.9
1989	895.0	126.3	889.4
1990	915.1	134.2	945.0
1991	930.6	138.2	973.2
1992	943.1	142.3	1,002.0
1993	964.2	146.3	1,030.2
1994	993.4	150.1	1,057.0
1995	1,027.5	153.9	1,083.7
1996	1,039.1	159.1	1,120.4
1997	1,056.8	161.8	1,139.4
1998	1,061.9	164.4	1,157.7
1999	1,068.3	168.8	1,188.7
2000	1,089.0	174.6	1,229.5
2001	1,093.9	177.3	1,248.5
2002	1,102.5	181.6	1,278.8
2003	1,178.3	184.6	1,299.9
2004	1,220.4	188.9	1,330.2
2005	1,260.9	195.3	1,375.3

Source: US BLS / Chemical Engineering [5]

Figure 7 Adjusted Consumer Price Index (CPI) vs. Marshal Swift Index (MSI)



Source: US BLS / *Chemical Engineering* [5]

Total Plant Cost Estimation and Financing

The total fixed plant costs were estimated using the equipment cost percentage method. After all the individual equipment costs were estimated as a function of their size, they were summed to return an estimate of the total equipment cost. The total estimated cost of equipment was then used to estimate the total capital costs involved in the construction of a dry mill ethanol plant. This method of capital cost estimation uses the total equipment cost estimate as a percentage of all other associated costs for a general liquid chemical production plant [13]. This method also returns an itemized set of estimates for all costs involved with the starting of a chemical plant. For example this method returns estimates of the construction, equipment installation, and engineering all as a multiple of the estimated total equipment costs.

This method claims to estimate the total costs within an accuracy of +/- 20 to 35 percent. There are two slightly different methods for the estimation of capital cost that were used in the DM model: the 'Fixed Cost Investment Percentage' (FCI) and the 'Ratio of Delivered Equipment Cost' (RDE) [13]. The RDE percentages more accurately estimated smaller capacity (10 – 40 MGY) dry mill plants while the FCI percentages more accurately estimated larger plants (65 – 100 MGY). Table 4 shows the total estimated capital cost for a 40 million gallon a year plant using the FCI method with an associated total cost of equipment of \$10,311,767.

Table 4 Dry Mill Capital Cost Estimate using FCI Method for a 40 MGY Plant

Fixed Cap Invest (FCI)			
<i>Error: (+ or - 30%)</i>			
	Itemized Expenditures	Cost Estimate	% of FCI
Direct Fixed Costs	Purchased Equip	\$10,311,767	22.9%
	Pur. Equip Instal	\$3,602,364	8.0%
	Instrumentation	\$4,232,778	9.4%
	Piping	\$3,287,157	7.3%
	Electrical	\$2,071,359	4.6%
	Buildings	\$2,071,359	4.6%
	Yard Improvement	\$810,532	1.8%
	Service Facilities	\$6,214,078	13.8%
Total Direct Capital Costs		\$32,601,393	72.4%
Indirect Fixed Costs	Engineering & Sprvsn	\$3,377,216	7.5%
	Construction Expense	\$4,142,719	9.2%
	Legal Expense	\$810,532	1.8%
	Contractors Fee	\$810,532	1.8%
	Contingency	\$3,287,157	7.3%
Total Indirect Capital Costs		\$12,428,156	27.6%
Tot Capt Cost (TCC)		\$45,029,549	100.0%
Working Capital		\$6,754,432	
Tot. Capt Invest (TCI)		\$51,783,981	

Source: DM Model Estimates / *Plant Design and Economics for Chemical Engineers* [13]

