

# **Comparison of Multieffect Distillation and Extractive Distillation Systems for Corn-Based Ethanol Plants**

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## **ABSTRACT**

Recent publications on ethanol production and purification shows optimized energy and water consumptions as low as 22,000 Btu/gal ethanol and 1.54 gal water/gal ethanol respectively using multieffect distillation. Karuppiah, et al<sup>10</sup> use column rating and mathematical optimization methods and shortcut design models to design evaluate and optimize the energy and water consumption. In this work, we compare shortcut design and rigorous simulation models for an ethanol purification distillation system, and we show that distillation systems based on shortcut design underestimate the true energy and water consumption of the distillation system. We then use ASPEN Plus, to design a multieffect distillation system and an extractive distillation system using rigorous simulation and compare the two for energy and water consumptions.

We show that the extractive distillation system has lower steam and cooling water consumptions and consequently lower energy and water consumptions than multieffect distillation in corn-to-ethanol production and purification. We also show that the extractive distillation system is cheaper than the multieffect distillation system on a cost per gal ethanol basis. This work gives an energy consumption of 29987 Btu/gal ethanol and water consumptions 2.82 gal/gal ethanol for the multieffect distillation system at a manufacturing cost of \$3.03/gal ethanol. For the extractive distillation system, we calculate an energy consumption of 28199 Btu/gal ethanol and a water consumption of 2.79 gal/gal ethanol at a manufacturing cost of \$2.88/gal ethanol.

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## Table of Contents

<b>List of Figures</b> .....	v
<b>List of Tables</b> .....	vii
<b>List of Aspen Plus Simulation Files</b> .....	viii
<b>1. Introduction</b> .....	1
<b>2. Corn-to-ethanol conversion</b> .....	2
<b>3. The Pre-distillation Section</b> .....	4
<b>4. Water-Ethanol Azeotrope</b> .....	6
<b>5. Literature Review</b> .....	7
5.1 Process Modeling Simulator .....	7
5.2 Distillation Model.....	7
5.3 Example of Shortcut design versus Rigorous Simulation .....	8
5.4 Final Calculated and Reported results.....	15
5.5 Wastewater Treatment Option .....	15
<b>6. Design Alternatives</b> .....	16
6.1 The Multieffect Distillation System (MDS) .....	20
6.1.1 Beer Section.....	20
6.1.2 Rectifying Section .....	24
6.1.3 MDS Heat Integration .....	25
6.2 The Extractive Distillation System (EDS) .....	28
6.3 The Post-distillation Section .....	30
<b>7. Comparing Design Alternatives</b> .....	32
7.1 Comparing Heat Duties .....	32
7.2 Calculating Water Consumption.....	32
7.3 Water Consumption in Design Alternatives .....	34
<b>8. Reuse of Treated Wastewater</b> .....	37
<b>9. Economic Analysis</b> .....	43
<b>10. Conclusions</b> .....	48
<b>References</b> .....	49
<b>Appendix A: List of annotated figures</b> .....	55
<b>Appendix B: Energy Consumption</b> .....	68
<b>Appendix C: Water Consumption</b> .....	75
<b>Appendix D: Economic Analysis</b> .....	76

## List of Figures

Figure 1: Pre-distillation section	5
Figure 2: Extension of water-ethanol azeotrope at 0.1 atmospheres	6
Figure 3: Results from shortcut design by DSTWU model in Aspen Plus	11
Figure 4: Results of rigorous simulation using RADFRAC model from Aspen Plus	13
Figure 5: Schematic of DOA Model	17
Figure 6: Multieffect Distillation System (MDS)	21
Figure 7: Effect of LP column operating pressure on reboiler duty	22
Figure 8: Effect of LP column operating pressure on condenser duty	23
Figure 9: Effect of beer section split ratio on energy consumption	24
Figure 10: Effect of rectifying section split ratio on energy consumption	25
Figure 11: MDS heat integration	27
Figure 12: Extractive Distillation System (EDS)	29
Figure 13: Multieffect evaporators	31
Figure 14: Comparing energy consumption	32
Figure 15: Closed loops for water in cooling tower system	34
Figure 16: Comparing water consumption	35
Figure 17: Wastewater treatment scheme	42
<b>Appendix A: List of annotated figures</b>	<b>55</b>
Figure 1: Pre-distillation section	55
Figure 2: Extension of water-ethanol azeotrope at 0.1 atmospheres	55
Figure 3: Results from shortcut design by DSTWU model in Aspen Plus	56
Figure 4: Results of rigorous simulation using RADFRAC model from Aspen Plus	57
Figure 5: Schematic of DOA Model	58
Figure 6: Multieffect Distillation System (MDS)	59
Figure 7: Effect of LP column operating pressure on reboiler duty	60
Figure 8: Effect of LP column operating pressure on condenser duty	60
Figure 9: Effect of beer section split ratio on energy consumption	61
Figure 10: Effect of rectifying section split ratio on energy consumption	62
Figure 11: MDS heat integration	63

Figure 12: Extractive Distillation System (EDS)	64
Figure 13: Multieffect evaporators	64
Figure 14: Comparing energy consumption	65
Figure 15: Closed loops for water in cooling tower system	66
Figure 16: Comparing water consumption	66
Figure 17: Wastewater treatment scheme	67

## List of Tables

Table 1: Variables for shortcut calculation of duties using equations (4) to (7)	9
Table 2: Comparing results from shortcut design models and rigorous simulation	14
Table 3: Survey of related published literature with Multieffect Distillation Systems	18
Table 4: Survey of related published literature with Extractive Distillation System	19
Table 5: Energy consumption in some corn-based ethanol plants	36
Table 6: Water consumption in some corn-based ethanol plants	36
Table 7: Wastewater quality from Little Sioux Ethanol Facility	38
Table 8: Ethanol stillage characteristics	39
Table 9: Cooling tower makeup water requirements	39
Table 10: Physical, biological and chemical treatments for improving water quality	40
Table 11: Onsite testing process options for deep treatment	41
Table 12: Mild treatment economics	41
Table 13: Basis of economics and equipment sizing	43
Table 14: Estimation of capital investment cost	45
Table 15: Estimation of total product cost	46
Table 16: Cost comparison	47

## List of Aspen Plus Simulation Files

File 1: Ethanol Water Azeotrope

File 2: Shortcut Design Vs Rigorous Simulation

File 3: Multieffect Distillation System \_No Heat Integration

File 4: MDS-Multieffect Distillation System with Heat Integration

File 5: MDS- Heat Integration

File 6: MDS- Sizing Condensers

File 7: MDS- Sizing Reboilers

File 8: EDS- Extractive Distillation System

File 9: EDS- Sizing Condensers

File 10: EDS- Sizing Reboilers

Files available in the office of Dr. Y.A. Liu at Virginia Tech

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## 1. Introduction

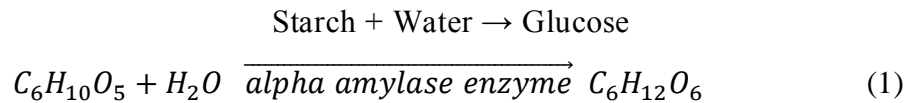
There are two main biofuel production processes; the wet milling and the dry milling (dry grind) processes. These processes are both water-intensive processes, but the dry grind process is less intensive. The United States produces over 60% of its ethanol via the dry milling process.<sup>1, 2</sup>

The dry grind ethanol process starts with the whole corn kernel. The corn kernel goes through a hammer mill where it turns to flour. It then cooks in a jet cooker where it becomes slurry. We use enzymes to treat the slurry and we add yeast to the slurry so it ferments. The effluent from the fermentation process contains ethanol and this is what we distill. The dry grind process has distillers grains as a by-product. Currently most dry grind processes use 3-15 gal water/gal ethanol. Pfromm<sup>3</sup> reports a low value of 2.85 gal water/gal ethanol. In 2010 Grossmann<sup>4</sup> reports the lowest values of 1.54 gal water/gal ethanol. The value Grossmann et al., reports comes from a shortcut design of an ethanol plant which is different from rigorous simulations.

The main focus of this work is finding the best distillation design option that optimizes energy and water savings in ethanol production and purification. Optimizing water and energy savings will eventually reduce the total annual cost. To do this we propose replacing the conventional distillation system of the dry milling process with either a multieffect distillation system or an extractive distillation system. We compare the two distillation design alternatives while keeping the pre-distillation sections and the post-distillation sections of the dry grind process the same.

## 2. Corn-to-ethanol conversion

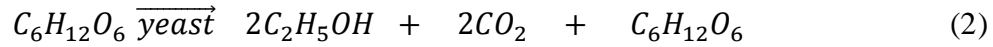
In the production of ethanol from corn, two bioprocesses must be present. The first bioprocess is a saccharification process, which is where the cellulose and/or starch in the corn enzymatically break down to monosaccharide components, such as glucose. The second required bioprocess is a fermentation process, in which the monosaccharide components (glucose) from the saccharification step convert to ethanol, normally forming carbon dioxide as a by-product. During the simultaneous saccharification and fermentation process, the saccharification is the rate limiting step. This is due to the difficulty in breaking down the cellulosic material in the corn to glucose. The enzymes in the reaction act as a catalyst and they influence the conversion of glucose from starch or cellulose<sup>2,5</sup>. Equation (1) describes the reaction of the saccharification step;



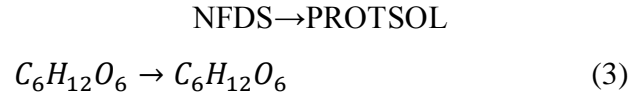
The glucose from this step then undergoes a two-step fermentation process. In the first step, the glucose converts to ethanol and carbon dioxide, and leaves some NFDS (Non-Fermentable Dissolved Solids or Sugars). NFDS are complex sugars which do not lead to the production of alcohol (ethanol). This step consists of a biphasic aerobic and anaerobic fermentation process. First with the aerobic fermentation process where the yeast “wakes up” and begins to reproduce consuming some of the sugar (glucose) to produce Adenosine Triphosphate (ATP) which is energy for reproduction. This aerobic fermentation results in yeast growth which is essential for the next step which is anaerobic fermentation. Since the system is not aerated, anaerobic fermentation occurs. In the anaerobic fermentation step, the yeast cells in the absence of oxygen consume sugar (glucose) and produce ethanol and carbon dioxide. Some starch also converts to non-fermentable sugars like xylose resulting in some left over sugars which we term Non-Fermentable Dissolved Solids (NFDS)<sup>3</sup>.

Equation (2) specifies the reaction of the first step of the fermentation process.





During this first step of the fermentation process, 100% of the fermentable glucose converts. In the second step, the non-fermentable dissolved solids or sugars (NFDS) convert to a soluble protein that we will call 'PROTSOL'. Equation (3) gives the reaction of the second step of the fermentation process.

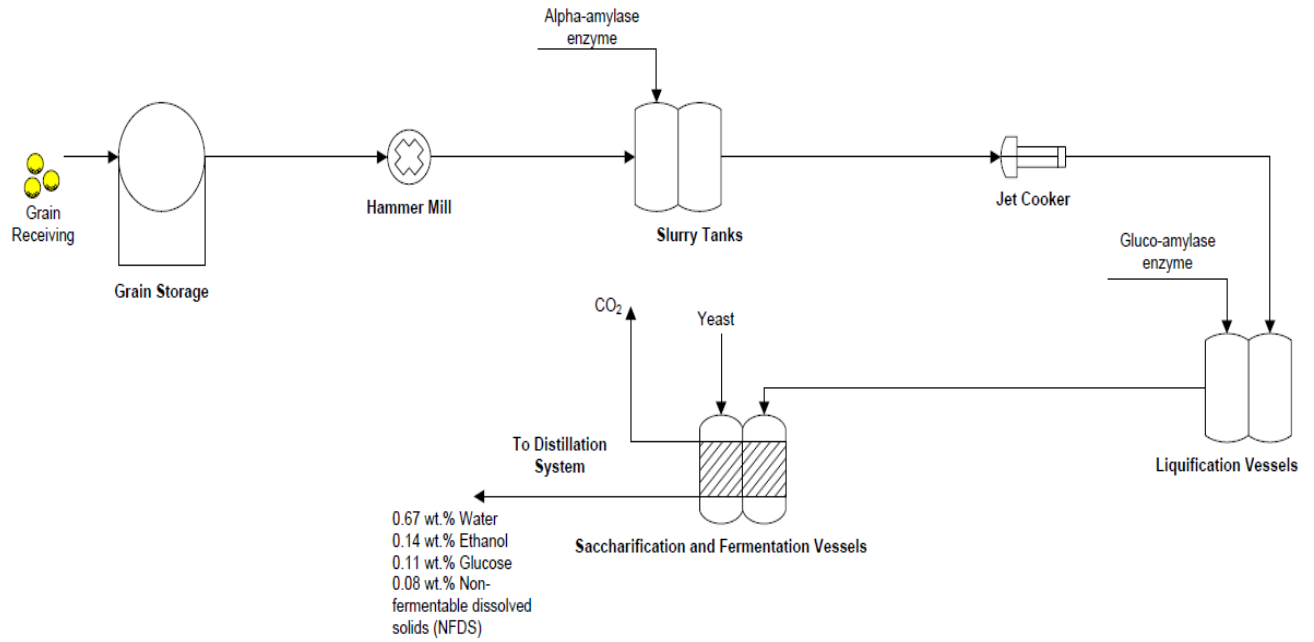


The saccharification and fermentation steps are the limiting steps in the production of ethanol from corn. In this process, we model both steps as continuous processes in a continuous stirred tank reactor<sup>4</sup>.

### 3. The Pre-distillation Section

The overall dry grind process we design has several different process units, including grain storage, grain milling, liquefaction, simultaneous saccharification and fermentation processes, distillation, dehydration, centrifugation, evaporation and drying. The grain milling process consists of 10 hammer mill corn grinders. In this section of the milling process, we mix the grains with hot water at 87.8 C. To start the conversion of starch to dextrin, we add the alpha-amylase enzyme. The next process is the jet cooker. We pump the slurry from the tanks into a jet cooker at 105 C for 5 min. This process helps hydrolyze the mash and pasteurizes the material. After the jet cooking stage, there is a secondary liquefaction step. During this process the starch inside the corn kernel converts to shorter chain dextrans. In addition, we add a second enzyme, glucoamylase, at this point. The primary and secondary liquefaction processes are batch processes. After the secondary liquefaction process, we cool the mash from 87.8 C to 32.2 C. We pump the mash to the fermentation process after this.

The next step is the simultaneous saccharification and fermentation step, in which the short chain dextrans convert to starch. We add yeast and through the fermentation process, the glucose converts to ethanol and carbon dioxide. This step is also a batch process. The effluent from the fermentation tank is composed of 67 wt% water, 14 wt% ethanol, 11 wt% glucose and 8 wt% non-dissolvable fermentable solids (sugars) and carbon dioxide dissolved in solution. Figure 1 illustrates the pre-distillation and distillation section of the dry-grind process.



**Figure 1-Pre-distillation section**

#### 4. Water-Ethanol Azeotrope

Using the property analysis tool in ASPEN Plus, we show that an azeotrope forms between ethanol and water at 95.6 wt % ethanol. Since an azeotrope exists between ethanol and water, conventional distillation is not feasible in the distillation of ethanol and water. For our design alternatives, we investigate using extractive distillation and multieffect distillation which includes vacuum distillation. Using extractive distillation with ethylene glycol as a solvent, we can break the azeotrope making distillation feasible. We also consider multieffect distillation which includes vacuum distillation columns. Using a vacuum, we can extend the azeotrope between ethanol and water. Figure 2 shows the azeotrope extended at 0.1 atmospheres.

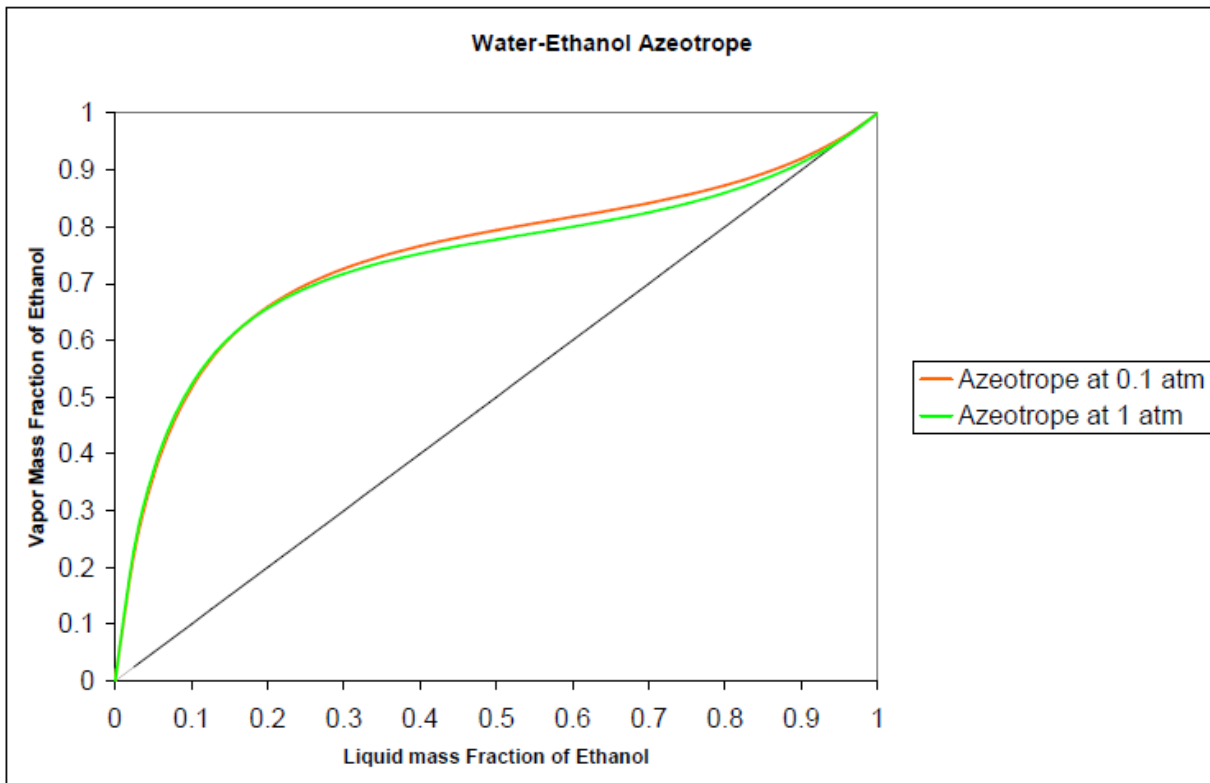


Figure 2-Extension of water-ethanol azeotrope at 0.1 atmospheres

## **5. Literature Review**

We review the published literature on ethanol production and purification using (1) multieffect distillation systems (MDS), and (2) extractive distillation systems (EDS). We compare the reported results of energy and water consumption for each publication on ethanol production. We identify the type of process model used (rigorous simulation or shortcut design), the distillation model used to design and/or optimize the distillation system, the final reported results and the wastewater treatment option. For the extractive distillation system, we also identify the solvent used.

### **5.1 Process Modeling Simulator**

The reported literatures use a number of process modeling simulators, including Aspen Plus, Aspen HYSYS, and SuperPro Designer. These simulators have mixture property and phase equilibrium data for a wide range of components. Aspen Plus simulator contains the NIST ThermoData Engine (TDE) which provides access to experimental mixture property and phase equilibrium data for over 23,000 component pairs<sup>6</sup>.

### **5.2 Distillation Model**

Rigorous models carry out stage-by-stage mass and energy balances and thermodynamic equilibrium calculations. They can accurately and consistently describe the steady state behavior of a wide range of components at different conditions. Shortcut models, such as the Fenske-Underwood-Gilliland (FUG) or the Winn-Underwood-Gilliland (WUG) methods<sup>7-9</sup> can give quick estimates of preliminary design parameters. Given the desired key component recoveries in both distillate and bottom products, the shortcut models calculate the minimum number of ideal stages required, the feed-stage location, the temperatures and heat duties of both the condenser and reboiler, the minimum reflux ratio, and the number of ideal stages required at a given operating reflux ratio. Considering the fact that short models are based on design correlations developed over 50 years ago, we should validate the accuracy of the preliminary design parameters by rigorous simulations, and make adjustments if necessary.

### 5.3 Example of Shortcut Design versus Rigorous Simulation

Using Aspen Plus, we compare the condenser and reboiler duties of distillation systems designed using two shortcut design models and a rigorous simulation model. Specifically, we compare the heat duties of condenser and reboiler obtained from the DSTWU model in Aspen Plus, and from using shortcut design equations from Karuppiah et al<sup>10</sup>. By specifying the recoveries of light and heavy key components, the DSTWU model uses the Winn method to estimate the minimum number of stages, the Underwood correlation to estimate the minimum reflux ratio, and the Gilliland correlation to estimate the number of ideal stages required at a given operating reflux ratio.

The system we design has components similar to that of a corn-based distillation system, with ethanol and water as the two main products. Since water and ethanol are polar solvents, we use the Non-Random-Two-Liquid (NRTL) activity coefficient model to calculate the phase equilibria<sup>11</sup>. In DSTWU, we specify an ethanol mass recovery of 99.6% in the overhead, and a water mass recovery of 11% in the bottoms. We also specify the number of theoretical stages and the condenser and reboiler pressures, keeping a 0.1 atm pressure drop across the column. From this, we obtain the required reflux ratio, the required feed stage and the distillate to feed ratio. Since the DSTWU performs rigorous calculations for the duties of the reboiler and condenser, we separately perform the shortcut calculations for the condenser and reboiler duties, following equations (63), (68), (85) and (88) from Karuppiah et al<sup>10</sup>, re-numbered as equations (4) to (7) below:

$$Q_{reb(BC1)} = F(BC1, Spl3) * (1 + R_{BC1}) * \Delta H_v^0(Water) * \left( \frac{T_c(Water) - T(BC1, Spl3)}{T_c(Water) - T_b(Water)} \right)^{n_{watson}} \quad (4)$$

$$Q_{reb(Rec1)} = (F(Rec1, Spl4) * R_{Rec1} - F(Rec1, Snk2)) * \Delta H_v^0(Water) * \left( \frac{T_c(Water) - T(Rec1, Snk2)}{T_c(Water) - T_b(Water)} \right)^{n_{watson}} \quad (5)$$

$$Q_{cond(BC1)} = -F(BC1, Spl2) * R_{BC1} * \sum_{h=\{ethanol, water\}} x_{f_{BC1}}(h) * \Delta H_v^0(h) * \left( \frac{T_c(h) - T(BC1, Spl2)}{T_c(h) - T_b(h)} \right)^{n_{watson}} \quad (6)$$

$$Q_{cond(Rec1)} = -F(Rec1, Spl4) * R_{Rec1} * \sum_{h=\{ethanol, water\}} x_{f_{Rec1}}(h) * \Delta H_v^0(h) * \left( \frac{T_c(h) - T(Rec1, Spl4)}{T_c(h) - T_b(h)} \right)^{n_{watson}} \quad (7)$$

Table 1 specifies the variables and their values in Equations (4) to (7).

**Table 1- Variables for shortcut calculation of duties using equations (4) to (7)**

Parameter	Description	Value	Units
$F(BC1, Spl2)$	Total flow from BC1 to Spl2 (Beer column distillate flow)	323.81	kmol/hr
$F(Rec1, Spl4)$	Total flow from Rec1 to Spl4 (rectifying column distillate flow)	187.16	kmol/hr
$F(Rec1, Snk2)$	Total flow from Rec1 to Snk2 (rectifying column bottoms flow)	136.65	kmol/hr
$R_{BC1}$	Reflux ratio of beer column	0.55	Unitless
$R_{Rec1}$	Reflux ratio of rectifying column	1	Unitless
$\Delta H_v^0(Water)$	Standard enthalpy of vaporization of water at its boiling point <sup>12</sup>	40657	kJ/kmol
$\Delta H_v^0(Ethanol)$	Standard enthalpy of vaporization of ethanol at its boiling point <sup>12</sup>	38560	kJ/kmol
$x_{f_{BC1}}(Water)$	Mass fraction of water refluxed from condenser in beer column	0.30	Unitless
$x_{f_{BC1}}(Ethanol)$	Mass fraction of ethanol refluxed from condenser in beer column	0.70	Unitless
$x_{f_{Rec1}}(Water)$	Mass fraction of water refluxed from condenser in rectifying column	0.08	Unitless
$x_{f_{Rec1}}(Ethanol)$	Mass fraction of ethanol refluxed from condenser in rectifying column	0.92	Unitless
$T(BC1, Spl3)$	Temperature of stream between BC1 and Spl3 (Beer column bottoms temperature)	375.30	K

$T(Rec1, Snk2)$	Temperature of stream between Rec1 and Snk2 (Rectifying column bottoms temperature)	373.15	K
$T_c(Water)$	Critical temperature of water <sup>12</sup>	647.10	K
$T_c(Ethanol)$	Critical temperature of ethanol <sup>12</sup>	514.15	K
$T_b(Water)$	Boiling point temperature of water <sup>12</sup>	373.15	K
$T_b(Ethanol)$	Boiling point temperature of ethanol <sup>12</sup>	351.00	K
$n_{watson}$	Exponent used in Watson's correlation <sup>6</sup>	0.38	Unitless
$Q_{reb(BC1)}$	Heat duty for beer column reboiler	5.65	MW
$Q_{reb(Rec1)}$	Heat duty for rectifying column reboiler	0.57	MW
$Q_{Reb-Total}$	Total heat duty of distillation system	6.22	MW
$Q_{cond(BC1)}$	Cooling duty for beer column condenser	-1.95	MW
$Q_{cond(Rec1)}$	Cooling duty for rectifying column condenser	-2.02	MW
$Q_{cond-Total}$	Total cooling duty	-3.98	MW

Figure 3 shows the results of the shortcut design

# SHORTCUT DESIGN

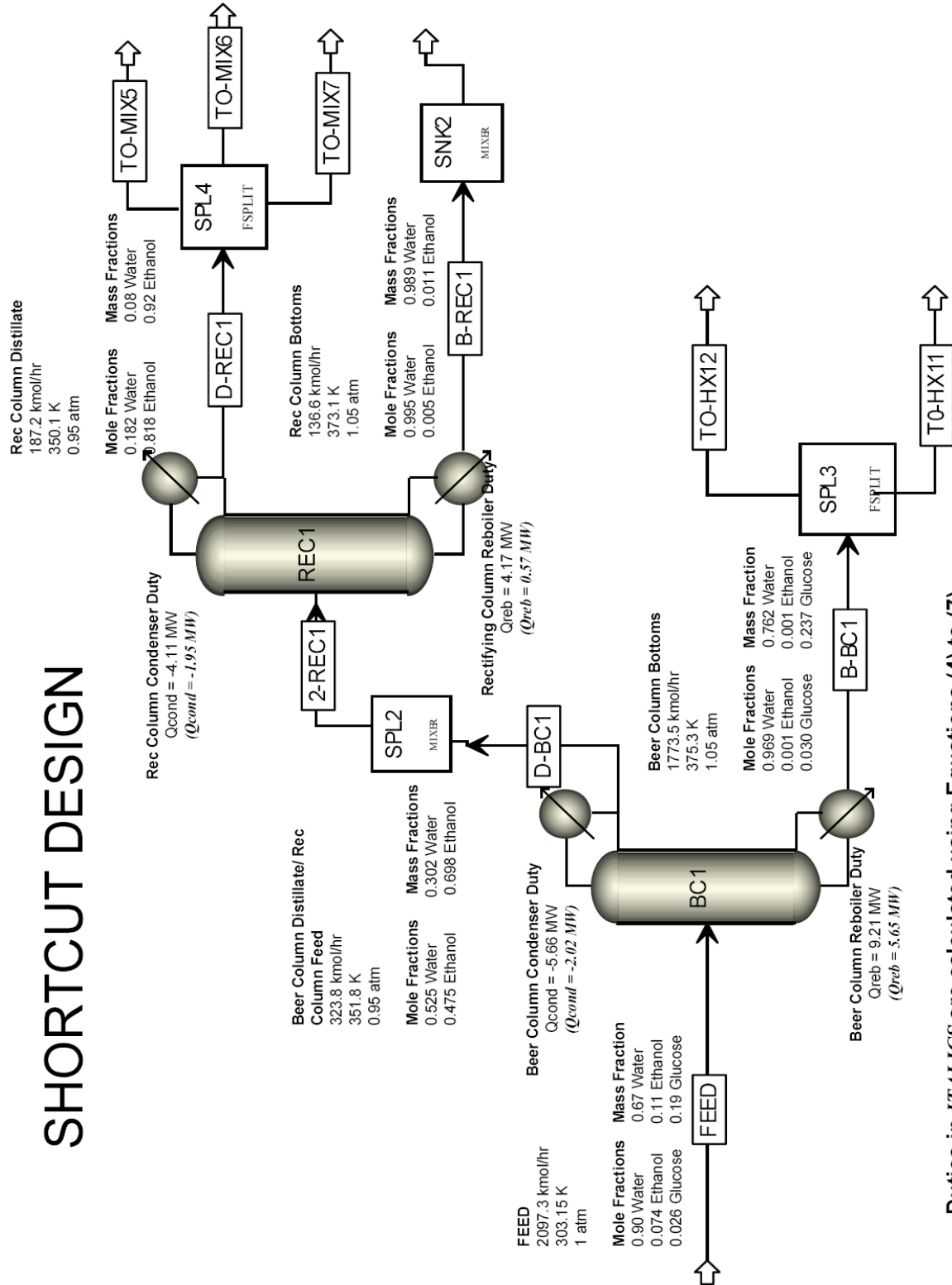


Figure 3-Results from shortcut design by DSTWU model in Aspen Plus

We use the results from the shortcut design to set the specifications for the rigorous simulation, still keeping a 0.1 atm pressure drop across the column. We set the mass recovery of both columns to 99.6% ethanol, same as the shortcut design. We also set the mass purity to the purity obtained by the shortcut design (92.01 weight % ethanol). Figure 4 shows the flowsheet for the rigorous simulation

# RIGOROUS SIMULATION

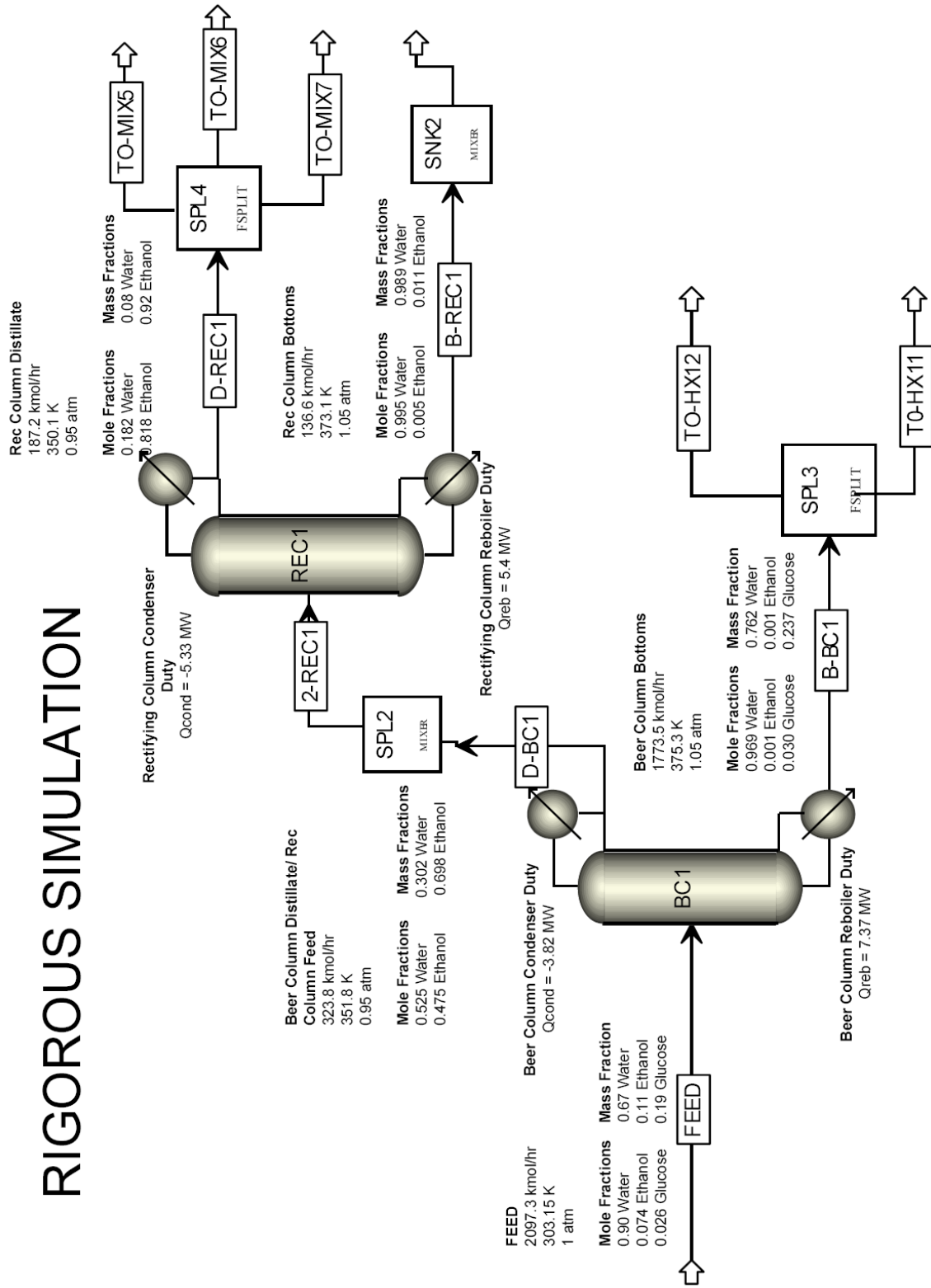


Figure 4-Results of rigorous simulation using RADFRAC model from Aspen Plus

We run the simulation and compare the total reboiler and condenser duties for the different distillation systems. Table 2 compares the reboiler duties for two shortcut design models and from the rigorous simulation.

**Table 2-Comparing results from shortcut design models and rigorous simulation**

Unit	Shortcut design: Equations (4)-(7) from Karuppiah et al <sup>10</sup>	Shortcut design: DSTWU model from Aspen Plus	Rigorous simulation: RADFRAC model from Aspen Plus
Beer column reboiler duty (MW)	5.65	9.21	7.37
Rectifying column reboiler duty (MW)	0.57	4.17	5.40
Total reboiler duty (MW)	6.22	13.38	12.77
Beer column condenser duty (MW)	-1.95	-5.66	-3.82
Rectifying column condenser duty (MW)	-2.02	-4.11	-5.33
Total condenser duty (MW)	-3.98	-9.77	-9.15

Table 2 shows that that the total reboiler duty from the rigorous simulation is 2.1 times higher than the duty from the shortcut design model using equations (4)-(5), which represents a 70% difference. The condenser duty from the rigorous simulation is 2.3 times higher than that from the shortcut design using equations (6) and (7), which represents a 78.8% differences. There is a 73.1% difference between the condenser duties calculated from equations (4)-(5) and from the DSTWU model in Aspen Plus, and a 78.8% difference between the reboiler duties calculated from equations (6)-(7) and from the DSTWU model. By contrast, the differences between the results from DSTWU and RADFRAC models in Aspen Plus for both condenser and reboiler duties are minor (6.6% and 4.7%). From this comparison, we conclude that column rating based on shortcut design models, equations (4) to (7), and the subsequent mathematical

optimization based on non-rigorous condenser and reboiler duty calculations tend to underestimate the true energy consumption.

#### **5.4 Final Calculated and Reported Results**

We identify the key results reported: energy and water consumptions and economic analysis. The most important change needed in the ethanol industry today is the optimization of energy and water consumption its production. Making ethanol a more competitive fuel requires practical and rigorous reductions in process manufacturing. Reporting a reduction in the energy and water consumption in ethanol production is one of the key factors in determining the worth of a particular design. In this work, the most efficient design we choose is the one with the lower energy and/or water consumption which resulted in lower total annual costs.

#### **5.5 Wastewater Treatment Option**

The last criterion we consider in the literature review is the option of wastewater treatment. Including a wastewater treatment option is necessary when optimizing the water consumption in ethanol production and purification. In this work, we consider water treatment and reuse to reduce the overall water consumption. Tables 3 and 4 compare the published literature and our work based on the preceding considerations.

## **6. Design Alternatives**

We model both our processes in ASPEN Plus with the help of a simulation file developed by the Department of Agriculture (DOA), which we show in Figure 5<sup>4</sup>. As described above the pre-distillation section is the same for the two distillation design alternatives. Since the distillation process is the most energy-intensive process in the corn-to-ethanol process, we focus more on optimizing this step which would greatly reduce the energy and water consumptions for the entire process.

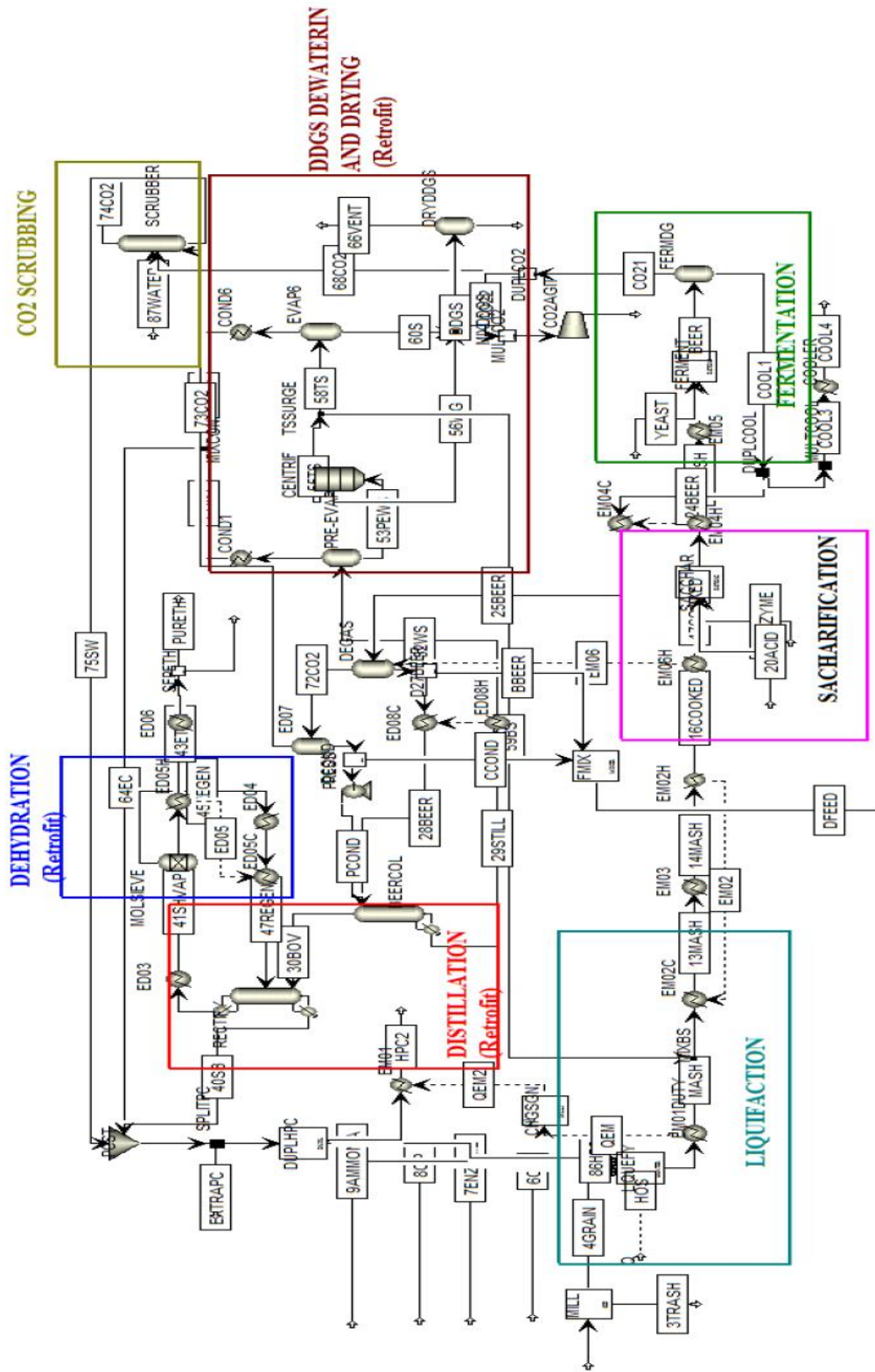


Figure 5—Schematic of DOA Model<sup>4</sup>

**Table 3-Survey of related published literature with Multieffect Distillation Systems**

Reference	Modeling tool	Distillation model	Energy usage calculation	Water usage calculation	Economic analysis	Wastewater treatment option
This work	Aspen Plus	Rigorous simulation	Yes	Yes	Yes	Yes
Xingjuan et al. (2011) <sup>13</sup>	Aspen Plus	Rigorous simulation	Yes	None	None	None
Grossmann et al. (2010) <sup>14</sup>	Mathematical Programming Techniques	Shortcut design	Yes	Yes	Yes	Yes
Karuppiah et al. (2008) <sup>10</sup>	Mathematical Programming Techniques	Shortcut design	Yes	None	None	Yes
Piccolo et al., (2007) <sup>14</sup>	Aspen Plus	Rigorous simulation	Yes	None	Yes	None
Kwiatkowski et al., (2006) <sup>15</sup>	SuperPro Designer	Rigorous simulation	Yes	None	Yes	None
Shapouri et al., (2002) <sup>16</sup>	Aspen Plus	Rigorous simulation	Yes	None	Yes	None

**Table 4- Survey of related published literature with Extractive Distillation Systems**

Reference	Modeling tool	Distillation model	Solvent	Energy usage calculation	Water usage calculation	Economic analysis	Wastewater treatment option
This work	Aspen Plus	Rigorous simulation	Ethylene glycol	Yes	Yes	Yes	Yes
Figueirêdo et al., (2011) <sup>17</sup>	Aspen Plus	Rigorous simulation	Ethylene glycol	Yes	None	None	None
Ravagnani et al. (2009) <sup>18</sup>	HYSYS simulator	Rigorous simulation	Ethylene glycol/ Tetraethylene	Yes	None	Yes	None
Hoch et al. (2008) <sup>19</sup>	MINLP/DISTIL/ HYSYS	Rigorous simulation	Ethylene glycol	Yes	None	Yes	None
Emhamed et al. (2008) <sup>20</sup>	MINLP	Shortcut design	Methanol	Yes	None	Yes	None
Ligero et al., (2003) <sup>21</sup>	Linearization	Shortcut design	Salts	Yes	None	None	None
Pinto et al. (2000) <sup>22</sup>	Aspen Plus	Rigorous simulation	Saline agents (NaCl, KCl, KI, CaCl <sub>2</sub> )	Yes	None	None	None
Lee and Pahl (1985) <sup>23</sup>	None	Experimental (Othmer-type equilibrium still)	Solvents listed below table **	None	None	None	None

\*\* Tetraethylene Glycol, Triethylene Glycol, Trimethylene Glycol, Diethylene Glycol, Ethylene Glycol, Butanediol, Glycerin, Sulfolane, N-Methylpyrrolidone, Phenylthioethanol and Di-n-Propyl Sulfon

## **6.1 The Multieffect Distillation System (MDS)**

Our MDS has two integrated beer columns and two integrated rectifying columns. We simulate and optimize each set of columns separately. Figure 6 shows a detailed schematic for the entire system.

### **6.1.1 Beer Section**

For the beer section, we have 6 manipulated variables for each column (mass distillate to feed ratio, molar reflux ratio, number of feed stages, feed stage, pressure, and the split fraction). We vary these manipulated variables to achieve the highest mass recovery at 99.9%. We investigate many different combinations of manipulated variables and the effect of the operating pressures and reflux ratio on the reboiler duty of beer column. For the purpose of heat integration, we operate the columns at different pressures.

We set the high-pressure (HP) column to atmospheric pressure, and vary the pressure of the low-pressure (LP) column for the optimum balance among the pressure, mass purity, and reboiler duty. Since there is a cost to inducing a vacuum, we investigate the effect of operating pressure on the condenser and reboiler duties for the columns. We choose the combination that gives the maximum reduction of the reboiler duty after heat integration. Figure 7 shows the relationship between the reboiler duty and the operating pressure of the LP column at the maximum attained purity (94 mass% ethanol).



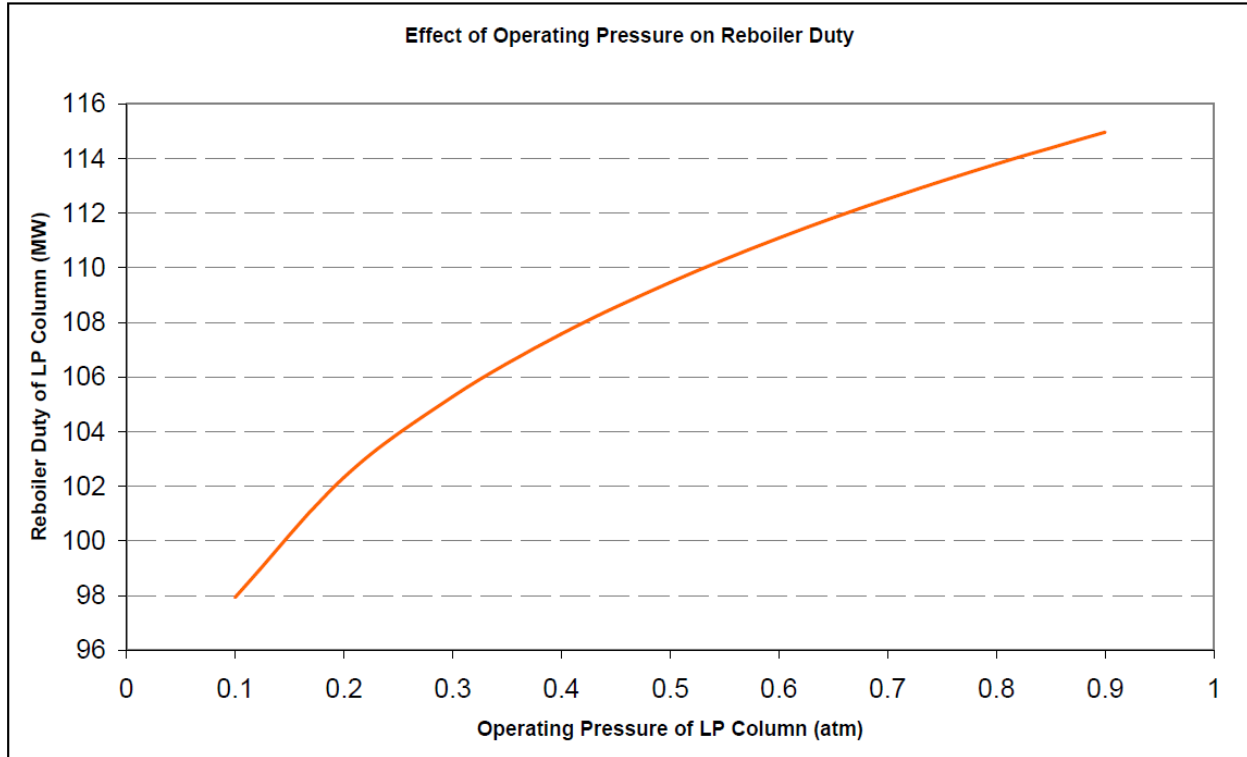


Figure 7-Effect of LP column operating pressure on reboiler duty

Figure 7 shows that the reboiler duty decreases as the operating pressure decreases. Thus, the optimum operating pressure for the LP column is the lowest operating pressure possible. Karuppiah et al. (2008)<sup>10</sup> report an operating pressure of 0.36 atm for the LP column of the beer section and an operating pressure of 0.52 atm for the LP column of the rectifying section. They also report operating pressure for the HP columns of 1.7 atm and 1.64 atm for the beer and rectifying columns, respectively. Figure 6 illustrates that going from 0.53 atm to 0.1 atm for the LP column reduces the reboiler duty by 11.5 MW, which translates into about 1477 Btu/gal ethanol.