The DM model incorporates both the FCI and RDE method of capital cost estimation. FCI estimates are used as the capital cost estimate for plants in the 10 – 40 MGY range, while RDE is used to estimate capital costs for plants with annual capacities over 85 MGY. Capital costs for dry mills with plant capacities between 40 and 85 MGY are found as linear function of the two estimation methods:

$$\text{If Total Capacity (MGY)} < 40; \text{ then } f(\text{Capacity}) = 0$$

$$\text{If Total Capacity (MGY)} > 85; \text{ then } f(\text{Capacity}) = 1$$

$$\text{All Else } f(\text{Capacity}) = 1 - [(\text{Capacity (MGY)} - 40) * .0215]$$

$$\text{DM Total Capital Cost (\$)} = f(\text{Capacity}) * \text{FCI (\$)} + (1 - f(\text{Capacity})) * \text{RDE (\$)}$$

The total capital cost estimate that is calculated is then used to simulate the financing of the dry mill along with user entered values for financial variables. Users enter values in three major financial categories; loan terms, timing, and rates. Loan term variables determine the size of the loan and include requirements for: equity as percentages of total fixed investment, revenues, and sweep payments. Timing variables determine how long the build and payment periods are. Rate variables determine the yearly interest payments, and real and nominal terms. The model assumes a two year construction period in which the interest is accrued. The annual payment is first calculated in nominal terms over the user specified number of years and interest rate smf then in real terms over the same horizon. The model incorporates a sweep by allowing

the user to enter values for the percentage use of profits that may accrue over a year. The use of profits to pay back equity faster than the agreed upon loan term is a sweep payment. The financial information includes the rate of return on the investment, net present value of the plant, and other indicators of project worth. The first step is determining the total capital investment required using the total capital cost estimate:

$$\text{Working Capital (\$)} = \text{Operating Cost (\$)} * \text{Working K Required (\%)}$$

$$\text{Capital Investment (\$)} = \text{Total Capital Cost (\$)} + \text{Working Capital (\$)}$$

It is assumed that interest is accrued over the build period and added to the capital investment to return an estimate of total capital investment:

$$\text{Accrued Interest (\$)} = f(\text{Total Capital Cost (\$)}, \text{Year 1 Cost (\%)}, \text{Interest Rate (\%)})$$

$$\text{Total Capital Investment (\$)} = \text{Capital Investment (\$)} + \text{Accrued Interest (\$)}$$

The total capital investment is the amount of capital required for the project. The lender also requires an initial percentage of the total capital investment be paid by the borrower. With user entered values on the equity percentage, the amount and equity required are calculated:

$$\text{Equity Required (\$)} = \text{Total Capital Investment (\$)} * \text{Equity Percentage (\%)}$$

$$\text{Principal (\$)} = \text{Total Capital Investment (\$)} * (1 - \text{Equity Percentage (\%)})$$

Equal annual loan payments are then calculated in nominal dollars as a function of the loan amount, interest rate, and loan years:

$$\text{Loan Payment (\$/year)} = [\text{Interest Rate} * \text{Principal}] / [1 - (1 + \text{Interest Rate})^{-\text{Loan Years}}]$$

Principal and interest payments are also calculated in nominal year 1 dollars for the entire life of the loan. Each of these payments is then calculated in real dollars by deflating the nominal payments by the user entered inflationary rate:

$$\text{Real Annual Payment (\$)} = \text{Annual Payment (\$)} / (1 + \text{Inflation (\%)})^{\text{Year}}$$

Annual gross profits are calculated as the difference between annual revenue and operating costs.

$$\text{Gross Profits (\$/year)} = \text{Revenue (\$/year)} - \text{Operating Cost (\$/year)}$$

Annual revenue, in real dollar values, is calculated by multiplying the hourly flow of an output by its price. Revenue may be received for ethanol, DDGS, CO₂, and governmental subsidies.

$$\text{EtOH (gal/year)} = \text{EtOH (gal/hr)} * 8,760 \text{ (hr/yr)} * \text{Utilization (\%)}$$

$$\text{EtOH Revenue (\$/yr)} = \text{EtOH (gal/year)} * \text{EtOH Price (\$/gal)}$$

$$\text{Revenue (\$/yr)} = \text{EtOH (\$/yr)} + \text{DDGS (\$/yr)} + \text{CO}_2 \text{ (\$/yr)} + \text{Subsidy (\$/yr)}$$