Figure 8 shows that the condenser duty decreases as the LP column pressure increases.. When we decrease the operating pressure from atmospheric pressure to 0.1 atm, we reduce the reboiler duty by 17 MW, but only increase the condenser duty by 6.3 MW. Thus, there is a tradeoff between increasing condenser duty and decreasing reboiler duty, as we lower the LP column pressure.

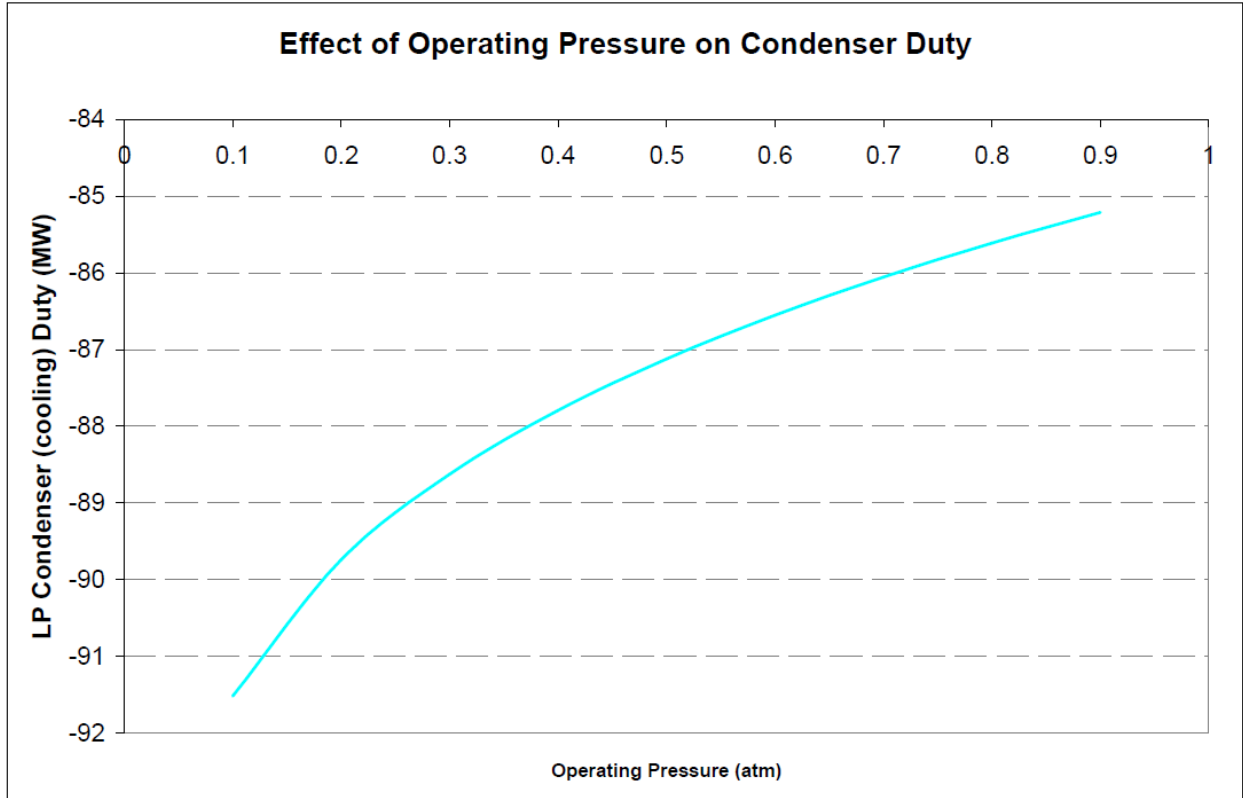


Figure 8-Effect of LP column operating pressure on condenser duty

We also investigate the effect of the split fractions on the beer columns. Since the two columns have different feed rates and operate at different pressures, different split fractions would have different effects on the total heat duty. Figure 9 shows the effect of the split fraction on the total reboiler duty (HP reboiler duty + LP reboiler duty). As the split fraction to the LP column of the beer section increases, the total energy consumption of the MDS reduces. Increasing the feed past 90% to the LP column, however, does not meet the minimum ethanol recovery of 99.6% ethanol. Karuppiah et al.,<sup>10</sup> report a split fraction of 0.09 to the LP column of the beer section and a split fraction of 0.31 to the LP column of the rectifying section. By sending 90% of the feed to the LP column as compared to 10%, we reduce the total energy consumption by approximately 5000 Btu/gal ethanol.

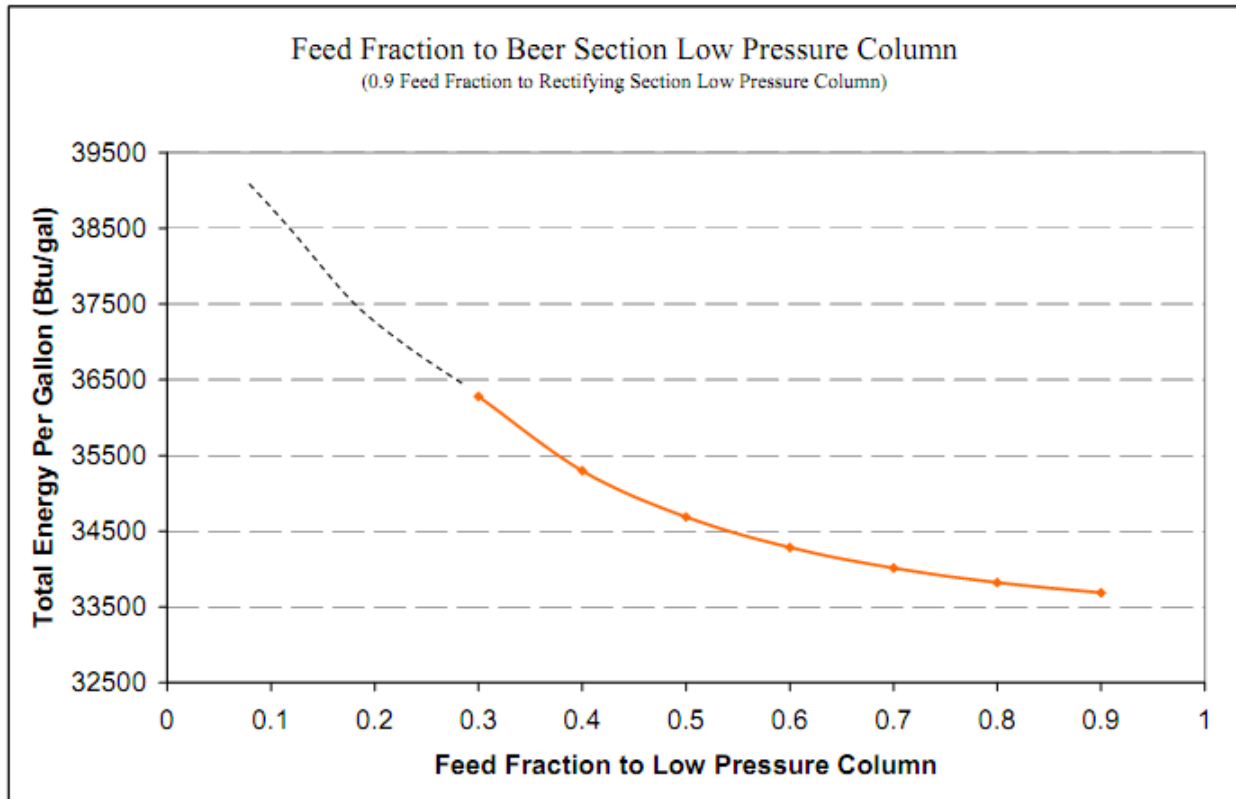


Figure 9 - Effect of beer section split ratio on energy consumption

### 6.1.2 Rectifying Section

For the rectifying section, we also have the same 6 internal manipulated variables for each column (mass distillate to feed ratio, molar reflux ratio, number of feed stages, feed stage, pressure, and the split fraction for the rectifying system). We vary these manipulated variables to achieve the highest mass recovery at 99.9%. We start by setting the split fraction to 0.5 going to the HP column and 0.5 to the LP column. We set the HP operating pressure to atmospheric pressure and set the LP operating pressure to 0.1 atm. We vary the internal specifications of each column to achieve a 94% mass ethanol purity. We find that the reboiler duty of the rectifying section decreases as operating pressure of the LP column in the rectifying section decreases. We achieve a maximum purity and the minimum reboiler duty at operating pressures of 0.1 atm for the LP column and atmospheric pressure for HP column. operating pressure.

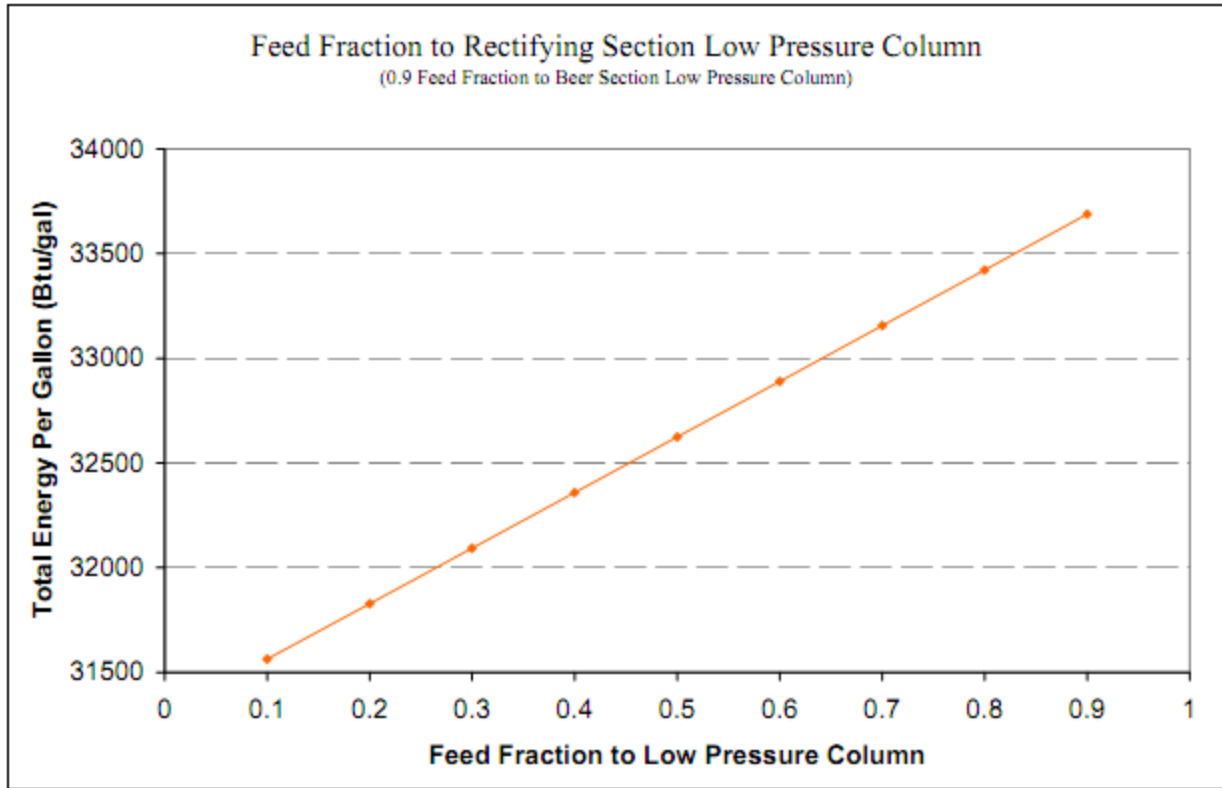


Figure 10-Effect of rectifying section split ratio on energy consumption

Figure 10 shows that the total energy consumption (before heat integration) reduces as the feed to the LP column of the rectifying section reduces. We are able to attain the minimum ethanol recovery (99.6% ethanol) at a feed fraction above 0.1 to the LP column. The total energy consumption reduces by 250 Btu/gal ethanol for every 10% feed reduction to the LP column of the rectifying section.

### 6.1.3 MDS Heat Integration

The total energy consumption we present above includes the beer and rectifying section heat integration. We perform a heat integration scheme on the MDS for the beer column and the rectifying column to decrease the reboiler duty. For the beer column, we use the reboiler stream from the HP column to serve as part of the heat source for the reboiler of the LP column. We calculated a total reboiler duty of 115 MW (392,535,452 Btu/hr) for the beer column without heat integration. With heat integration, we are able to recycle and reuse 14.8 MW (50,335,214

Btu/hr) of the heat, which is 12.8 % of the reboiler duty of the beer section. This reduction translates to a total energy usage reduction of 2112 Btu/gal ethanol.

We also perform heat integration for the rectifying section. Like the beer section, we use the HP column reboiler stream as a heat source for the LP column reboiler. With heat integration, we reduce the total heat duty of the beer section from 154 MW (525,893,545 Btu/hr) to 98 MW (333,192,157 Btu/hr), which represents a 36.7% reduction or 8085 Btu/gal ethanol. Overall, heat integration reduces the total heat duty of the MDS by 40.3%, or 10197 Btu/gal ethanol. Figure 11 shows the heat integration schemes, with dashed lines representing the hot and cold stream for integration.

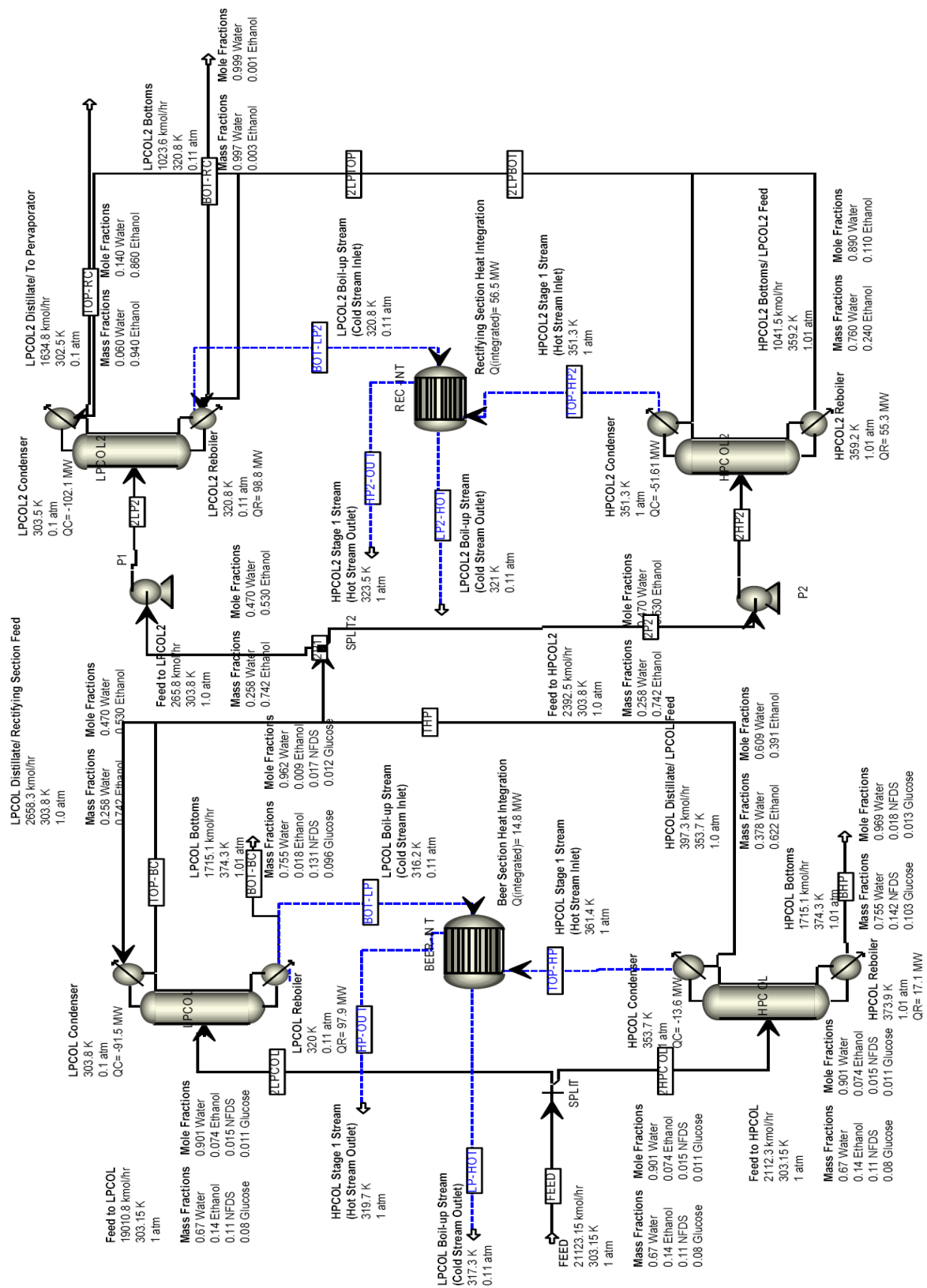


Figure 11-MDS heat integration

## 6.2 The Extractive Distillation System (EDS)

We also consider an EDS at atmospheric pressure with ethylene glycol (EG) as a solvent. We divide the EDS into 3 sections. The first is the beer section which consist of 3 columns (Col 1-1, 1-2, 1-3), the second is the rectifying section consisting of 2 columns (Col 2-1, 2-2) and the third is the solvent recovery column (Col 3).

The process begins in the beer columns (Col 1-1, 1-2, 1-3) with the separation of solids and other non-volatile compounds from water and ethanol. The first section of columns (beer section) has sieve trays for the bottom half and the top half is packed. The feed location is half way up the column in order to ensure that all solids and non-volatiles do not obstruct the packing in the top half of the column. The beer section purifies the ethanol to 87 wt%. Unlike the MDS, all the columns in the different sections have the same specifications. We split the feeds to each section equally since the split fraction has no essentially effect on the reboiler or condenser duties. We set the beer section to have a total mass recovery of 99.9% ethanol, so the bottoms product contains trace ethanol. We feed the overhead to the rectifying section which purifies the effluent to 99.5 wt% ethanol.

The bottoms product of the rectifying section contains 96.4 wt.% EG, which is 100% of the EG in the EDS. We feed the bottoms to the solvent recovery column. The overhead of the rectifying section is almost pure water with only 80 PPB EG, making it safe to recycle into the fermentation process. The water and EG components have a boiling point difference of 77°C, making it fairly easy to separate EG from water, and reuse it as a solvent.

We design the process to uses the minimum amount of EG. A low amount of EG solvent reduces the required duties of the reboiler and condenser for the ethanol purification and solvent recovery columns. Figure 12 illustrates our complete process flowsheet for the EDS.

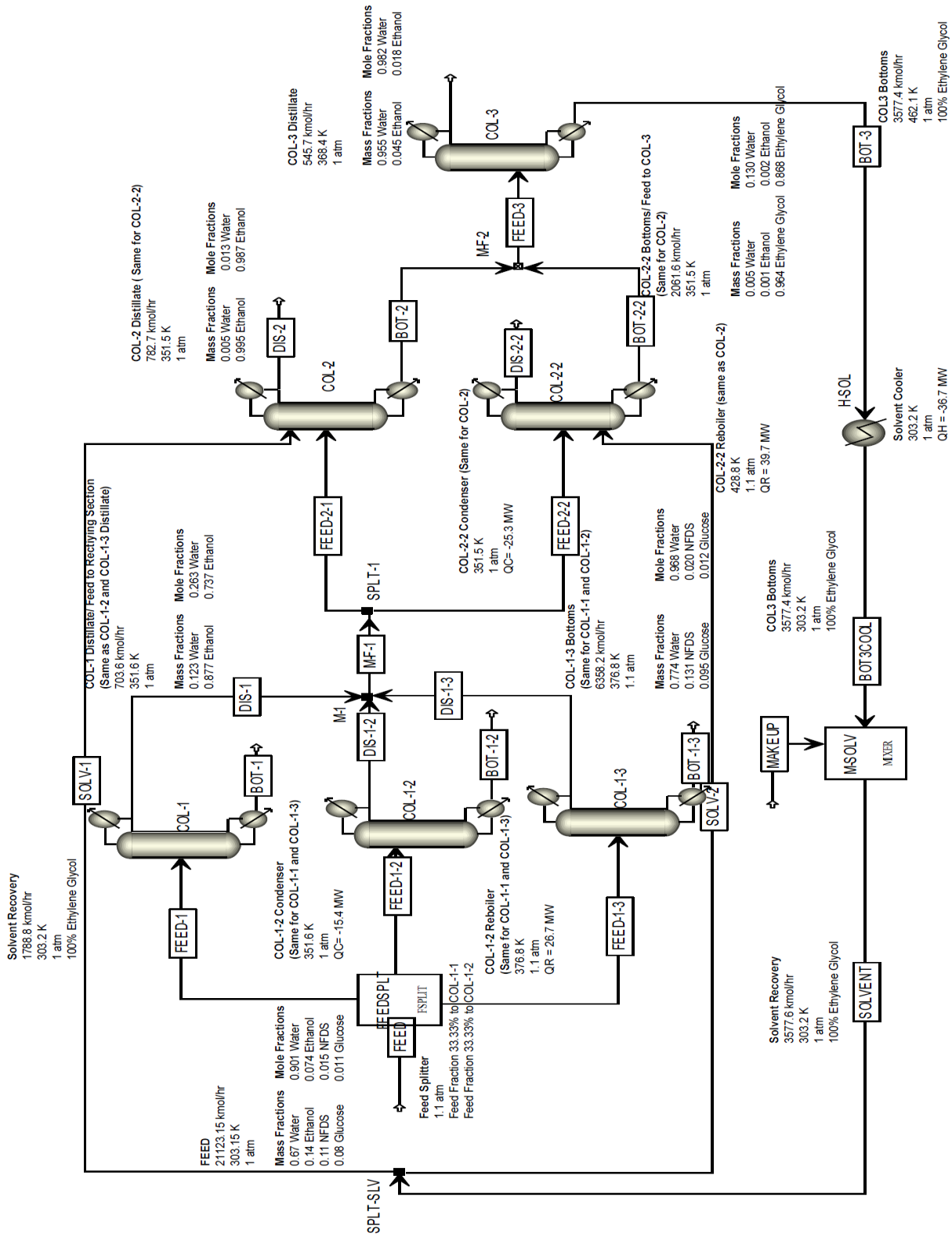


Figure 12 - Extractive Distillation System (EDS)

### 6.3 The Post-distillation Section

We use the same post-distillation section for both design alternatives. We model a centrifuge using a stream splitter, and follow the specifications from the DOA model. A design specification modifies the split fractions in the centrifuge block, and the resulting thin-stillage stream contains 53% moisture. Another split block, with a split fraction of 0.268, recycles thin stillage back to the liquefaction stage. The multieffect evaporator is nested within a hierarchy block (Figure 13). It consists of 5 effects, each 5 degrees Celsius lower than the previous effect. A steam heater provides the heat for the first effect. The vapor product passes through a condenser, which also acts as a pressure manipulator to prevent a temperature crossover, and the resulting heat duty dictates the duty of the next effect. This simulates the vapor product from one effect condensing as it heats the second effect, and so on.