Annual operating costs are comprised of indirect and direct operating costs. Direct operating costs are the costs associated with inputs that can directly be measured in the

production of ethanol, including: grain, chemicals, water, and utilities. Direct operating costs are calculated by multiplying their unit hourly flow rate by their cost per unit:

$$\text{Direct Cost (\$/year)} = \text{Flow (unit/hour)} * 8,760 \text{ (hours/year)} * \text{Utilization (\%)}$$

$$\text{Total Direct Cost (\$/year)} = \text{Sum (Direct Costs (\$/year))}$$

Indirect costs are the costs associated with producing ethanol but do not enter the process directly. These costs include labor, plant maintenance, taxes, and other miscellaneous costs. Direct costs are calculated as a function of a value that they are related to. For example annual tax costs are calculated as a function of total revenue:

$$\text{Tax Payment (\$/year)} = \text{Net Revenue (\$/year)} * \text{Tax Rate (\%)}$$

$$\text{Total Indirect Cost (\$/year)} = \text{Sum (Indirect Costs (\$/year))}$$

$$\text{Operating Cost (\$/year)} = \text{Total Indirect Cost (\$/year)} + \text{Total Direct Cost (\$/year)}$$

The sweep payment for the financial simulation is calculated as a percentage of net profits. Net profits are calculated by subtracting the minimum annual loan payment from gross payments which will then applied against the remaining principal:

$$\text{Sweep (\$/yr)} = (\text{Revenue} - \text{Operating Costs} - \text{Loan Payment (\$/year)}) * \text{Sweep (\%)}$$

Annual revenues, operating costs, and loan payment schedule are then used to calculate indicators of plant value. Net present value, benefit cost ratio, and internal rate of return are calculated for the life of the plant, with and without allowing for the payment of a sweep.

Model Validity

The DM model was checked for validity in a number of ways including; internal mass balance, comparison with other models, and compared to other sources. It was found that the model checked out based on internal mass balance, returned the same or similar values as other models, and was fairly accurate at modeling both capital costs and variable costs and revenues.

Mass balance checks were performed to indicate whether the model was closed or not. If the model was not closed the mass of inputs could only equal the mass of outputs under specific parameter values. The DM model was found to have an equal mass balance under any combination of parameter values.

The DM model was compared to a dry mill model presented by Tiffany and Eideman [15]. When the parameter values were set to the same values input and output values were found to be similar. Financial terms were also found to be the same after accounting for differences in dealing with interest accrued over the build period, which was not allowed in the TE model.

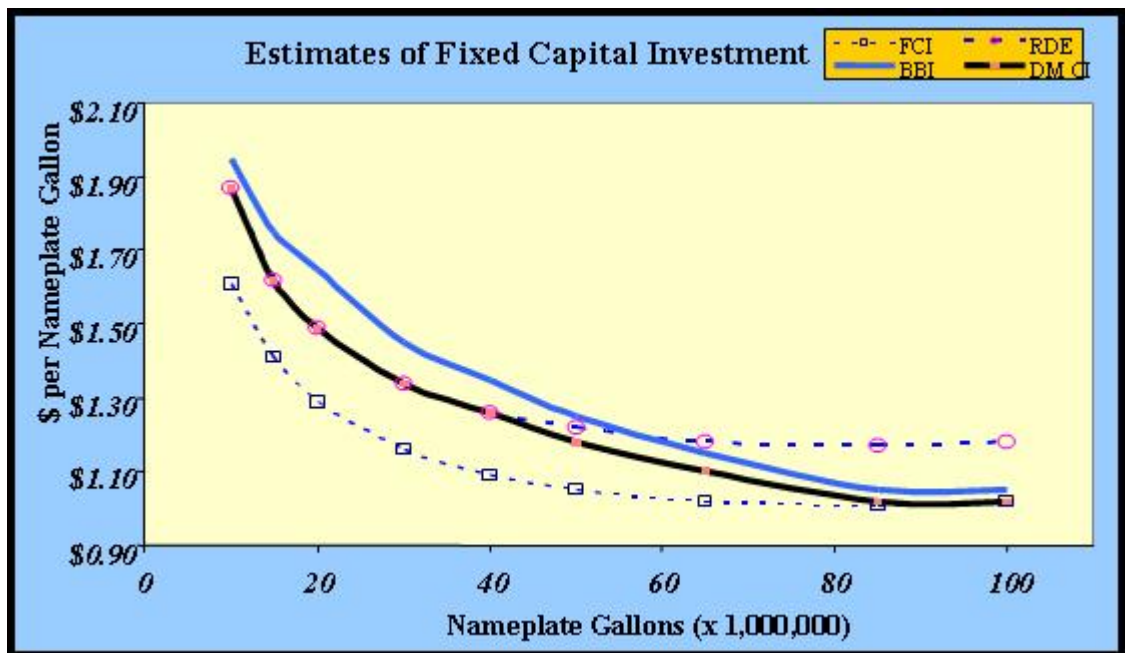
The *Ethanol Production Handbook*, published by BBI, contains a table with estimates of total fixed costs for varying sized plants [2]. When the BBI estimates were compared with the estimated total fixed costs returned by the function in the DM model (DM-TCC), using a linear combination of the FCI and RDE total capital cost estimate they were found to be quite similar (Table 5 and Figure 8). The total capital cost estimation is found to work quite well and accurately estimate the capital costs associated with all plant size ranges.