A design specification varies the flow rate of the steam feed to the first effect, ensuring that the final condensate consists of 45% moisture. The condensate streams represent recycle streams, and provide water for the next fermentation. The syrup stream feeds into an atmospheric flash drum, which is the model for the dryer. A design specification varies the dryer heat-duty until the DDGS contains 7.2% moisture. In the case of the MDS system, the top product enters a pervaporator, which we model using a standard separation block, and the resulting product stream is pure ethanol. Since the water leaving the pervaporator is a vapor, we condense it before recycle.

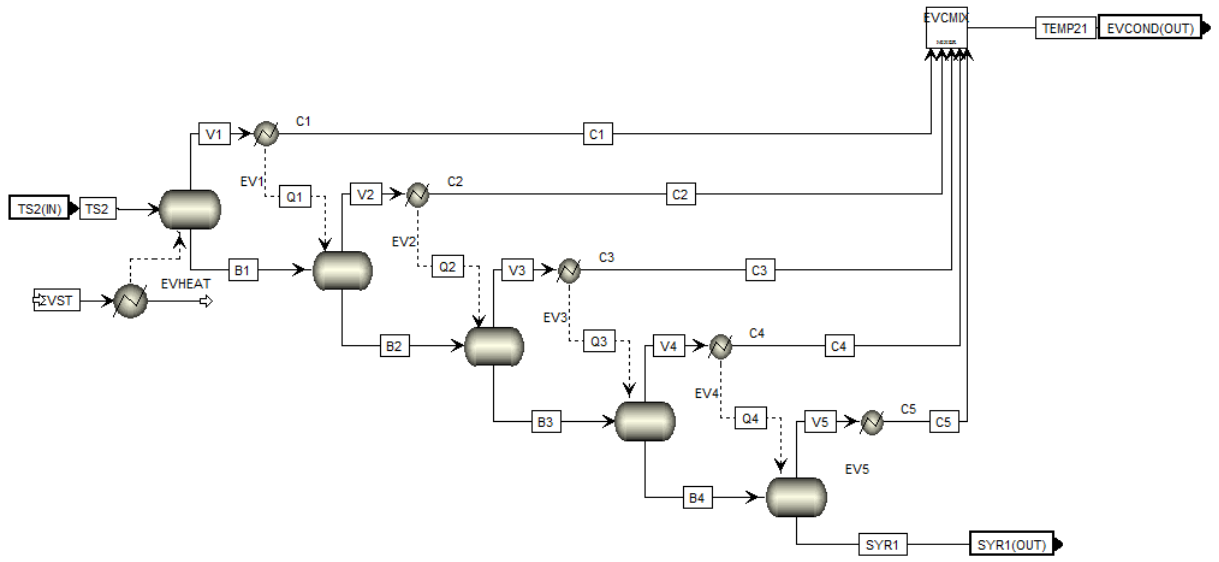


Figure 13- Multieffect evaporators

## 7. Comparing Design Alternatives

### 7.1 Comparing Heat Duties

We compare both distillation systems for energy usage. Figure 14 shows that the EDS uses the least amount of heating duty and the least amount of cooling duty for the distillation of ethanol for corn-based ethanol plants. The EDS uses 28200 Btu/gal ethanol while the MDS uses a 30000 Btu/gal ethanol, a difference of 6.1%.

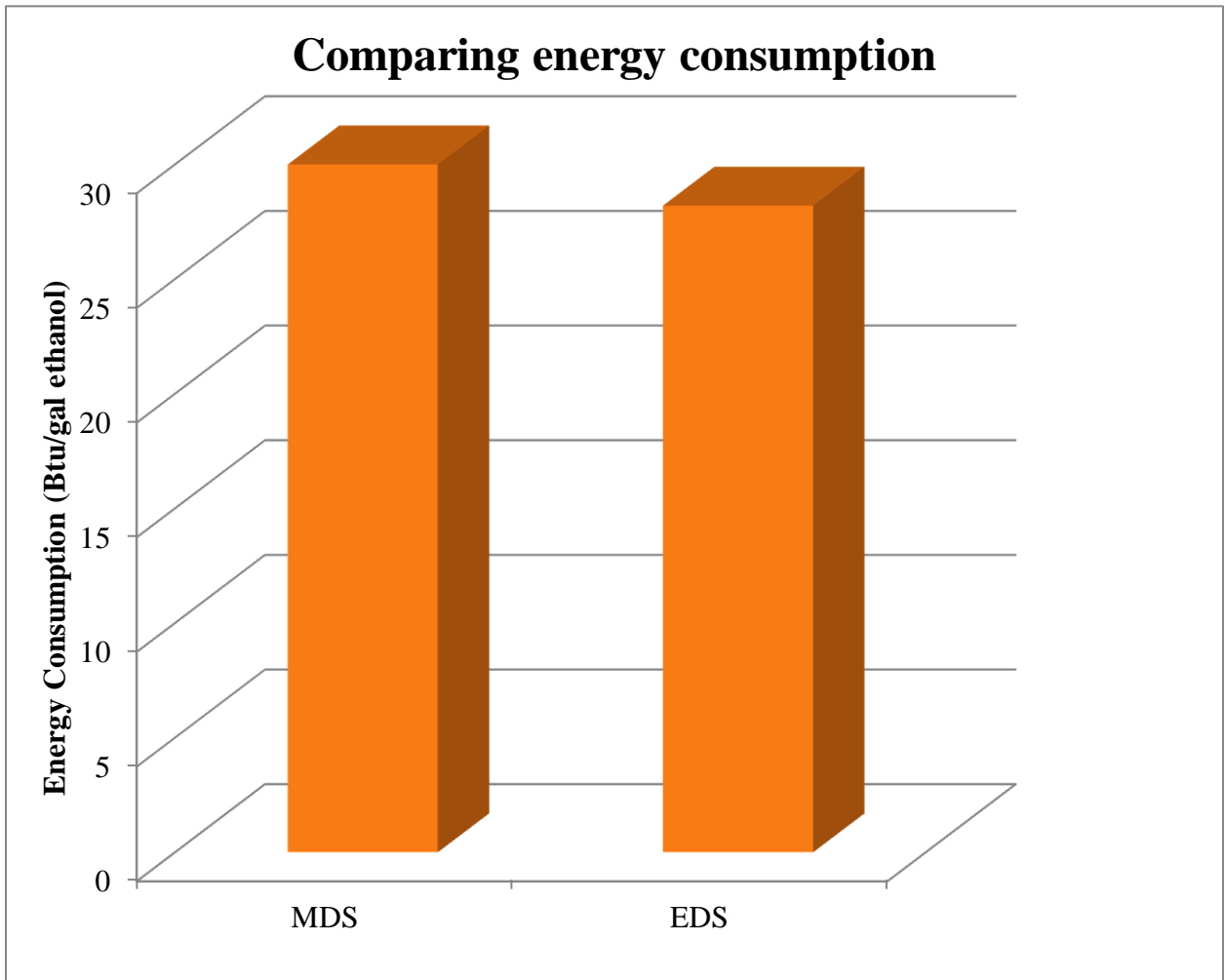


Figure 14-Comparing energy consumption

### 7.2 Calculating Water Consumption

We model all our processes in open loops to ensure convergence for all the process units. After designing and evaluating the system, we close our open loops to calculate our fresh water

consumption and energy consumption. We assume minimal losses due to boiler leaks, and determine the fraction of steam lost due to leaks to be 1/99.

To calculate the fresh makeup water needed for the whole system, we calculate water lost by drift, evaporation loss, and blow-down. To do this, we assume 6 cycles of concentration<sup>30</sup>. We define the cycles of concentration (COC) as the ratio of the concentration of dissolved salts in the blow-down to the concentration of dissolved salts in the makeup water<sup>24</sup> which we show in Equation (8):

$$COC = \frac{X_B}{X_M} = \frac{\text{dissolved solids in blowdown}}{\text{dissolved solids in makeup water}} \text{ (Mann and Liu, 1999)}^{24} \quad (8)$$

The evaporation loss in the cooling tower is the amount of cooling water lost due to evaporation. Water lost by drift is the water carried off by wind from evaporation or splashes. Drift loss depends on wind speed and it usually varies between 0.1 and 0.2 percent of the water supplied to the tower. Although there are many new technologies that can reduce drift loss to about 0.1 percent of water supplied to the tower, in calculations we use 0.2 percent. The blow-down (boiler and cooling tower) is the water which contains dissolved solids that must be removed from the cooling tower and/or the boiler, in order to avoid contaminant buildup in the cooling tower and/or boiler water<sup>25</sup>. For industrial practice, depending on the cycles of concentration, there is a maximum allowable amount of total dissolved solids (TDS). Blow-down helps keep the TDS at a minimum. Removing blow-down and adding fresh makeup water slows down mineral scale building, giving the cooling tower or boiler a longer life-time<sup>26</sup>.

We use Equations (9) to (12) to determine the evaporation and wind drift from the cooling tower, and the blow-down rate from the cooling tower and the boiler.

$$\text{Evaporation Loss} = 0.00085(\text{Water Flow})(1.8)(\text{Outlet Temp} - \text{Inlet Temp})^{27} \quad (9)$$

$$\text{Wind Drift} = 0.0002 * \text{Water Flow, gpm}^{27} \quad (10)$$

$$\text{Cooling Tower Blowdown} = \frac{\text{Evaporation} - (\text{COC} - 1)\text{Wind Drift}}{\text{COC} - 1} \quad (11)$$

$$Boiler\ Blowdown = \frac{Steam\ Flow}{cycles\ of\ concentration - 1} \quad (12)$$

Since the required makeup should be at least equal to the sum of the water lost (evaporation loss, drift loss and blow down) we use Equation (13) to calculate the minimum required makeup water;

$$M(\text{makeup water}) = E(\text{evaporation loss}) + D(\text{drift loss}) + B(\text{blow down}) \quad (13)$$

Figure 15 illustrates a closed loop of water flow between the cooling tower and the heat exchanger network.

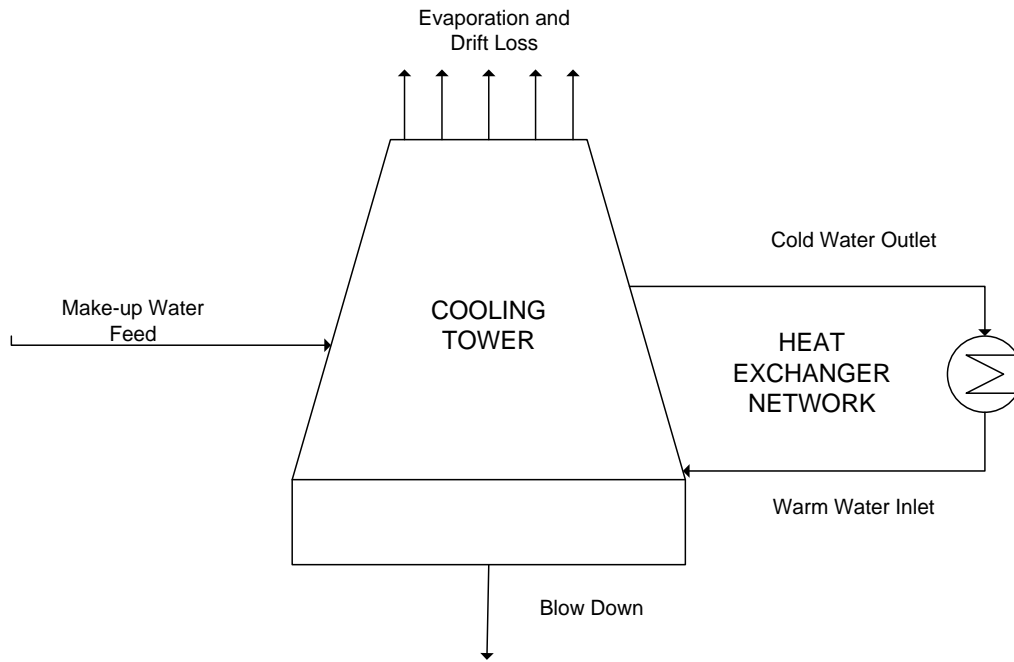


Figure 15-Closed loops for water in cooling tower system

### 7.3 Water Consumption in Design Alternatives

After closing the loops, we calculate the evaporation loss, drift loss and blow down for our different design alternatives. We add the evaporation loss, drift loss and blow down to get the required make up water for each process. We then divide the required make up water by the amount of ethanol produced by each system to get the amount of water needed per gallon of

ethanol produced. Figure 16 compares the resulting freshwater consumptions of the MDS and EDS. The EDS uses slightly less freshwater than the MDS.

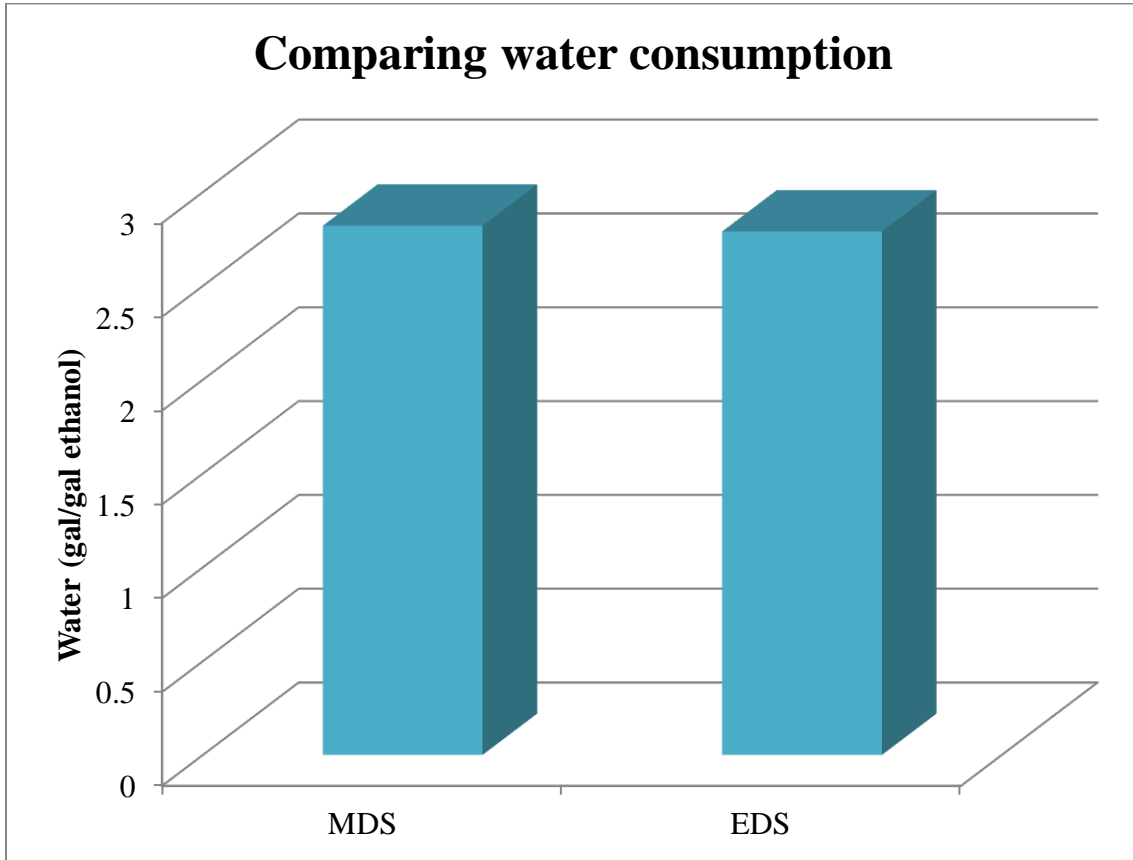


Figure 16-Comparing water consumption

Again, we show that the extractive distillation option is more efficient than the multieffect distillation option as it use less water per gallon ethanol we believe that this is closer to industrially observed values as it is generated via a rigorous process model.

We compare our results with other published literature in terms of energy consumed and water consumed. Tables 5 and 6 show the reported values of energy and water consumption in some literature on corn-based ethanol plants.

**Table 5-Energy consumption in some corn-based ethanol plants**

Reference	Energy Consumption (Btu/gal)
Primentel, (1991) <sup>28</sup>	73,687
Lorenz et al. (1995) <sup>29</sup>	53,956
Shapouri et al., (2002) <sup>16</sup>	51,779
Wang et al., (2007) <sup>30</sup>	38,323
MnTAP (2008) <sup>31</sup>	34,000
Karuppiah et al., (2008) <sup>10</sup>	21,916 <sup>i</sup>
This Document	33,471

**Table 6- Water consumption in some corn-based ethanol plants**

Reference	Water Consumption (gal/gal)
MnTAP (2008) <sup>31</sup>	3.4
Pfromm (2008) <sup>3</sup>	2.85
Grossmann et al., (2010) <sup>4</sup>	1.54 <sup>ii</sup>
This Document	2.79

## 8. Reuse of Treated Wastewater

We also perform a study on the possibility of treating the wastewater and using it as part of the utility makeup water. Improved technologies in wastewater treatment make it possible to treat most of the wastewater and reuse it. In our process, the main sources of recycle water are process wash water, boiler blowdown and cooling tower blowdown. We cannot recycle evaporation loss and drift loss water since we have no way of trapping them. Reusing the treated wastewater from these ethanol plants will further reduce the overall water consumption in the plant. In the typical dry grind corn-to-ethanol process cooling tower makeup accounts for 68% of the total makeup water and boiler blowdown accounts for 32% of the total makeup water<sup>1</sup>, thus reusing the treated wastewater from the cooling tower and boiler blowdown will tremendously reduce the freshwater consumption.

A study by the Metropolitan Council Environmental Services (MCES) shows that it is possible for ethanol plants to reuse treated wastewater from a municipal wastewater treatment plant (MWWTP)<sup>31</sup>. The discharge from the MWWTP is good enough to use as non-contact cooling water in ethanol plants. A recently built power plant in Mankato, Minnesota, takes advantage of treated wastewater. It uses the effluent from the MWWTP for cooling, thereby requiring no additional water for cooling purposes<sup>31</sup>.

In industry, the main concerns when treating cooling tower blowdown for reuse in ethanol plants are pathogens, organics, ammonia, chlorides, calcium, magnesium, heavy metals and total dissolved solids (TDS)<sup>32</sup>. Since the cooling water for the cooling tower is non-contact cooling water, the requirements are different from contact water. Using mild treatment of wastewater plant effluent allows for the reuse of the treated wastewater as the cooling tower makeup water and further deep treatment for boiler makeup water. The wastewater stream from ethanol plants is usually high in organic content and nutrients. A wastewater treatment plant in Decatur, Illinois (ADM Decatur) proposed a solution for treating such effluent streams. They use a membrane filtration system from GE Water and Process Technologies to treat these effluents. The membrane acts as a physical barrier to suspended solids and colloidal material. Their treatment of the wastewater results in high quality treated water which they use as cooling tower makeup water<sup>33</sup>.

Another example of industrial wastewater reuse in ethanol plants is a company (White Energy) in Russell, Kansas. White Energy has an ethanol plant that produces about 40 million gallons of ethanol a year since 2001. With the help of a team from GE Water and Process Technologies, White Energy created an integrated water reuse and chemical treatment strategy that recovers wastewater from the ethanol production process and recycles the treated discharge as makeup water for the plant's cooling towers. Their system of water reuse reduces the plant's annual water consumption by about 43 million gallons<sup>34</sup>.

The wastewater quality from ethanol plants depends on the quality of the water into the plant. We look at the effluent from an ethanol plant in Sioux City, Iowa (Little Sioux Ethanol Facility, Iowa). We compare the surface water, the ground water and the tower effluent water quality. Table 7 shows the water quality of the wastewater from the Little Sioux ethanol facility.

**Table 7-Wastewater quality from Little Sioux Ethanol Facility<sup>44</sup>**

Constituent (mg/L)	Surface Water	Ground Water	Tower Effluent
TDS	703	2113	3240
Ca <sup>2+</sup>	129	305	638
Mg <sup>2+</sup>	58	138	185
K <sup>+</sup>	2	0	33
Na <sup>+</sup>	20	148	297
Cl <sup>-</sup>	35	23	27
SO <sub>4</sub> <sup>2-</sup>	105	1420	2265

Most corn and cellulosic ethanol plants have similar salt, sulfate and total dissolved solids (TDS) wastewater quality as the wastewater quality from Little Sioux Ethanol facility that we show in table 7. We also examine the chemical oxygen demand (COD) levels in the stillage from ethanol plants. Table 8 shows ethanol stillage characteristics with corn as a feed stock from ethanol purification plants.

**Table 8-Ethanol stillage characteristics<sup>45</sup>**

Constituent (mg/L)	Corn (thin stillage) characteristics
COD	64500
N	755
P	1170
pH	3.3 - 4.0

We use these values as a basis for our wastewater treatment option. For our wastewater treatment option, we start with a waste water treatment plant (WWTP). We treat the wastewater from the ethanol plant until the WWTP is environmentally acceptable. We then further treat the environmentally acceptable effluent from the WWTP through mild treatment for reuse as the cooling tower makeup water and through further deep treatment for the boiler makeup water. By doing this we can further reduce the overall water consumption. Table 9 shows an example of WWTP effluent qualities and the cooling tower makeup water requirements.

**Table 9-Cooling tower makeup water requirements<sup>35</sup>**

Water Quality	WWTP effluent (example)	Cooling tower makeup water
Hardness (CaCO <sub>3</sub> ) mg/L	40 to 65	25.5
Alkalinity (CaCO <sub>3</sub> ) mg/L	20 to 160	23.2
Chloride, mg/L	70 to 200	10.0
Sulfate, mg/L	45 to 390	15.0
COD, mg/L	65 to 75 (COD <sub>Cr</sub> )	1.0 (COD <sub>Mn</sub> )
Suspended solids, mg/L	71.0	1.0
Oil, mg/L	1.5	0.0
Ammonia, mg/L	2 to 15	0.1
pH	6.5 to 7.8	6.6
Bacterial, #/mL	1.6 x 10 <sup>5</sup>	1.6 x 10 <sup>2</sup>

There are various methods of mild treatment for the WWTP effluent. Some mild treatment methods include biological filtration, multimedia filtration, and disinfection. An effective and

economical scheme for further mild treatment of WWTP effluent for reuse as cooling tower makeup water is a combination of physical, biological and chemical treatments for improving water qualities for odor control, corrosion, scaling and bacteria growth. Using different mild treatment options we can treat the WWTP effluent for various chemical oxygen demand (COD) levels. Table 10 shows how we use a combination of physical biological and chemical treatments for wastewater treatment before reuse and after reuse at different COD levels.

**Table 10—Physical, biological and chemical treatments for improving water quality<sup>35</sup>**

COD (mg/L)	Treatment before reuse	Treatment after reuse
65	Filtration and disinfection	Disinfection, corrosion, scaling control with sticky mud removal and washing
65~120	Flocculation, sedimentation, filtration and disinfection	Flocculation, sedimentation, filtration and disinfection
120~160	Aerated biological filtration, flocculation, sedimentation, filtration and disinfection	Aerated biological filtration, flocculation, sedimentation, filtration and disinfection

To implement these mild treatment options, we first choose the water treatment chemicals to control odor, corrosion, scaling and microorganism growth. After choosing the chemicals, we move on to a bench-scale static laboratory tests, then to onsite dynamic plant tests. These onsite tests last for 2 to 6 months. During the onsite tests, we gradually increasing the percentage of treated WWTP effluent being used. First we start with about 20% treated WWTP effluent and then 40% and gradually increase until 100% reuse of treated WWTP effluent.

After the mild treatment we can then begin deep treatment for use as boiler makeup water. There also various methods of deep treatment for the WWTP effluent. The most common deep treatment methods include ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). The specific method of deep treatment depends on the pretreated water quality. To implement deep treatment of the WWTP effluent, we develop testing plans based on the water quality. After developing these plans, we perform onsite tests for 2 to 3 months where we study the effects of the feed water qualities, the operating conditions and the membrane performance. After this, we

optimize the operating conditions, the RO and UF process designs, and finally the engineering design and construction. Table 11 shows some onsite testing process options for deep treatment

**Table 11-Onsite testing process options for deep treatment<sup>35</sup>**

Option	First Step	Second Step	Final Step
1	Aerated biological filter	Multimedia filter	UF and RO
2	High-efficiency fiber filter	Biological activated carbon adsorption	UF and RO
3	Aerated biological filter	Multimedia filter	UF

The cost of implementing these treatments options depends on what kind of treatment option we use. The investment costs are the pretreatment facilities and water piping. The operating costs consist of the pretreatment utilities, equipment depreciation, labor, materials, and treatment chemicals<sup>35</sup>. Table 12 gives some estimates for the investment and operating costs of the mild treatment options. Figure 17 shows the wastewater treatment and reuse scheme.

**Table 12-Mild treatment economics<sup>35</sup>**

COD (mg/L)	Pretreatment of WWTP effluent before reuse, capacity (million m <sup>3</sup> /year)	Investment cost	Operating cost of pretreatment before reuse (\$/m <sup>3</sup> )	Operating cost of treatment after reuse (\$/m <sup>3</sup> )
<65	200	117,100	0.06	0.18
65~120	200	175,610	0.09	0.18
120~160	200	439,030	0.15	0.18

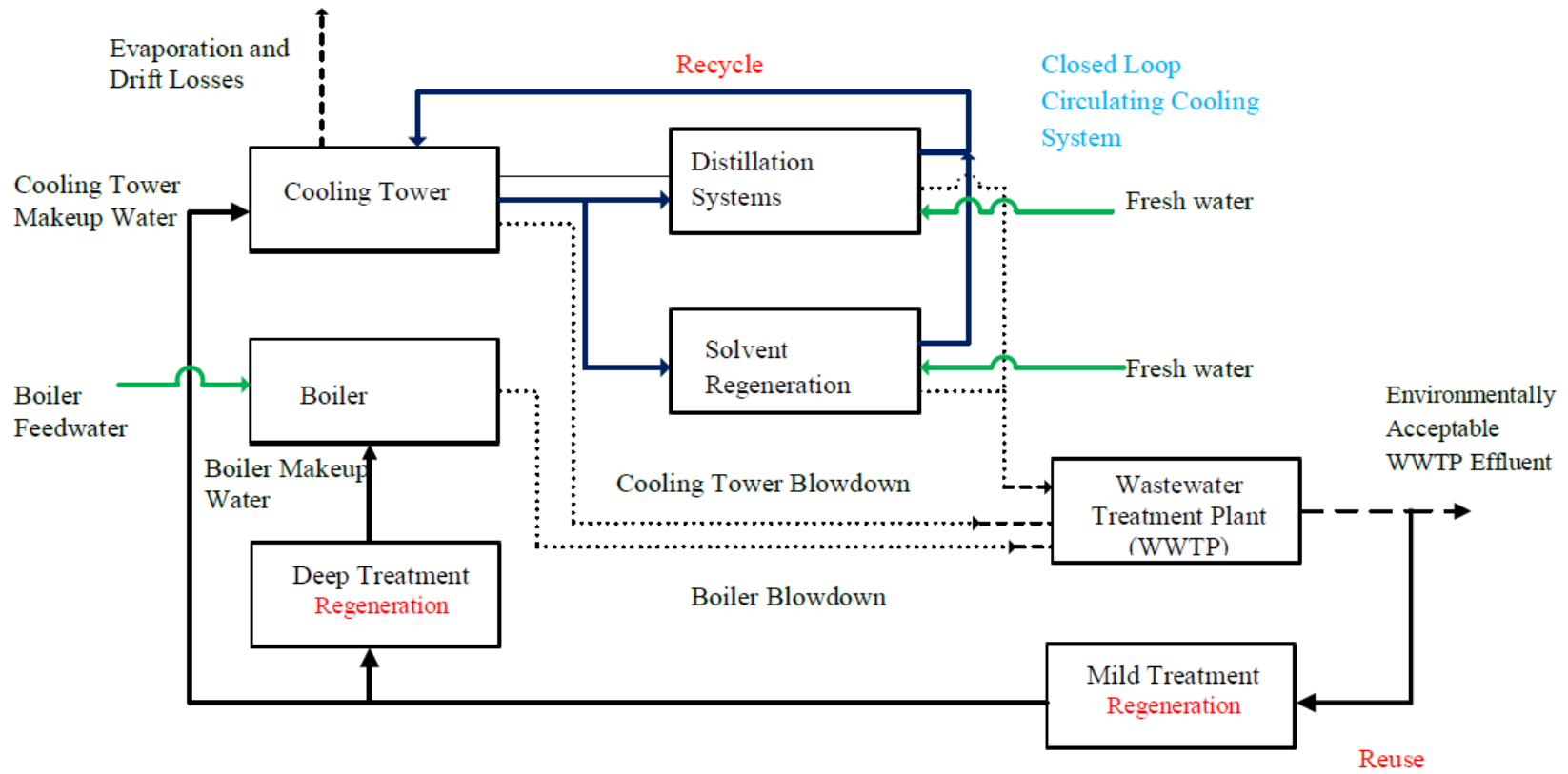


Figure 17- Wastewater treatment scheme

## 9. Economic Analysis

In order to calculate the operating costs we used the Peter-Timmerhaus<sup>39</sup> method for capital investment. We calculated the purchased equipment cost using Econ Expert. From the purchase equipment cost we were able to use the Peter-Timmerhaus method to calculate the Total Capital Investment. The raw material used by both distillation systems differs only with the addition of ethylene glycol for the extractive distillation system. Using ASPEN Plus, we calculate the steam and electricity utilities needed for each distillation system. We were then able to calculate the total annual utilities and hence the operating cost.

**Table 13-Basis of economics and equipment sizing**

### Columns

Column Diameter (m): Aspen Sizing

Column Height: Number of Trays with 2ft spacing plus 25% extra length

Column Packed Height: 80% of column height

Packing Material: Random ceramic

Column Material: Stainless Steel

### Condensers

Heat-transfer coefficient = 264 Btu/hr ft<sup>2</sup> F

Log-Mean-Temperature Difference (LMTD) = 12 F

Exchanger Area (m<sup>2</sup>): Aspen Sizing

Exchanger Material: Stainless Steel

### Reboilers

Heat-transfer coefficient = 616 Btu/hr ft<sup>2</sup> F

Log Mean Temperature Difference (LMTD) = 616 F

Exchanger Area (m<sup>2</sup>): Aspen Sizing

Exchanger Material: Stainless Steel

### Pumps

Pump shaft power: 70 kW

Pump Material: Stainless Steel

#### Storage Vessels

Total Vessel Volume (m<sup>3</sup>): 120% of volume of material stored

Vessel Material: Carbon Steel

#### Evaporator

Heat Transfer area (m<sup>2</sup>): Aspen Sizing

Evaporator Material: Stainless Steel

The capital cost for these process equipments were estimated via EconExpert.<sup>42, 43</sup> To estimate the costs, we use a Chemical Engineering Plant Cost Index (CEPCI) of 364.8

#### Energy cost

Steam = \$17.1 per ton

Electricity = \$0.05 per kW

**Table 14-Estimation of capital investment cost<sup>43</sup>**

**I. Direct Costs**

- a. Installation, including insulation and painting (35% of purchased equipment cost)
- b. Instrumentation and controls, installed (25% of purchased equipment cost)
- c. Piping, installed (30% of purchased-equipment cost)
- d. Electrical, installed (30% of purchased equipment cost)
- e. Buildings, process and auxiliary (40% of purchased equipment cost)
- f. Service facilities and yard improvements (40% of purchased equipment cost)
- g. Land (6% of purchased-equipment cost)

**II. Indirect Costs**

- a. Engineering and supervision (15% of direct costs)
- b. Construction expense and contractor's fee (15% of direct costs)
- c. Contingency (0.8% of direct costs)

**III. Fixed Capital Investment = Direct Cost + Indirect Cost**

**III. Working Capital = 15% of Total Capital Investment**

**IV. Total Capital Investment = Fixed Capital Investment + Working Capital**

**Table 15-Estimation of total product cost<sup>35</sup>**

**A. Direct Production Costs**

1. Raw Material (cost of corn + cost of chemicals + cost of yeast + cost of enzymes + cost of denaturants)
2. Operating Labor (1% of Total Product Cost)
3. Directory Supervisions (18% of Operating Labor)
4. Engineering Support (4 positions @ \$80,000 x 1.6 benefits)
5. Utilities (Energy Costs)
6. Maintenance and Repairs (5% of Fixed Capital Investment)
7. Operating Supplies (15% of Maintenance and Repairs)
8. Laboratory Charges (15% of Operating Labor)
9. Patents and Royalties (3% of Total Product Cost)

**B. Fixed Charges**

1. Depreciation (10% of Machinery and Equipment and 2% of Buildings)
2. Local Taxes (2 % of fixed Capital Investment)
3. Insurance (0.6% of Fixed Capital Investment)
4. Rent (10% of Buildings)

**C. Plant Overhead Cost (10% of Total Product Cost)**

**D. General Expenses**

1. Administrative Cost (15% of Operating Labor Supervision and Maintenance)
2. Distribution and Selling Cost (2% of Total Product Cost)
3. Research and development Cost (5% of Total Product Cost)
4. Financing (interest) (5% of Total Capital Investment)

**I. Manufacturing Cost = Direct production costs + Fixed charges + Plant Overhead cost**

**Total Product Cost = Manufacturing Cost + General Expenses**

**Annual Operating Cost = 120% of Total Product Cost**

$$\text{Total Annual Cost} = \frac{\text{Capital Cost}}{\text{Payback Period}} + \text{Energy Cost}^{42}$$

Payback period = 5 years

**Table 16-Cost comparison**

	Dry-grind with MDS	Dry-gind with EDS
Total Capital Investment	\$269,734,700	\$296,607,000
Total Annual Utilities	\$294,034,400	\$266,450,000
Total Product Cost	\$550,777,700	\$523,317,900
Annual Operating Cost	\$605,855,500	\$575,649,700
Total Annual Cost	\$85,451,100	\$53,177,000
Cost Per Gallon	\$3.03	\$2.88

We show that the dry-grind process with extractive distillation is cheaper and more efficient than that with multieffect distillation.

## 10. Conclusions

Biofuel production is a viable and potentially promising source of alternative energy. Since the Biofuel production and recovery process is a water intensive process, as biofuel production and recovery plants become more popular exploited, industrial water consumption would also increase. Water and energy are extensively used in industry. This work presents a detailed comparison of two identical dry-grind process with different distillations systems; extractive and multieffect distillation. The key highlights of this report are;

- A brief summary of existing literature on ethanol production and purification via biomass.
- A brief summary of reported values of energy and water consumption in ethanol production and purification.
- An overall description of the dry-grind process.
- A detailed design and comparison of short cut design and rigorous simulation.
- A rigorous design (using ASPEN Plus) of identical dry-grind process with different distillation options.
- A description of both ASPEN Plus distillation designs.
- A detailed and fair comparison between multieffect distillation and extractive distillation for ethanol purification in terms of energy consumption, water consumption, cost and overall efficiency.
- A description of the heat integration method used in multieffect distillation.
- A description of industrial wastewater treatment options applicable to corn-based ethanol plants.

## References

- 1) Aden, A.; Water Usage for Current and Future Ethanol Production. *National Renewable Energy Laboratory*, Sept.-Oct. **2007**.
- 2) Renewable Fuels Association, 2007. Available from: <<http://www.ethanolrfa.org>>.
- 3) Pfromm, P.H. The Minimum Water Consumption of Ethanol Production via Biomass Fermentation. *The Open Chemical Engineering Journal* **2008**, 5, 1-2.
- 4) Grossmann, I. E.; Mariano, M. Energy and Water Optimization in Biofuel Plants. *Chinese Journal of Chemical Engineering* **2010**, 18 (6), 14-22.
- 5) Butzen, S.; Haeefele, D. Dry-grind Ethanol Production from Corn. *Crop Insights*. **2008**, 18 (11), 1-4.
- 6) Wooley, R. J.; Putsche, V. Development of an ASPEN PLUS Physical Property Database for Biofuels Components. *Golden, Colorado: NREL*, **1996**, PDF.
- 7) Fenske, M. R. Fractionation of Straight-run Pennsylvania Gasoline. *Ind. Eng. Chem. Res.* **1932**, 24, 482.
- 8) Underwood, A. J.V. Fractional Distillation of Multicomponent Mixtures- Calculation of Minimum Reflux Ratio. *J. Inst. Pet.* **1946**, 32, 614-626.
- 9) Gilliland, E. R. Multicomponent Rectification. *Ind. Eng. Chem. Res.* **1940**, 32, 1220.
- 10) Karuppiah, R.; Peschel, A.; Mariano, M.; Martinson, W.; Zullo, L.; Grossmann, I.E. Energy Optimization for the Design of Corn-based Ethanol Plants. *AIChE Journal*. **2008**, 54 (6), 1499-1525.

- 11) Renon H.; Prausnitz J. M. Local Compositions in Thermodynamic Excess Functions for Liquid Mixtures. *AIChE Journal*. **1968**, 14, 135–144.
- 12) Yaws, C.L. Chemical Properties Handbook. *McGraw-Hill*. **1999**.
- 13) Xiangjuan, Q.; Lingdong, S. Study of New High Efficiency Energy-Conservation Multieffects Bio-Ethanol Distillation Technology. *Advance Materials Research*. **2011**, 627 (32), 236-238.
- 14) Piccolo, C.; Bezzo, F. Ethanol from lignocellulosic biomass: A comparison between conversion technologies. *Computer-aided chemical engineering*. **2007**, 24, 1277–1282.
- 15) Kwiatkowski, J.; McAloon, A.; Taylor, F.; Johnston, D. Modeling the Process and Costs of Fuel Ethanol Production by the Corn Dry-grind Process. *Industrial Crops and Products*. **2006**, 23 (3), 288-296.
- 16) Shapouri, H.; Duffield, J. A.; Wang, M.; The energy balance of corn ethanol: An update. *USDA, Office of Energy Policy and New Uses, Agricultural Economics*. **2002**, 813, 20.
- 17) Feitosa De Figueiredo, M.; Guedes, B.P.; Monteiro De Araujo, J.M.; Vasconcelos, L.G.; Brito, R.P. Optimal Design of Extractive Distillation Columns-A Systematic Procedure Using a Process Simulator. *Chemical Engineering Research and Design*. **2011**, 89.3, 341-346.
- 18) Ravagnani, M.A.S.S.; Reis, M.H.M.; Maciel Filho, R.; Wolf-Maciel, M.R. Anhydrous Ethanol Production by Extractive Distillation: A Solvent Case Study. *Process Safety and Environmental Protection*. **2010**, 88, 67-73.

- 19) Hoch, P.M.; Espinosa, J. Conceptual Design and Simulation Tools Applied to the Evolutionary Optimization of a Bioethanol Purification Plant. *Ind. Eng. Chem. Res.* **2008**, 47 (19), 7381-7389.
- 20) Emhamed, A. M.; Czuczai, B.; Rev, E.; Lelkes, Z. Analysis of extractive distillation with mathematical programming. *Ind. Eng. Chem. Res.* **2008**, 47, 9983–9995.
- 21) Ligeró, E.; Ravagnani, T. Dehydration of Ethanol with Salt Extractive Distillation: A Comparative Analysis between Processes with Salt Recovery. *Chemical Engineering and Processing.* **2003**, 42 (7), 543-552.
- 22) Pinto, R.T.P.; Wolf-Maciél, M.R.; Lintomen, L.; Saline Extractive Distillation Process for Ethanol Purification. *Computers & Chemical Engineering.* **2000**, 24 (2-7), 1689-1694.
- 23) Fu Ming, L.; Pahl, R.H. Solvent Screening Study and Conceptual Extractive Distillation Process to Produce Anhydrous Ethanol from Fermentation Broth. *Industrial & Engineering Chemistry Process Design and Development.* **1985**, 24 (1), 168-172.
- 24) Mann, James G., and Y. A. Liu. *Industrial Water Reuse and Wastewater Minimization.* McGraw-Hill, **1999**.
- 25) Alliance for Water Efficiency.  
<[http://www.allianceforwaterefficiency.org/cooling\\_tower\\_intro.aspx](http://www.allianceforwaterefficiency.org/cooling_tower_intro.aspx)>.
- 26) Drinking Water Contaminants. *EPA Office of Water Home | Water | US EPA*; available at <http://water.epa.gov/drink/contaminants/index.cfm#listmcl> (accessed 24 August 2011)
- 27) Green, D.W.; Perry, R. H. *Perry's Chemical Engineers' Handbook.* **2008**, 8<sup>th</sup> edition, 12-20.

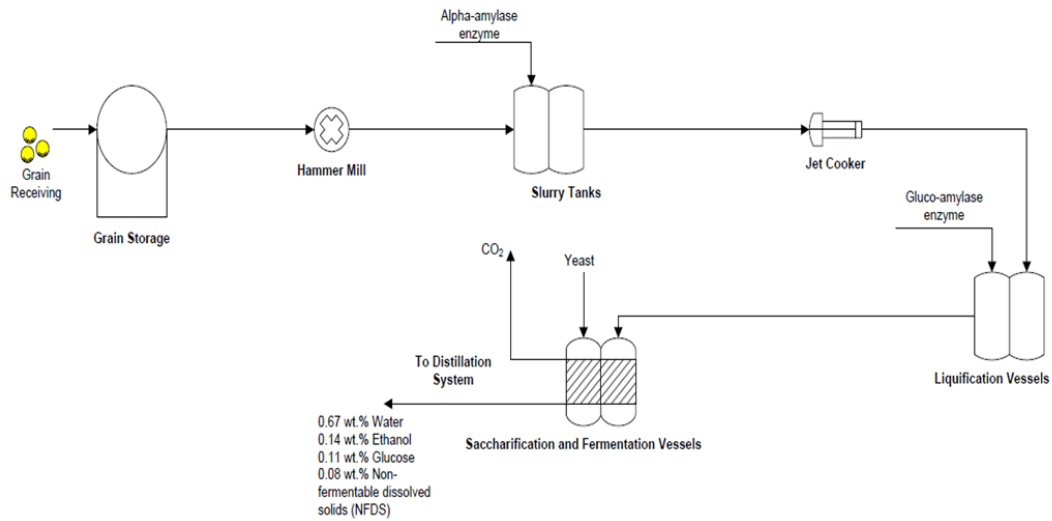
- 28) Pimentel, D. Ethanol fuels: Energy security, economics, and the environment. *J. Agric. Environ. Ethics*. **1991**, 4, 1–13.
- 29) Lorenz, D.; Morris, D. How Much Energy Does it Take to Make a Gallon of Ethanol? Revised and Updated. *Institute for Local Self-Reliance*. **1995**, PDF.
- 30) Wang, M.; Wu, M.; Huo, H. Life-Cycle Energy and Greenhouse Gas Emission Impacts of Different Corn Ethanol Plant Types. *Environ. Res. Lett.* **2007**, 2, 1-13.
- 31) Minnesota Technical Assistance Program, MTAP, Ethanol Benchmarking and best practices. The production process and potential for improvement available at, [www.mntap.umn.edu/MnTAP%20Ethanol%20Report.pdf](http://www.mntap.umn.edu/MnTAP%20Ethanol%20Report.pdf) (accessed 24 August 2011).
- 32) Manning, D. Minnesota Ethanol Facilities and Wastewater Reuse. *Metropolitan Council Environmental Services*. **2006**
- 33) ADM Decatur. Case Study: Tertiary Treatment of Grain Processing Wastewater for Reuse. *GE Water and Process Technologies*. PDF
- 34) GE. Water Reuse Helps White Energy Save over \$200,000 per Year. *GE Water and Process Technologies*. **2006**. PDF
- 35) Liu, Y.A. How to Develop and Implement Substantial Water Savings in Global Top 10 Chemical Companies. Second Gregory D. Botsaris lecture, Department of Chemical and Biological Engineering, Tufts University, Medford, Massachusetts, October (2008); Keynote Opening Address, Annual Meeting, Chemical Industry and Engineering Society of China, Zhengzhou, Henan, October 22 (2011).

- 36) United States, Environmental Protection Agency, May 1998, EPA 833-F-98-002, Office of Water (4204), available at; <http://www.epa.gov/npdespub/pubs/bastre.pdf>. (accessed September 1 2011)
- 37) Hultz, B.; Krichten, R.; DiFranco, P.; Greenwood, E.; Harrison, G. Technologies for Industrial Water Reuse. *GE Water and Process Technologies*. PPT.
- 38) CDM. Treating Brackish Water In Sandoval County. *CDM*. **2010**. Available at [http://westcas.com/PDF/Winter\\_2010\\_presentations/Treating\\_brackish\\_water\\_Sandoval\\_County\\_Fowlie.pdf](http://westcas.com/PDF/Winter_2010_presentations/Treating_brackish_water_Sandoval_County_Fowlie.pdf). (accessed August 2011)
- 39) Peters, M. S.; Timmerhaus, K. D.; West, R. E. Plant Design and Economics for Chemical Engineers. *McGraw-Hill, New York*. 2003, 5<sup>th</sup> edition.
- 40) Palligarnai, V.T; Gael D. Ulrich, G.D. EconExpert. *Chemical Engineering Process Design*. <http://www.ulrichvasudesign.com/econ.html>. (accessed Aug 2011)
- 41) Palligarnai, V.T.; Ulrich, G.D. Chemical Engineering Process Design and Economics: A Practical Guide. *Process Pub*. **2004**.
- 42) Diemer, R.B.; Luyben, W.L. Design and Control of a Methyl Acetate Process Using Carbonylation of Dimethyl Ether. *Ind. Eng. Chem. Res.* **2010**, 12224-12241.
- 43) Renon, H.; Prausnitz, J. M. Local Compositions in Thermodynamic Excess Functions for Liquid Mixtures. *AIChE J.* **1968**, 14(1), 135–144.
- 44) Parkin, G.; Weyer, P.; Just, C.L. Riding the Bioeconomy Wave: Smooth Sailing or Rough Water for the Environment and Public Health? *Proceedings of the 2007 Iowa Water Conference—Water and Bioenergy*, **March 6, 2007**, Iowa State Center, Ames, Iowa. Available online at <http://www.aep.iastate.edu/water/2007/parkin.html>

45) Wilkie, A.C.; Riedesel, K.J.; Owens, J.M. Stillage Characterization and Anaerobic Treatment of Ethanol Stillage from Conventional and Cellulosic Feedstocks. *Biomass and Bioenergy*. **2000**, 19, 63-102.

46) Aspen Plus. Aspen Plus Bioethanol from Corn Stover Model. *Aspen Technology*, July **2008**. PDF

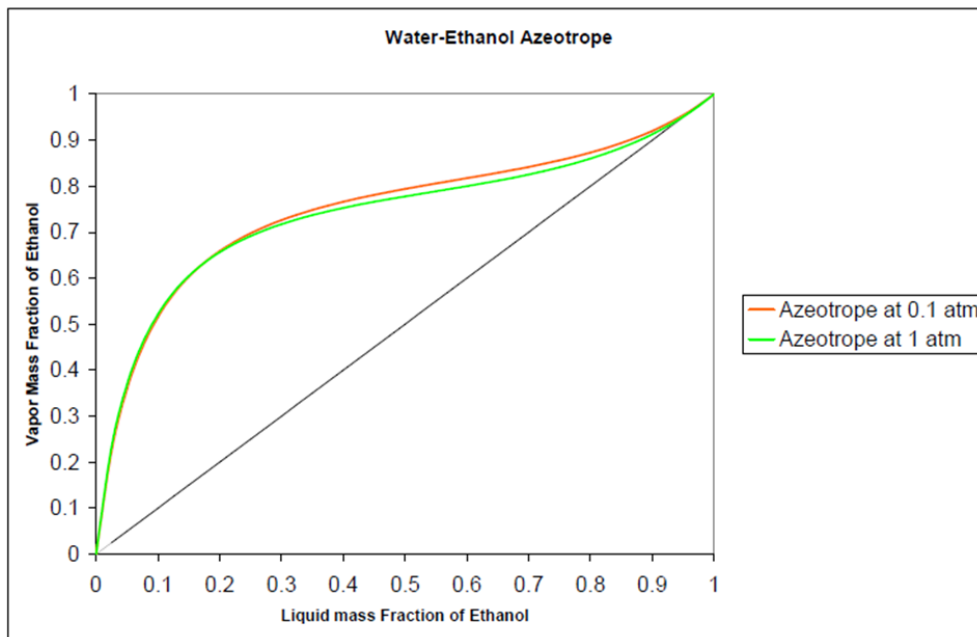
## Appendix A: Annotated list of figures



1.