Table 5 Capital Cost Estimates: DM Model and BBI

Capital Cost Estimates: DM Model and BBI BBI Ethanol Handbook (2004)			
Annual Capacity (gal/yr)	DM Model		BBI
	Total Capital Cost	\$ / Gallon	
100,000,000	\$101,988,000	\$1.02	\$1.05
85,000,000	\$86,799,000	\$1.02	\$1.05
65,000,000	\$71,487,000	\$1.10	\$1.15
50,000,000	\$59,237,000	\$1.18	\$1.25
40,000,000	\$50,619,000	\$1.27	\$1.35
30,000,000	\$40,337,000	\$1.34	\$1.45
20,000,000	\$29,863,000	\$1.49	\$1.65
15,000,000	\$24,376,000	\$1.63	\$1.75
10,000,000	\$18,504,000	\$1.85	\$1.95
5,000,000	\$11,789,000	\$2.36	\$2.50

Source: *The Ethanol Plant Development Handbook* [2] / DM Model Estimates

Figure 8 Fixed Capital Investment Estimates DM Model and BBI



Source: BBI [2] and DM Model

To test the robustness and reliability of the DM model, its results were compared to actual ethanol plant data. The data came from a USDA survey of 25 ethanol plants conducted in 2002 [15]. Model process parameters were set to the average values from the survey, and economic parameters were set to 2002 averages. Two different plant capacities of the model

were run, 40 and 80 MGY. The resulting outputs of these runs along with the USDA averages appear in Table 6. As this table shows, the DM model variable costs, per gallon of ethanol produced, are very similar to the average responses in the 2002 survey. This would suggest that the DM model is a good representation of an average ethanol plant, which it is designed to be.

Table 6 Comparison of DM Results and USDA Survey

Variable Costs per gal EtOH Produced				
*USDA (Shapouri 2005)				
Credit / Debit	USDA (x M gal)		DM Models	
	(10 - 30)	(40 - 100)	40 MGY	80 MGY
CO2 Cred	0.004	0.006	0.010	0.015
DDGS Cred	0.243	0.261	0.299	0.271
Grain Cost	0.797	0.801	0.877	0.840
Net Feedstock	0.550	0.534	0.568	0.554
Elect	0.040	0.035	0.040	0.039
Fuels	0.161	0.110	0.160	0.112
Water	0.003	0.002	0.004	0.004
Denaturant	0.036	0.034	0.072	0.062
Enzymes	0.038	0.037	0.040	0.040
Yeast	0.004	0.005	0.010	0.006
Chemicals	0.023	0.023	0.010	0.013
Labor	0.060	0.048	0.010	0.020
Maintenance	0.040	0.047	0.020	0.052
Total Variable Cost	0.955	0.875	0.934	0.902