**Figure 1-Pre-distillation section-**

Figure 1 illustrates the predistillation section of the dry grind process. It illustrates how the corn feed to the dry grind process goes through grain storage to a hammer mill for mashing, then to slurry tanks with the addition of enzymes and to jet cooker, liquefaction vessels and finally saccharification and fermentation and vessels in preparation for distillation.

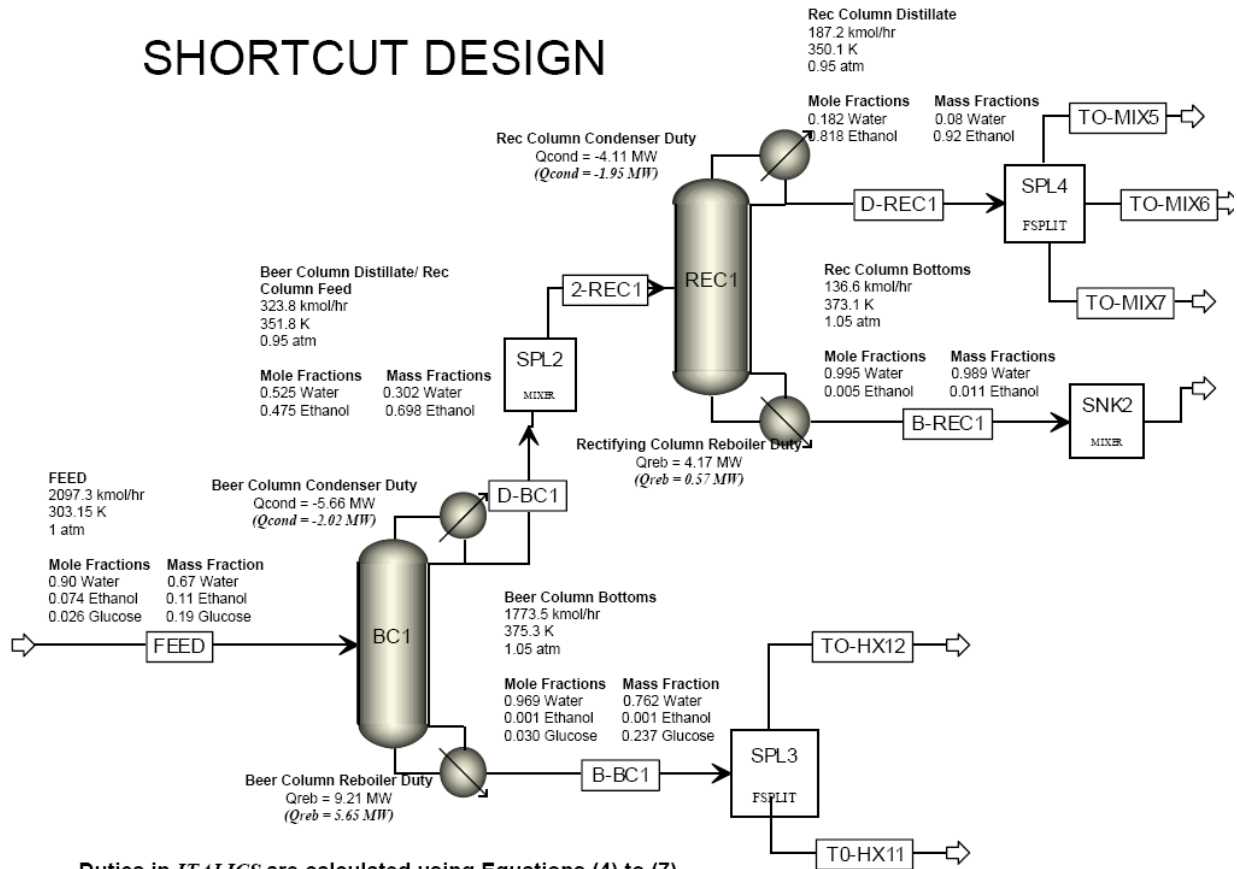


2.

**Figure 2-Extension of water-ethanol azeotrope at 0.1 atmospheres**

Figure 2 shows the azeotrope that occurs between the mixture of water and ethanol at atmospheric pressure and at 0.1 atmospheres.

## SHORTCUT DESIGN

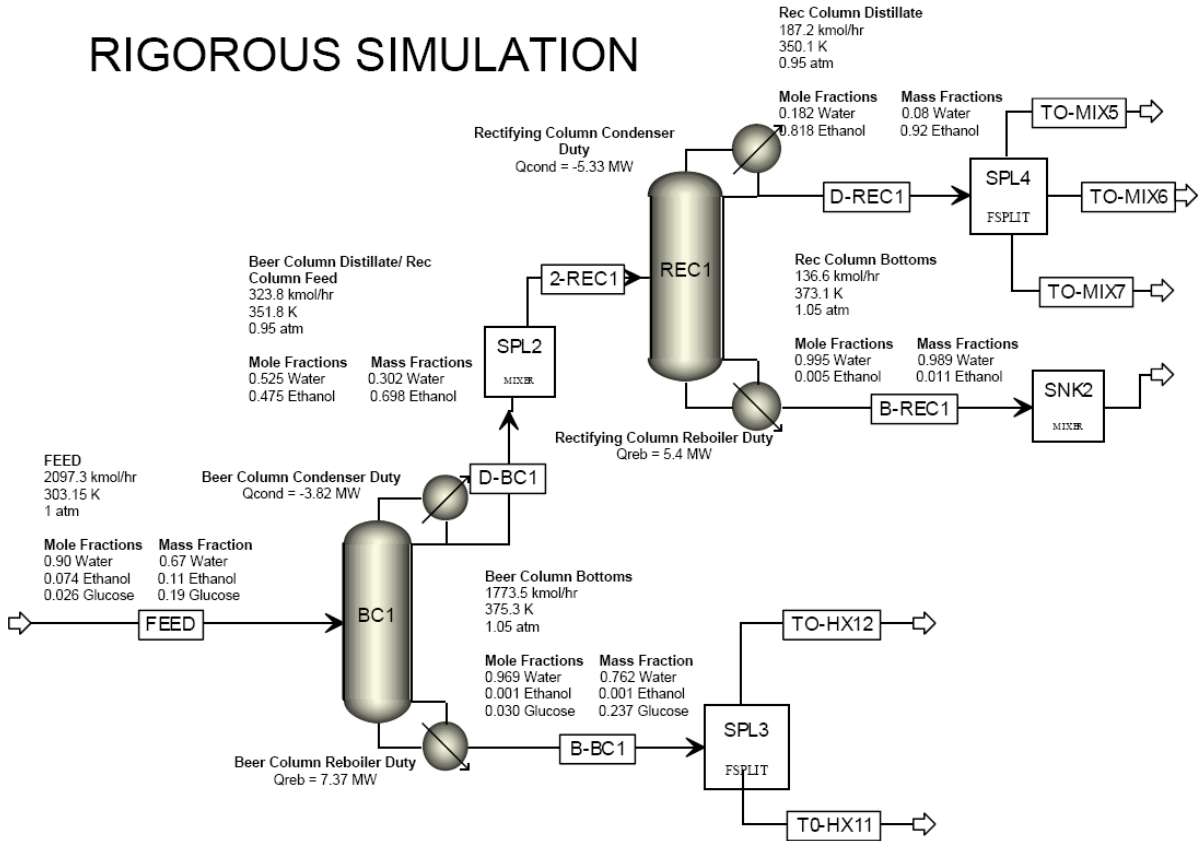


3. Duties in *ITALICS* are calculated using Equations (4) to (7)

Figure 3-Results from shortcut design by DSTWU model in Aspen Plus

Figure 3 shows a conventional distillation system for the distillation of corn to ethanol. The figure shows the shortcut calculations (non-rigorous stage by stage mass and energy calculations) of the energy consumption of the distillation system performed using equations and Aspen Plus software.

# RIGOROUS SIMULATION



4.

Figure 4-Results of rigorous simulation using RADFRAC model from Aspen Plus

Figure 4 shows a conventional distillation system for the distillation of corn to ethanol. The figure shows the values from the rigorous (stage by stage mass and energy balance calculations) of the energy calculations using Aspen Plus modeling software.

5.

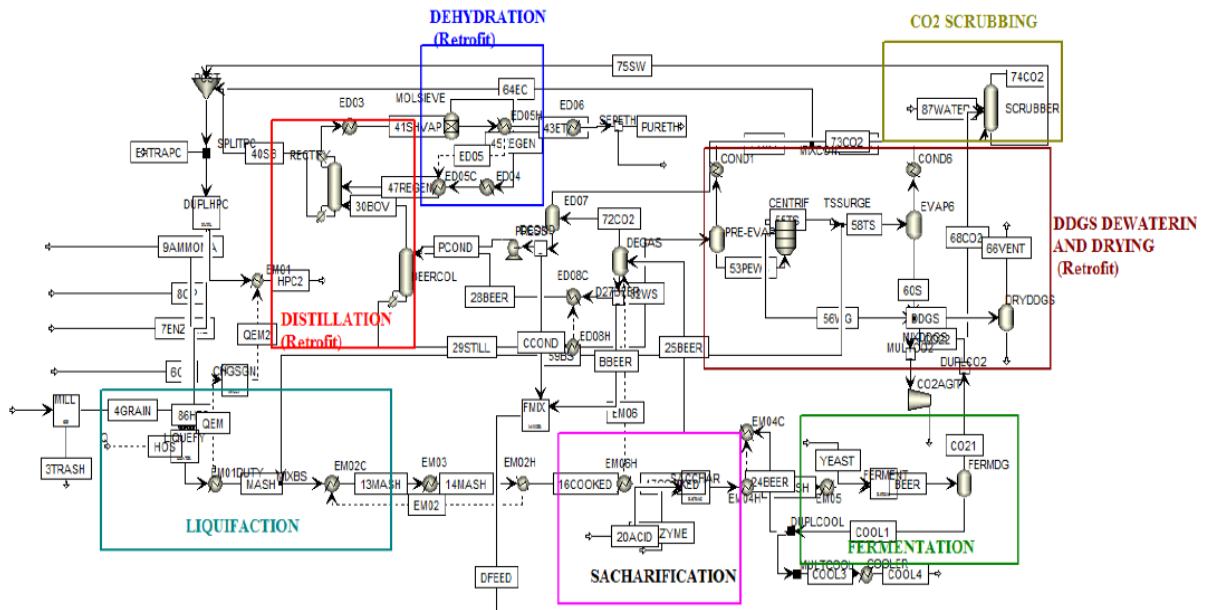


Figure 5-Schematic of DOA Model

Figure 5 is derived from Aspen Plus. (Aspen Plus. Aspen Plus Bioethanol from Corn Stover Model. Aspen Technology, July 2008. PDF) It shows the entire dry grind process modeled using Aspen Plus.

6.

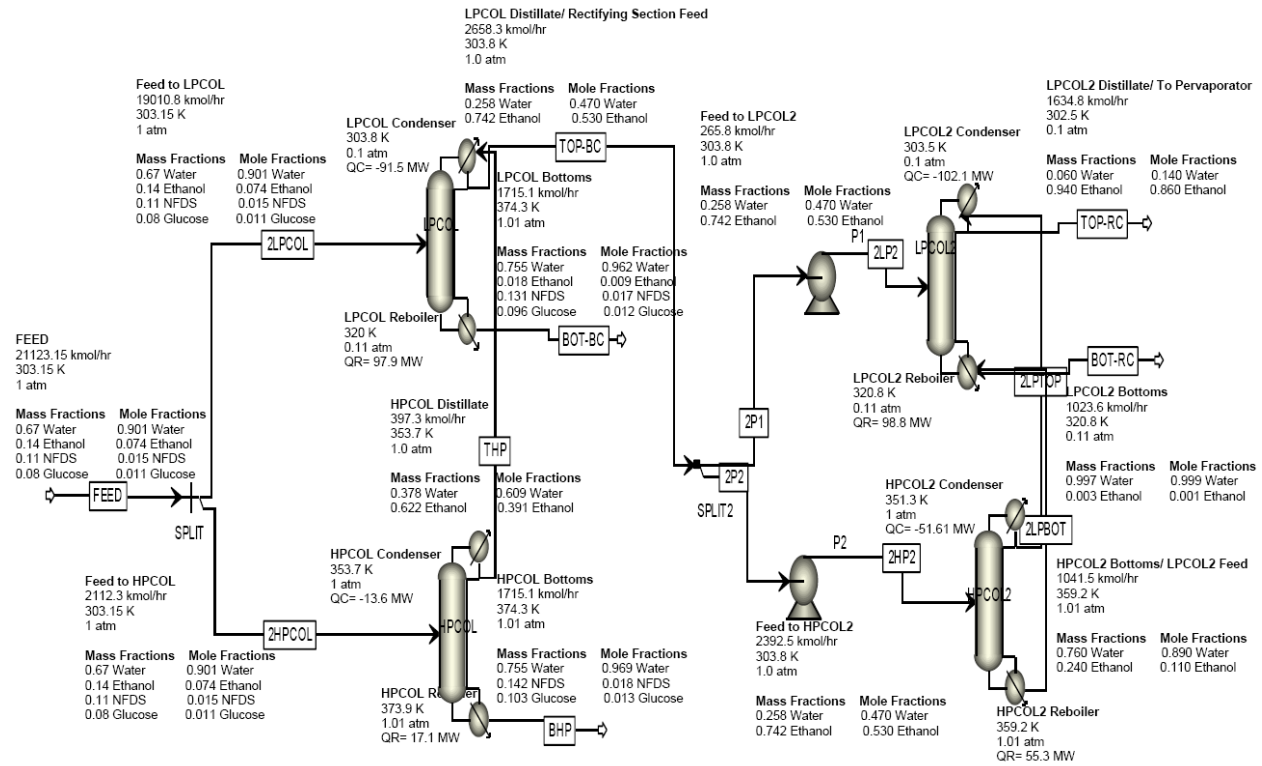
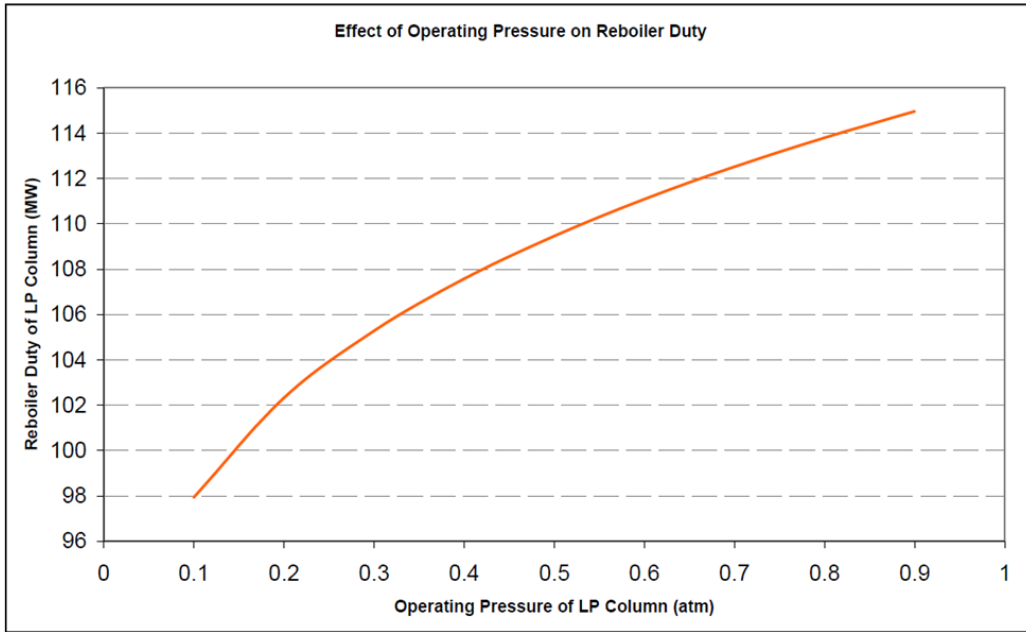


Figure 6-Multieffect Distillation System (MDS)

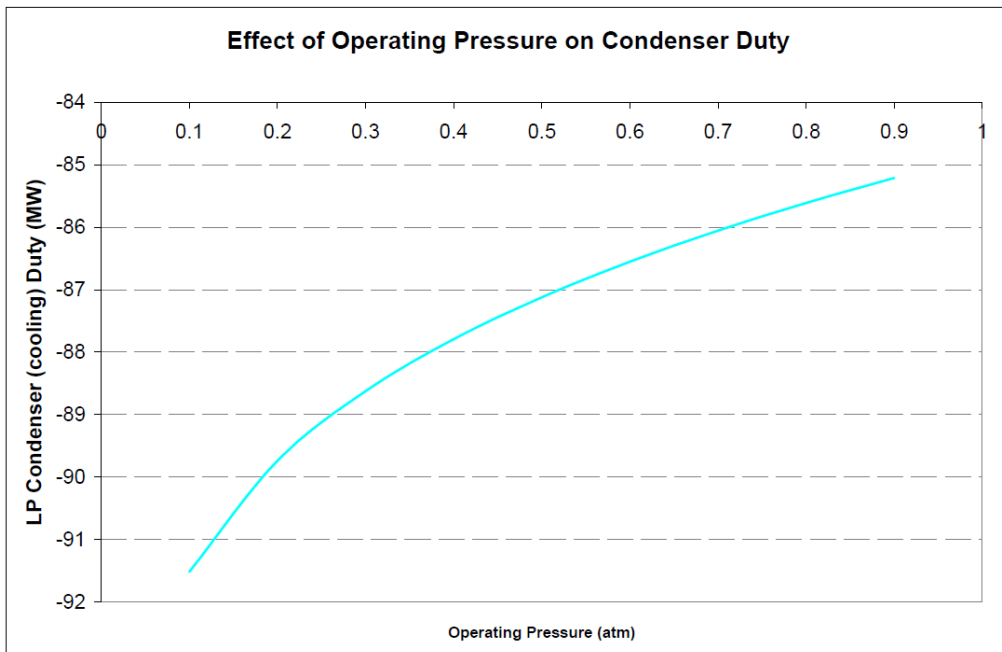
Figure 6 is of the multieffect distillation system. This figure shows the schematic for the multieffect distillation system along with the flows of each column, and the heating and cooling duties of each column. It also shows the different operating pressures for each column and the split ratios into the different columns.



7.

Figure 7-Effect of LP column operating pressure on reboiler duty

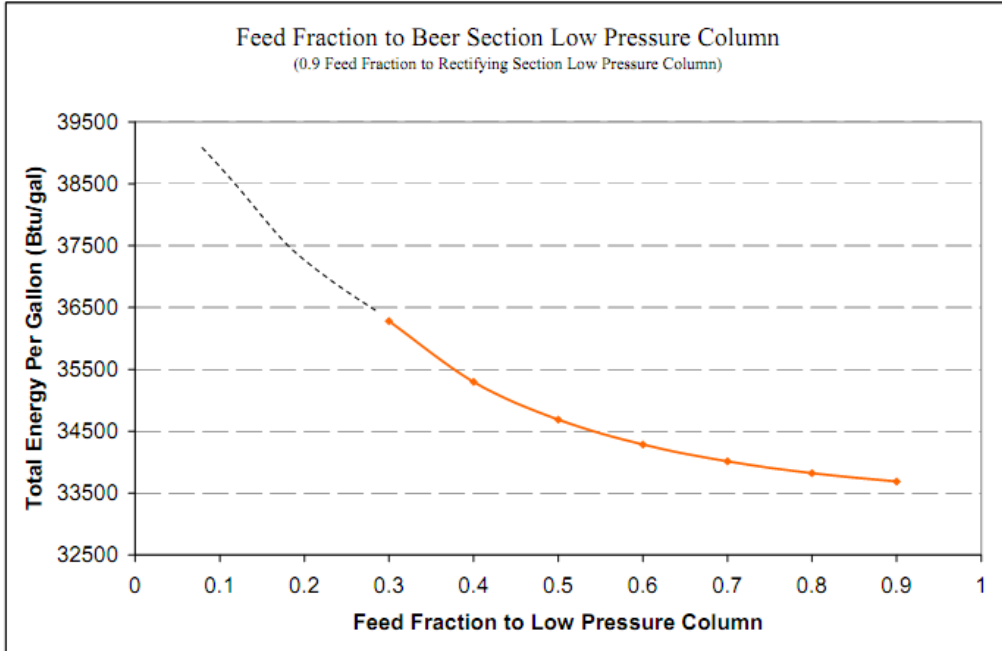
Figure 7 shows the relationship between the operating pressure of the lower pressure column of the beer section (first section of the distillation system) and the reboiler (heating) duty of that column. This figure is used to establish the optimum operating pressure for the lower pressure column (i.e. the operating pressure that minimizes reboiler duty)



8.

Figure 8-Effect of LP column operating pressure on condenser duty

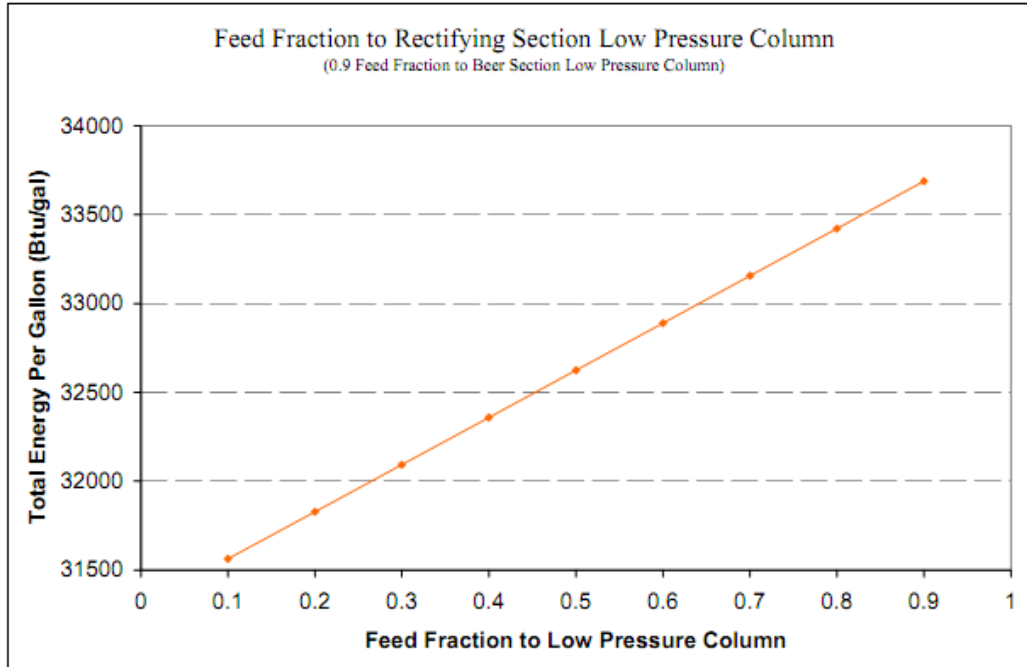
Figure 8 shows the relationship between the operating pressure of the lower pressure column of the beer section of the distillation system and the condenser (cooling) duty of the column. We use this figure to find the operating pressure that minimizes condenser duty.



9.

**Figure 9-Effect of beer section split ratio on energy consumption**

Figure 9 shows the relationship between the split fraction to the beer section of the multieffect distillation system with the total energy consumption per gallon of ethanol in units of Btu/gal ethanol. We use this figure to show the feed fraction to the beer section that minimizes the total energy consumption in the multieffect distillation system.



10.

**Figure 10-Effect of rectifying section split ratio on energy consumption**

Figure 10 shows the relationship between the feed fraction to the rectifying section and the total energy consumption of the multieffect distillation system after optimizing the feed fraction to beer section. We use this figure to show which feed ratio to the rectifying section minimizes the total energy consumption of the multieffect distillation system.

11.

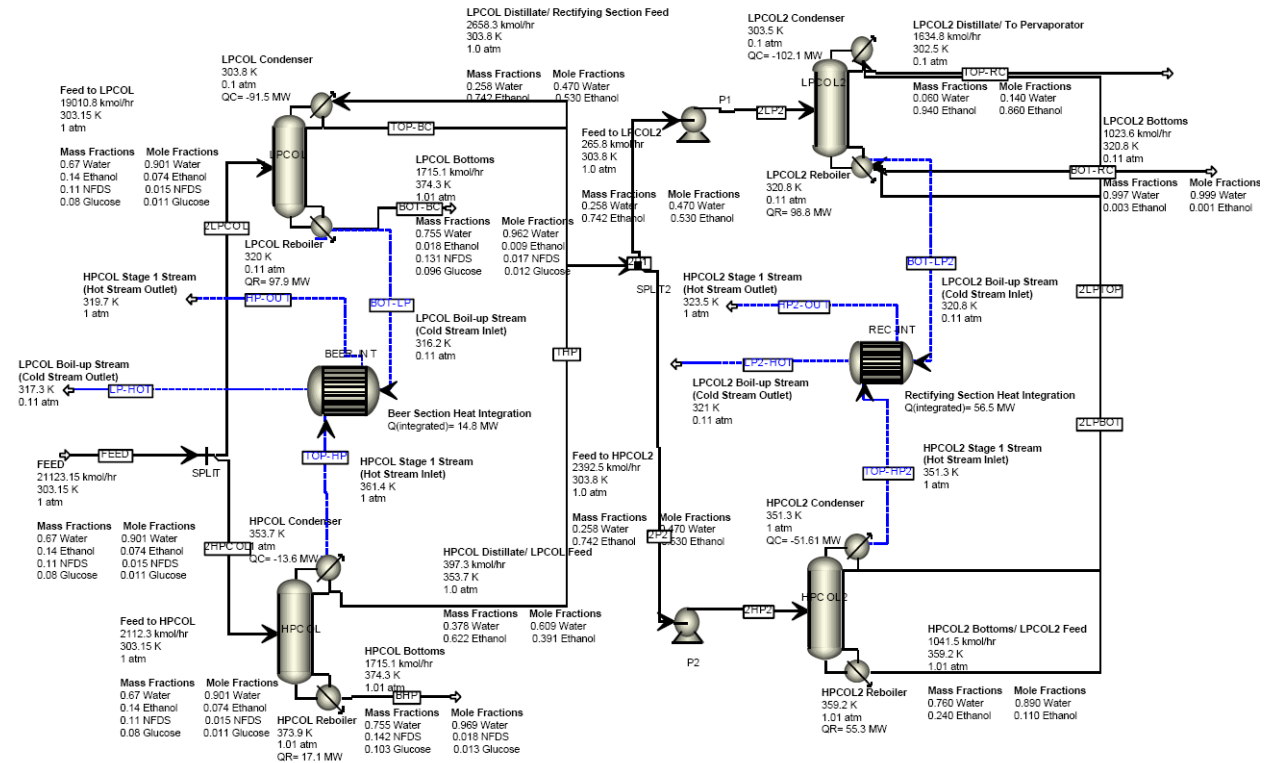
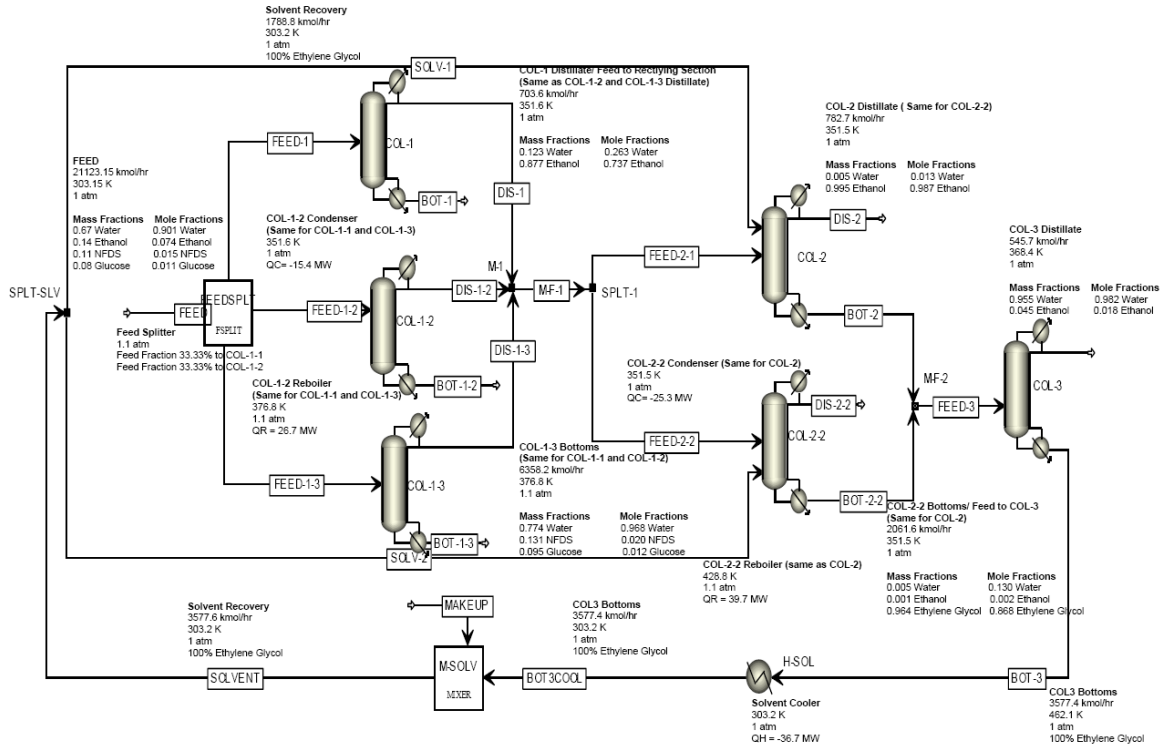


Figure 11-MDS heat integration

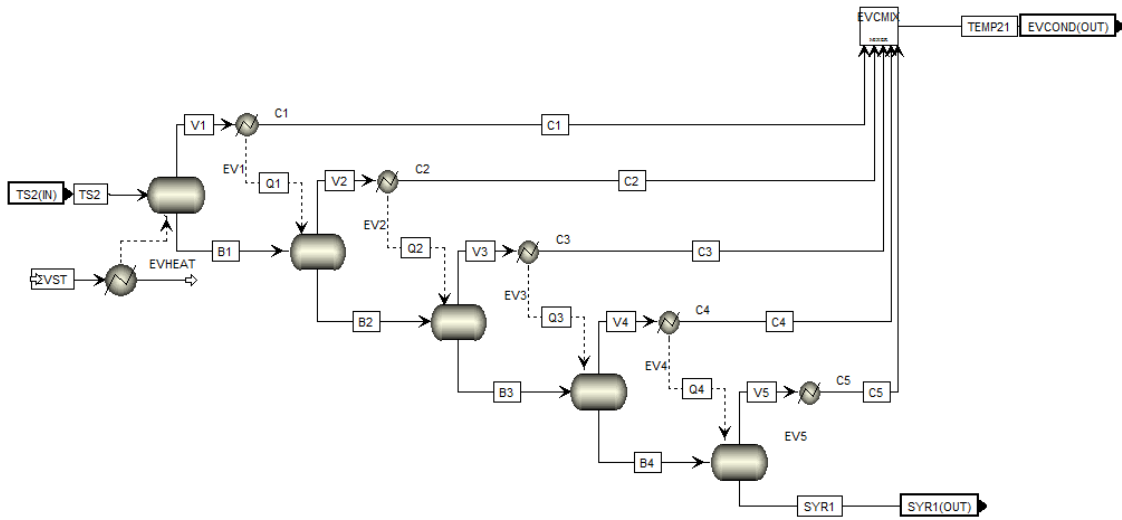
Figure 11 shows the schematic for the heat integration of the multi-effect distillation system. It specifies which streams get integrated in the beer and rectifying sections with dashed blue lines. It also shows the amount of heat duty that is integrated and the heat duty for all the columns in the multi-effect distillation system.



12.

Figure 12-Extractive Distillation System (EDS)

Figure 12 shows the schematic for the extractive distillation system. It also shows the heating and cooling duties of each column, the operating pressures of each column and the flow rates and compositions of the streams to each column of the extractive distillation system.



13.

Figure 13-Multi-effect evaporators

Figure 13 is of the evaporator for the post distillation section of the dry grind process. It is a five effect evaporator combination with each effect feeding to the next effect. We use these evaporator after both distillation systems.

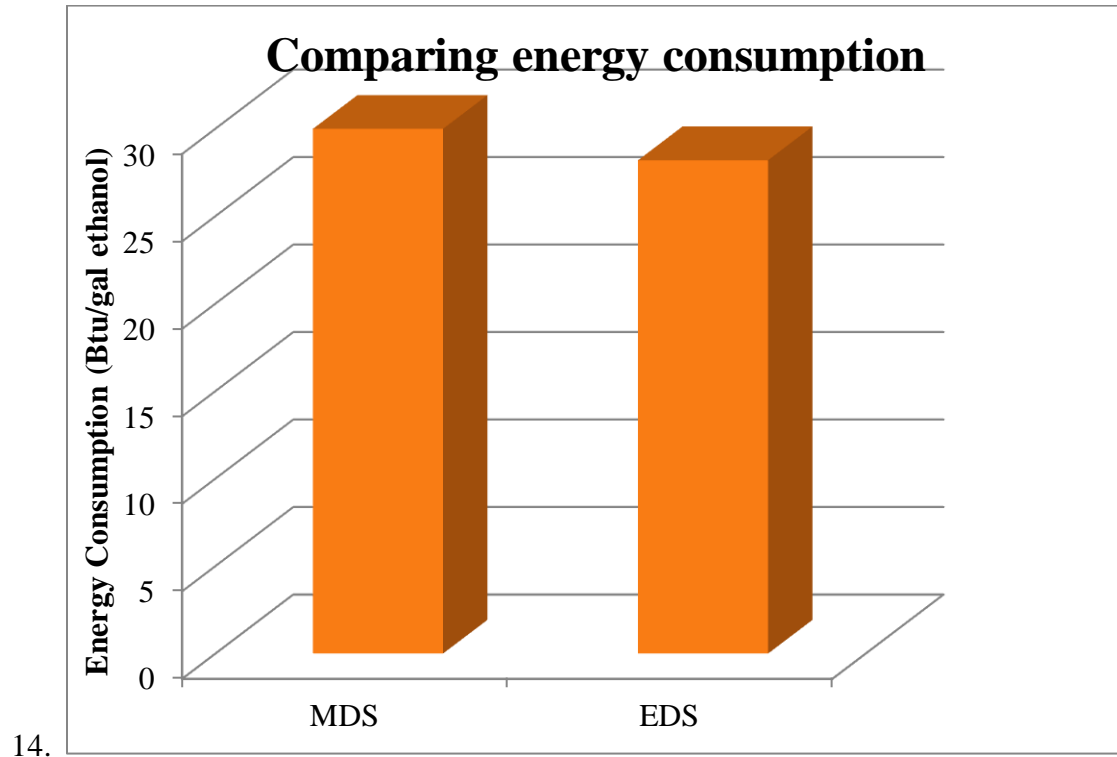
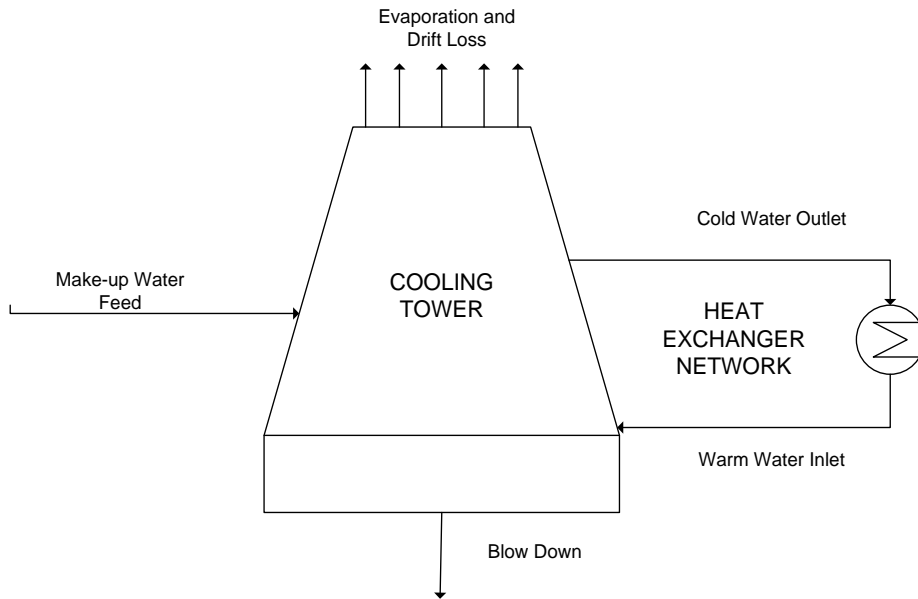


Figure 14-Comparing energy consumption

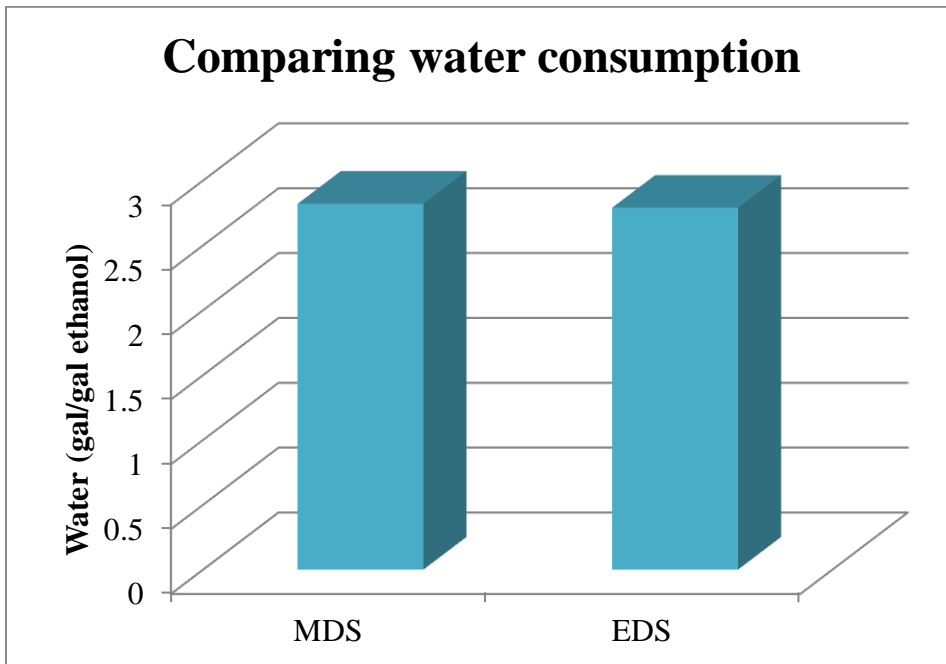
Figure 14 shows the comparison of the overall energy consumption between both distillation systems. We use this figure to show which distillation system is more energy efficient.



15.

Figure 15-Closed loops for water in cooling tower system

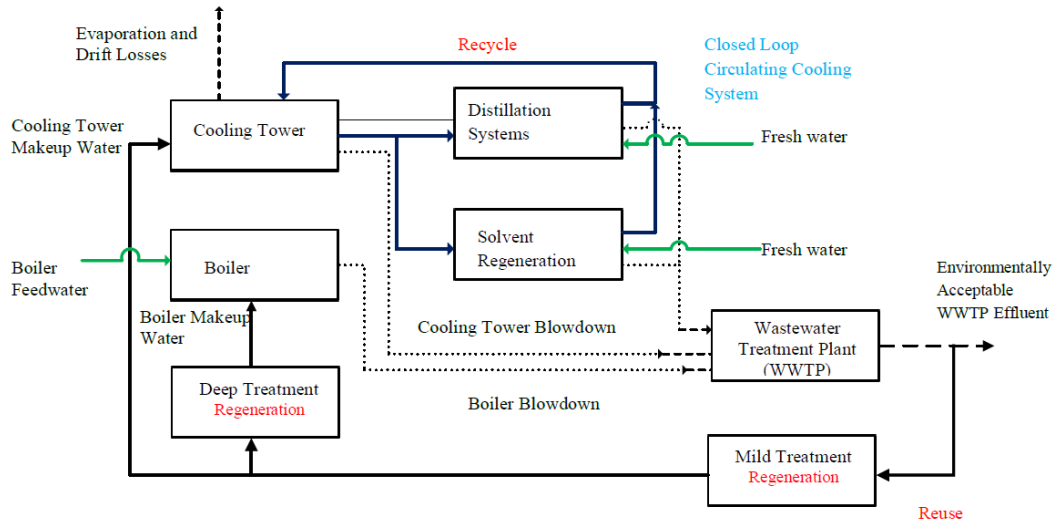
Figure 15 shows the cooling tower system for the dry grind process. It shows how we closed the loops for circulating water in the process. It also shows the areas of water loss in the cooling tower, cooling tower blowdown, evaporation loss and drift loss.



16.

Figure 16-Comparing water consumption

Figure 16 shows a comparison of the water consumption between both distillation systems (the multieffect and extractive distillation system) We use this to show which system is more water efficient.



17.

Figure 17-Wastewater treatment scheme

Figure 17 shows the schematic of the waste water treatment of effluent water from a wastewater treatment plant (WWTP). It shows the treatment methods used for the cooling water makeup and the boiler blowdown.

## Appendix B: Energy Consumption

Finding optimum operating conditions for distillation systems

Status	VARY 2 HPCOL2 COL- SPEC MASS- D:F	VARY 3 HPCOL2 COL- SPEC MOLE- RR	VARY 4 LPCOL2 COL- SPEC MASS- D:F	VARY 5 LPCOL2 COL- SPEC MOLE- RR	XETRC	RECET	KW	TQN
1	0.720513	1	0.788571	8.5	0.947304	0.999576	1997651	6.82E+08
1	0.720513	1	0.788571	9	0.950581	0.999371	2077501	7.09E+08
1	0.720513	1	0.788571	10	0.940902	0.999531	2326598	7.94E+08
1	0.720513	1.5	0.788571	5	0.949691	0.999141	1356996	4.63E+08
1	0.720513	1.5	0.788571	6	0.950867	0.999514	1549479	5.29E+08
1	0.720513	1.5	0.788571	7.5	0.952494	0.999403	1836088	6.26E+08
1	0.720513	1.5	0.788571	8.5	0.948727	0.999495	2048920	6.99E+08
1	0.720513	1.5	0.788571	10	0.95061	0.999564	2333867	7.96E+08
1	0.720513	2	0.788571	4	0.949729	0.999265	1220237	4.16E+08
1	0.720513	2	0.788571	4.5	0.949457	0.999136	1318982	4.5E+08
1	0.720513	2	0.788571	5	0.950665	0.999616	1415840	4.83E+08
1	0.720513	2	0.788571	7.5	0.950174	0.999468	1905632	6.5E+08
1	0.720513	2	0.788571	8	0.950397	0.999499	2002730	6.83E+08
0	0.720513	2	0.788571	8.5	0.950102	0.999311	2101765	7.17E+08
0	0.720513	2	0.788571	9	0.95032	0.99954	2199165	7.5E+08
0	0.720513	2	0.788571	9.5	0.950355	0.999576	2297062	7.84E+08
0	0.720513	2	0.788571	10	0.950374	0.999597	2395004	8.17E+08
1	0.720513	2.5	0.788571	4	0.950116	0.999079	1278831	4.36E+08
1	0.720513	2.5	0.788571	5	0.950034	0.999255	1475328	5.03E+08
0	0.720513	2.5	0.788571	6	0.949875	0.999073	1671724	5.7E+08
0	0.720513	2.5	0.788571	6.5	0.950191	0.999405	1769109	6.04E+08
0	0.720513	2.5	0.788571	7	0.950243	0.999459	1867015	6.37E+08
0	0.720513	2.5	0.788571	7.5	0.950276	0.999494	1964954	6.7E+08
0	0.720513	2.5	0.788571	8	0.950305	0.999524	2062890	7.04E+08
0	0.720513	2.5	0.788571	8.5	0.950331	0.999552	2160829	7.37E+08
0	0.720513	2.5	0.788571	9	0.950357	0.999576	2258750	7.71E+08
0	0.720513	2.5	0.788571	9.5	0.950374	0.999597	2356706	8.04E+08
0	0.720513	2.5	0.788571	10	0.950392	0.999617	2454647	8.38E+08
0	0.720513	3	0.788571	5	0.950072	0.99928	1534935	5.24E+08
0	0.720513	3	0.788571	5.5	0.950133	0.999343	1632863	5.57E+08
0	0.720513	3	0.788571	6	0.950182	0.999395	1730803	5.91E+08
0	0.720513	3	0.788571	6.5	0.950225	0.99944	1828738	6.24E+08
0	0.720513	3	0.788571	7	0.950261	0.999478	1926675	6.57E+08
0	0.720513	3	0.788571	7.5	0.950293	0.999512	2024612	6.91E+08
0	0.720513	3	0.788571	8	0.950321	0.999541	2122551	7.24E+08
0	0.720513	3	0.788571	8.5	0.950346	0.999567	2220488	7.58E+08
0	0.720513	3	0.788571	9	0.950364	0.99959	2318446	7.91E+08