Source: 2002 Ethanol Cost-of-Production Survey [15] / DM Model Estimates

References

- 1) Alexander, R.J. 1994. Corn Dry Milling: Processes, Products, and Applications. Pages 351 – 371 in: Corn Chemistry and Technology. Watson, S.A. and Ramstad, P.E. eds. American Association of Cereal Chemist, St. Paul, MN
- 2) BBI International, 2003. “The Ethanol Plant Development Handbook,” Edition Four.
- 3) Boyer, C.D., and Shannon, J.C. 1994. Carbohydrates of the Kernel. Chapter 8, Pages 253 – 269 in: Corn Chemistry and Technology. Watson, S.A. and Ramstad, P.E. eds. American Association of Cereal Chemist, St. Paul, MN
- 4) DOE Energy Information Administration, (<http://www.eia.doe.gov>)
- 5) “Chemical Engineering Plant Cost Index,” Chemical Engineering, May 2005.
- 6) Evans, M.K. 1997. The Economic Impact of the Demand for Ethanol. Report to: Midwestern Governors’ Conference, Lombard Illinois.
- 7) Haas, D., Agbara, G. 2000. Tax Incentives for Petroleum and Ethanol Fuels. GAO/RCED-00-301R.
- 8) Maisch, W.F. 1994. Fermentation Processes and Products. Chapter 19, Pages 553 – 572 in: Corn Chemistry and Technology. Watson, S.A. and Ramstad, P.E. eds. American Association of Cereal Chemist, St. Paul, MN.
- 9) May, J.B. 1994. Wet Milling: Process and Products. Chapter 12, Pages 377 – 395 in: Corn Chemistry and Technology. Watson, S.A. and Ramstad, P.E. eds. American Association of Cereal Chemist, St. Paul, MN
- 10) McAloon, A., Taylor, F., Yee, W. Ibsen, K., Wooley, R. 2000. Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks. Report to: National Renewable Energy Laboratory, Golden, CO (NREL/TP-580-28893).
- 11) Musgrove, D., Dale, M.C. 2004. Feasibility Study for an Integrated Grain/Cellulose Ethanol Plant in Arizona. Report to: USDA, Washington DC, (USDA 02-025-086019322).
- 12) Orthoefer, F.T. 1994. Corn Starch Modification and Uses. Chapter 16, Pages 479 – 495 in: Corn Chemistry and Technology. Watson, S.A. and Ramstad, P.E. eds. American Association of Cereal Chemist, St. Paul, MN
- 13) Peters, M.S., Timmerhaus, K.D., and West, R.E. 2003. *Plant Design and Economics for Chemical Engineers*. McGraw-Hill, New York, NY.
- 14) Pimentel, D. 2003. Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative. Natural Resources Research, Vol. 12, No 2, June.
- 15) The Renewable Fuel Association, (www.ethanolrfa.org)

- 16) Shapouri, H., Gallagher, P., Graboski, M.S. 2002. USDA's 1998 Ethanol Cost-of-Production Survey. USDA, Agricultural Economic Report Number 808.
- 17) Tiffany, D.G., Eidman, V.R. 2003. Factors Associated with Success of Fuel Ethanol Producers. Staff Paper P03-7, Department of Applied Economics, University of Minnesota.
- 18) Watson, S.A. 1994. Structure and Composition of Corn. Chapter 3, Pages 53 – 78 in: Corn Chemistry and Technology. Watson, S.A. and Ramstad, P.E. eds. American Association of Cereal Chemist, St. Paul, MN
- 19) Weinkat, P.C., Klaaven, E., McKenzie, B.A. 1984. Alcohol Distillation: Basic Principles, Equipment, Performance Relationships, and Safety. www.ces.purdue.edu/extmedia/AE/AE-117.html
- 20) Zeochem Corporation, 2005. "Molecular Sieve Adsorbents for the Process Industries and Other Markets."