0	0.720513	3	0.788571	9.5	0.950388	0.999611	2416365	8.24E+08
0	0.720513	3	0.788571	10	0.950406	0.99963	2514299	8.58E+08
0	0.720513	3.5	0.788571	3.5	0.949828	0.999024	1300832	4.44E+08
0	0.720513	3.5	0.788571	4	0.949936	0.999137	1398761	4.77E+08
0	0.720513	3.5	0.788571	4.5	0.950022	0.999227	1496692	5.11E+08
0	0.720513	3.5	0.788571	5	0.950091	0.9993	1594627	5.44E+08
0	0.720513	3.5	0.788571	5.5	0.95015	0.99936	1692557	5.78E+08
0	0.720513	3.5	0.788571	6	0.950197	0.999411	1790498	6.11E+08
0	0.720513	3.5	0.788571	6.5	0.950238	0.999454	1888435	6.44E+08
0	0.720513	3.5	0.788571	7	0.950274	0.999492	1986371	6.78E+08
0	0.720513	3.5	0.788571	7.5	0.950305	0.999524	2084308	7.11E+08
0	0.720513	3.5	0.788571	8	0.950332	0.999553	2182246	7.45E+08
0	0.720513	3.5	0.788571	8.5	0.950356	0.999578	2280185	7.78E+08
0	0.720513	3.5	0.788571	9	0.950376	0.999601	2378134	8.11E+08
0	0.720513	3.5	0.788571	9.5	0.950397	0.999621	2476061	8.45E+08
0	0.720513	3.5	0.788571	10	0.950414	0.99964	2574004	8.78E+08
0	0.720513	4	0.788571	3.5	0.949847	0.999043	1360547	4.64E+08
0	0.720513	4	0.788571	4	0.949953	0.999154	1458478	4.98E+08
0	0.720513	4	0.788571	4.5	0.950038	0.999242	1556406	5.31E+08
0	0.720513	4	0.788571	5	0.9501	0.999314	1654357	5.64E+08
0	0.720513	4	0.788571	5.5	0.950159	0.999373	1752284	5.98E+08
0	0.720513	4	0.788571	6	0.950211	0.999423	1850205	6.31E+08
0	0.720513	4	0.788571	6.5	0.950249	0.999465	1948149	6.65E+08
0	0.720513	4	0.788571	7	0.950284	0.999502	2046087	6.98E+08
0	0.720513	4	0.788571	7.5	0.950314	0.999534	2144025	7.32E+08
0	0.720513	4	0.788571	8	0.950341	0.999562	2241962	7.65E+08
0	0.720513	4	0.788571	8.5	0.950365	0.999587	2339896	7.98E+08
0	0.720513	4	0.788571	9	0.950386	0.999609	2437838	8.32E+08
0	0.720513	4	0.788571	9.5	0.950401	0.999629	2535794	8.65E+08
0	0.720513	4	0.788571	10	0.950421	0.999647	2633720	8.99E+08
0	0.720513	4.5	0.788571	3.5	0.949861	0.999058	1420238	4.85E+08
0	0.720513	4.5	0.788571	4	0.949966	0.999168	1518165	5.18E+08
0	0.720513	4.5	0.788571	4.5	0.950048	0.999254	1616095	5.51E+08
0	0.720513	4.5	0.788571	5	0.950115	0.999324	1714029	5.85E+08
0	0.720513	4.5	0.788571	5.5	0.95017	0.999383	1811963	6.18E+08
0	0.720513	4.5	0.788571	6	0.950215	0.999432	1909904	6.52E+08
0	0.720513	4.5	0.788571	6.5	0.950257	0.999473	2007833	6.85E+08
0	0.720513	4.5	0.788571	7	0.95029	0.999509	2105775	7.19E+08
0	0.720513	4.5	0.788571	7.5	0.950321	0.999541	2203710	7.52E+08
0	0.720513	4.5	0.788571	8	0.950346	0.999568	2301652	7.85E+08
0	0.720513	4.5	0.788571	8.5	0.95037	0.999593	2399587	8.19E+08
0	0.720513	4.5	0.788571	9	0.950391	0.999615	2497527	8.52E+08
0	0.720513	4.5	0.788571	9.5	0.950406	0.999634	2595485	8.86E+08
0	0.720513	4.5	0.788571	10	0.950426	0.999652	2693408	9.19E+08
0	0.720513	5	0.788571	3.5	0.949872	0.999069	1480098	5.05E+08
0	0.720513	5	0.788571	4	0.949975	0.999177	1578030	5.38E+08
0	0.720513	5	0.788571	4.5	0.950056	0.999263	1675963	5.72E+08
0	0.720513	5	0.788571	5	0.950122	0.999332	1773898	6.05E+08
0	0.720513	5	0.788571	5.5	0.950177	0.99939	1871833	6.39E+08

0	0.720513	5	0.788571	6	0.950224	0.999438	1969765	6.72E+08
0	0.720513	5	0.788571	6.5	0.950262	0.999479	2067705	7.06E+08
0	0.720513	5	0.788571	7	0.950296	0.999515	2165642	7.39E+08
0	0.720513	5	0.788571	7.5	0.950327	0.999546	2263575	7.72E+08
0	0.720513	5	0.788571	8	0.950352	0.999573	2361517	8.06E+08
0	0.720513	5	0.788571	8.5	0.950373	0.999598	2459463	8.39E+08
0	0.720513	5	0.788571	9	0.950394	0.999619	2557403	8.73E+08
0	0.720513	5	0.788571	9.5	0.950416	0.999639	2655322	9.06E+08
0	0.720513	5	0.788571	10	0.950439	0.999656	2753227	9.39E+08
0	0.720513	5.5	0.788571	3.5	0.949882	0.999079	1539774	5.25E+08
0	0.720513	5.5	0.788571	4	0.949984	0.999186	1637703	5.59E+08
0	0.720513	5.5	0.788571	4.5	0.950064	0.999271	1735637	5.92E+08
0	0.720513	5.5	0.788571	5	0.950129	0.999339	1833572	6.26E+08
0	0.720513	5.5	0.788571	5.5	0.950183	0.999396	1931508	6.59E+08
0	0.720513	5.5	0.788571	6	0.950228	0.999444	2029443	6.92E+08
0	0.720513	5.5	0.788571	6.5	0.950268	0.999485	2127378	7.26E+08
0	0.720513	5.5	0.788571	7	0.950301	0.99952	2225319	7.59E+08
0	0.720513	5.5	0.788571	7.5	0.95033	0.999551	2323254	7.93E+08
0	0.720513	5.5	0.788571	8	0.950356	0.999578	2421192	8.26E+08
0	0.720513	5.5	0.788571	8.5	0.950379	0.999602	2519128	8.6E+08
0	0.720513	5.5	0.788571	9	0.950399	0.999623	2617072	8.93E+08
0	0.720513	5.5	0.788571	9.5	0.950417	0.999642	2715009	9.26E+08
0	0.720513	5.5	0.788571	10	0.950434	0.99966	2812945	9.6E+08
0	0.720513	6	0.788571	3.5	0.949888	0.999086	1599620	5.46E+08
0	0.720513	6	0.788571	4	0.949989	0.999192	1697552	5.79E+08
0	0.720513	6	0.788571	4.5	0.950069	0.999276	1795484	6.13E+08
0	0.720513	6	0.788571	5	0.950134	0.999344	1893418	6.46E+08
0	0.720513	6	0.788571	5.5	0.950185	0.999401	1991360	6.79E+08
0	0.720513	6	0.788571	6	0.950233	0.999448	2089289	7.13E+08
0	0.720513	6	0.788571	6.5	0.95027	0.999489	2187231	7.46E+08
0	0.720513	6	0.788571	7	0.950304	0.999524	2285165	7.8E+08
0	0.720513	6	0.788571	7.5	0.950333	0.999554	2383104	8.13E+08
0	0.720513	6	0.788571	8	0.950359	0.999581	2481041	8.47E+08
0	0.720513	6	0.788571	8.5	0.950381	0.999605	2578980	8.8E+08
0	0.720513	6	0.788571	9	0.950399	0.999626	2676931	9.13E+08
0	0.720513	6	0.788571	9.5	0.95042	0.999645	2774855	9.47E+08
0	0.720513	6	0.788571	10	0.950432	0.999662	2872820	9.8E+08
0	0.720513	6.5	0.788571	3.5	0.949894	0.999093	1659505	5.66E+08
0	0.720513	6.5	0.788571	4	0.949995	0.999198	1757434	6E+08
0	0.720513	6.5	0.788571	4.5	0.950074	0.999281	1855369	6.33E+08
0	0.720513	6.5	0.788571	5	0.950138	0.999349	1953304	6.66E+08
0	0.720513	6.5	0.788571	5.5	0.950191	0.999405	2051239	7E+08
0	0.720513	6.5	0.788571	6	0.950237	0.999452	2149173	7.33E+08
0	0.720513	6.5	0.788571	6.5	0.950274	0.999492	2247115	7.67E+08
0	0.720513	6.5	0.788571	7	0.950309	0.999527	2345044	8E+08
0	0.720513	6.5	0.788571	7.5	0.950337	0.999557	2442985	8.34E+08
0	0.720513	6.5	0.788571	8	0.950362	0.999584	2540922	8.67E+08
0	0.720513	6.5	0.788571	8.5	0.950384	0.999607	2638863	9E+08
0	0.720513	6.5	0.788571	9	0.950405	0.999628	2736801	9.34E+08

0	0.720513	6.5	0.788571	9.5	0.950422	0.999647	2834744	9.67E+08
0	0.720513	6.5	0.788571	10	0.950438	0.999664	2932682	1E+09
0	0.720513	7	0.788571	3.5	0.9499	0.999098	1719328	5.87E+08
0	0.720513	7	0.788571	4	0.949999	0.999202	1817260	6.2E+08
0	0.720513	7	0.788571	4.5	0.950078	0.999285	1915193	6.53E+08
0	0.720513	7	0.788571	5	0.950142	0.999352	2013125	6.87E+08
0	0.720513	7	0.788571	5.5	0.950194	0.999408	2111064	7.2E+08
0	0.720513	7	0.788571	6	0.950239	0.999455	2209001	7.54E+08
0	0.720513	7	0.788571	6.5	0.950277	0.999495	2306937	7.87E+08
0	0.720513	7	0.788571	7	0.950309	0.999529	2404877	8.21E+08
0	0.720513	7	0.788571	7.5	0.950338	0.99956	2502814	8.54E+08
0	0.720513	7	0.788571	8	0.950363	0.999586	2600753	8.87E+08
0	0.720513	7	0.788571	8.5	0.950387	0.99961	2698687	9.21E+08
0	0.720513	7	0.788571	9	0.950406	0.99963	2796628	9.54E+08
0	0.720513	7	0.788571	9.5	0.950424	0.999649	2894564	9.88E+08
0	0.720513	7	0.788571	10	0.950438	0.999666	2992515	1.02E+09
0	0.720513	7.5	0.788571	3.5	0.949901	0.999102	1779182	6.07E+08
0	0.720513	7.5	0.788571	4	0.950002	0.999206	1877108	6.4E+08
0	0.720513	7.5	0.788571	4.5	0.950081	0.999289	1975041	6.74E+08
0	0.720513	7.5	0.788571	5	0.950145	0.999356	2072975	7.07E+08
0	0.720513	7.5	0.788571	5.5	0.950197	0.999411	2170912	7.41E+08
0	0.720513	7.5	0.788571	6	0.950242	0.999458	2268846	7.74E+08
0	0.720513	7.5	0.788571	6.5	0.950279	0.999497	2366785	8.08E+08
0	0.720513	7.5	0.788571	7	0.95031	0.999532	2464731	8.41E+08
0	0.720513	7.5	0.788571	7.5	0.950341	0.999562	2562660	8.74E+08
0	0.720513	7.5	0.788571	8	0.950365	0.999588	2660598	9.08E+08
0	0.720513	7.5	0.788571	8.5	0.950388	0.999611	2758539	9.41E+08
0	0.720513	7.5	0.788571	9	0.950408	0.999632	2856475	9.75E+08
0	0.720513	7.5	0.788571	9.5	0.950425	0.999651	2954418	1.01E+09
0	0.720513	7.5	0.788571	10	0.950444	0.999668	3052339	1.04E+09
0	0.720513	8	0.788571	3.5	0.949909	0.999106	1839055	6.28E+08
0	0.720513	8	0.788571	4	0.950005	0.99921	1936991	6.61E+08
0	0.720513	8	0.788571	4.5	0.950083	0.999292	2034926	6.94E+08
0	0.720513	8	0.788571	5	0.950146	0.999358	2132861	7.28E+08
0	0.720513	8	0.788571	5.5	0.9502	0.999413	2230793	7.61E+08
0	0.720513	8	0.788571	6	0.950244	0.99946	2328731	7.95E+08
0	0.720513	8	0.788571	6.5	0.950278	0.999499	2426681	8.28E+08
0	0.720513	8	0.788571	7	0.950312	0.999534	2524611	8.61E+08
0	0.720513	8	0.788571	7.5	0.950342	0.999564	2622544	8.95E+08
0	0.720513	8	0.788571	8	0.950367	0.99959	2720481	9.28E+08
0	0.720513	8	0.788571	8.5	0.950389	0.999613	2818423	9.62E+08
0	0.720513	8	0.788571	9	0.950409	0.999634	2916358	9.95E+08
0	0.720513	8	0.788571	9.5	0.950427	0.999652	3014297	1.03E+09
0	0.720513	8	0.788571	10	0.950443	0.999669	3112238	1.06E+09
0	0.720513	8.5	0.788571	3.5	0.94991	0.999109	1898948	6.48E+08
0	0.720513	8.5	0.788571	4	0.950009	0.999212	1996878	6.81E+08
0	0.720513	8.5	0.788571	4.5	0.950083	0.999294	2094819	7.15E+08
0	0.720513	8.5	0.788571	5	0.950149	0.999361	2192748	7.48E+08
0	0.720513	8.5	0.788571	5.5	0.950201	0.999416	2290684	7.82E+08

0	0.720513	8.5	0.788571	6	0.950244	0.999462	2388623	8.15E+08
0	0.720513	8.5	0.788571	6.5	0.950283	0.999501	2486555	8.48E+08
0	0.720513	8.5	0.788571	7	0.950315	0.999535	2584495	8.82E+08
0	0.720513	8.5	0.788571	7.5	0.950339	0.999565	2682451	9.15E+08
0	0.720513	8.5	0.788571	8	0.950368	0.999591	2780373	9.49E+08
0	0.720513	8.5	0.788571	8.5	0.950391	0.999614	2878305	9.82E+08
0	0.720513	8.5	0.788571	9	0.950406	0.999635	2976268	1.02E+09
0	0.720513	8.5	0.788571	9.5	0.950428	0.999654	3074188	1.05E+09
0	0.720513	8.5	0.788571	10	0.950445	0.99967	3172122	1.08E+09
0	0.720513	9	0.788571	3.5	0.949913	0.999112	1958858	6.68E+08
0	0.720513	9	0.788571	4	0.950011	0.999215	2056789	7.02E+08
0	0.720513	9	0.788571	4.5	0.950088	0.999296	2154723	7.35E+08
0	0.720513	9	0.788571	5	0.950145	0.999363	2252674	7.69E+08
0	0.720513	9	0.788571	5.5	0.950211	0.999417	2350569	8.02E+08
0	0.720513	9	0.788571	6	0.950245	0.999463	2448537	8.35E+08
0	0.720513	9	0.788571	6.5	0.950284	0.999503	2546468	8.69E+08
0	0.720513	9	0.788571	7	0.950316	0.999537	2644408	9.02E+08
0	0.720513	9	0.788571	7.5	0.950347	0.999566	2742333	9.36E+08
0	0.720513	9	0.788571	8	0.950372	0.999592	2840272	9.69E+08
0	0.720513	9	0.788571	8.5	0.950393	0.999616	2938213	1E+09
0	0.720513	9	0.788571	9	0.950411	0.999636	3036160	1.04E+09
0	0.720513	9	0.788571	9.5	0.950426	0.999655	3134116	1.07E+09
0	0.720513	9	0.788571	10	0.950445	0.999671	3232037	1.1E+09
0	0.720513	9.5	0.788571	3.5	0.949915	0.999115	2018764	6.89E+08
0	0.720513	9.5	0.788571	4	0.950012	0.999217	2116697	7.22E+08
0	0.720513	9.5	0.788571	4.5	0.950092	0.999298	2214622	7.56E+08
0	0.720513	9.5	0.788571	5	0.950153	0.999364	2312561	7.89E+08
0	0.720513	9.5	0.788571	5.5	0.950206	0.999419	2410497	8.22E+08
0	0.720513	9.5	0.788571	6	0.95025	0.999465	2508431	8.56E+08
0	0.720513	9.5	0.788571	6.5	0.950286	0.999504	2606372	8.89E+08
0	0.720513	9.5	0.788571	7	0.950318	0.999538	2704309	9.23E+08
0	0.720513	9.5	0.788571	7.5	0.950346	0.999568	2802248	9.56E+08
0	0.720513	9.5	0.788571	8	0.950372	0.999594	2900182	9.9E+08
0	0.720513	9.5	0.788571	8.5	0.950391	0.999617	2998134	1.02E+09
0	0.720513	9.5	0.788571	9	0.950412	0.999637	3096067	1.06E+09
0	0.720513	9.5	0.788571	9.5	0.950428	0.999656	3194013	1.09E+09
0	0.720513	9.5	0.788571	10	0.950446	0.999672	3291939	1.12E+09
0	0.720513	10	0.788571	3.5	0.949918	0.999117	2078706	7.09E+08
0	0.720513	10	0.788571	4	0.950013	0.999219	2176643	7.43E+08
0	0.720513	10	0.788571	4.5	0.950092	0.9993	2274573	7.76E+08
0	0.720513	10	0.788571	5	0.950155	0.999366	2372505	8.1E+08
0	0.720513	10	0.788571	5.5	0.950206	0.99942	2470444	8.43E+08
0	0.720513	10	0.788571	6	0.950248	0.999466	2568385	8.76E+08
0	0.720513	10	0.788571	6.5	0.950287	0.999505	2666318	9.1E+08
0	0.720513	10	0.788571	7	0.950322	0.999539	2764244	9.43E+08
0	0.720513	10	0.788571	7.5	0.950344	0.999569	2862204	9.77E+08
0	0.720513	10	0.788571	8	0.950372	0.999595	2960131	1.01E+09
0	0.720513	10	0.788571	8.5	0.950394	0.999618	3058067	1.04E+09
0	0.720513	10	0.788571	9	0.950413	0.999638	3156009	1.08E+09

0	0.720513	10	0.788571	9.5	0.95043	0.999656	3253952	1.11E+09
0	0.720513	10	0.788571	10	0.950446	0.999673	3351888	1.14E+09

Finding optimum operating pressure for rectifying section

HP2 Pressure	LP2 Pressure	Purity	HP2 Duty	LP2 Duty
1	0.7	0.946502	45929.37	124890.7
1	0.6	0.94744	45929.37	125290.6
1	0.4	0.949758	45929.37	126258.6
1	0.3	0.9513	45929.37	126880.9
1	0.2	0.953227	45929.37	127702.4
1	0.1	0.953877	45929.37	129420.9
0.9	0.8	0.946001	45895.14	124535.9
0.9	0.6	0.947742	45895.14	125302.7
0.9	0.5	0.948818	45895.14	125750.6
0.9	0.4	0.950075	45895.14	126268.1
0.9	0.3	0.9516	45895.14	126892.9
0.9	0.2	0.953474	45895.14	127725
0.9	0.1	0.953885	45895.14	129492.9
0.8	0.6	0.948112	45856.7	125308.7
0.8	0.5	0.949188	45856.7	125755.4
0.8	0.4	0.950437	45856.7	126274.7
0.8	0.3	0.951954	45856.7	126900.6
0.8	0.2	0.953703	45856.7	127758
0.8	0.1	0.953891	45856.7	129572.5
0.7	0.6	0.948523	45813.76	125313.8
0.7	0.5	0.949571	45813.76	125765.9
0.7	0.4	0.950816	45813.76	126285.3
0.7	0.3	0.952317	45813.76	126914.6
0.7	0.2	0.953851	45813.76	127816.2
0.7	0.1	0.953899	45813.76	129659.6
0.6	0.5	0.950016	45760.29	125775.2
0.6	0.4	0.951243	45762.61	126297.9
0.6	0.3	0.952721	45762.61	126931.7
0.6	0.2	0.95391	45762.61	127903.4
0.6	0.1	0.953908	45762.61	129757.6
0.5	0.4	0.951694	45706.87	126318.5
0.5	0.3	0.953134	45706.87	126959.1
0.5	0.2	0.953925	45706.87	128013.8
0.5	0.1	0.953917	45706.87	129868.4
0.4	0.3	0.953622	45627.79	126995.2
0.4	0.2	0.95394	45630.71	128145.7
0.4	0.1	0.953929	45630.71	130001.1
0.3	0.2	0.953955	45535.62	128308.3
0.3	0.1	0.953943	45535.62	130163.3
0.2	0.1	0.953962	45399.75	130379.7

## Heating and cooling duties

Operating Pressure	Reb Duty MW	Operating Pressure	Cond Duty MW
0.1	97.9354709	0.1	-91.518361
0.2	102.323806	0.2	-89.741212
0.3	105.285076	0.3	-88.626321
0.4	107.574549	0.4	-87.794239
0.5	109.464346	0.5	-87.121364
0.6	111.086498	0.6	-86.552111
0.7	112.515224	0.7	-86.055768
0.8	113.796954	0.8	-85.613725
0.9	114.962735	0.9	-85.213816

## Heat Integration

2LP2	2HP2	LP2QN	HP2QN	TOTAL	Heat-Int	New Total
0.1	0.9	125119.9	59908.12	185028	2598.483	182429.5
0.2	0.8	127168.3	53250.04	180418.4	2632.769	177785.6
0.3	0.7	129216	46595.02	175811	2667.136	173143.8
0.4	0.6	131264	39938.51	171202.5	2701.598	168500.9
0.5	0.5	133315.8	33282.01	166597.8	2736.21	163861.6
0.6	0.4	135364.9	26625.52	161990.4	2770.876	159219.6
0.7	0.3	137415.8	19968.54	157384.3	2805.666	154578.7
0.8	0.2	139467.4	13312.53	152779.9	2840.565	149939.3
0.9	0.1	141519.1	6656.138	148175.2	2875.569	145299.7
0.95	0.05	142544.9	3327.985	145872.9	2893.109	142979.8
0.96	0.04	142729.7	2744.751	145474.5	2896.287	142578.2

## Appendix C: Water Consumption

Block	Water Mass Flow lb/hr	Water vol Flow gal/hr	Water vol flow gal/min	Outlet Temp (F)	Inlet Temp (F)	dT
MDS	755760	91055.4	1517.59	214	86	128
EDS	755760	91055.4	1517.59	242	86	156

	Water Mass Flow (lb/hr)	Water Vol Flow (gal/min)	Outlet Temp (F)	Inlet Temp (F)	dT
MDS	190000	379.469	90	50	40
EDS	180000	359.497	90	50	40

Steam Mass Flow (lb/hr)	Steam Vol Flow (gal/hr)	Steam Vol Flow (gal/min)	Evap Loss (gal/min)	Wind Drift (gal/min)
1000000	125000	2083.33	297.205	0.30352
604500	75563	1259.38	362.218	0.30352

Evap Loss (gal/min)	Wind Drift (gal/min)	Blow Down (gal/min)	Makeup Water gal/min	Makeup Water (gal/hr)
23.2235	0.0759	4.5688	27.8682	1672.09
22.0012	0.0719	4.32834	26.4014	1584.09

## Appendix D: Economic Analysis

Unit	Sale Price (\$)	Delivery factor	Total Price (\$)
Grains Receiving and Storage	\$9,678,530.43	1.1	\$10,646,383.47
Liquefaction and Saccharification	\$15,087,120.96	1.1	\$16,595,833.06
Fermentation	\$29,889,579.27	1.1	\$32,878,537.20
Common Support System	\$4,839,265.22	1.1	\$5,323,191.74
Rolling Stock and Shop Equipment	\$1,059,188.53	1.1	\$1,165,107.39
Start-up cost	\$2,086,993.70	1.1	\$2,295,693.07
Spare Parts Cost	\$156,916.82	1.1	\$172,608.50
LP Col 1	\$768,778.00	1.1	\$845,655.80
Reboiler-LP-1	\$390,285.00	1.1	\$429,313.50
Condenser LP-1	\$238,853.00	1.1	\$262,738.30
Pump LP-1	\$100,000.00	1.1	\$110,000.00
Vacuum Pump	\$91,344.00	1.1	\$100,478.40
HP Col 1	\$768,778.00	1.1	\$845,655.80
Reboiler HP-1	\$57,061.00	1.1	\$62,767.10
Condenser HP-1	\$40,175.00	1.1	\$44,192.50
LP Col 2	\$837,219.00	1.1	\$920,940.90
Reboiler LP-2	\$390,285.00	1.1	\$429,313.50
Condenser LP-2	\$40,175.00	1.1	\$44,192.50
Pump LP-2	\$100,000.00	1.1	\$110,000.00
Vacuum Pump	\$91,344.00	1.1	\$100,478.40
HP Col 2	\$837,219.00	1.1	\$920,940.90
Reboiler HP-2	\$90,970.00	1.1	\$100,067.00
Condenser HP-2	\$40,175.00	1.1	\$44,192.50
CO2 Scrubber	\$457,102.00	1.1	\$502,812.20
9 Slurry Pumps	\$1,000,000.00	1.1	\$1,100,000.00
Vacuum Pump	\$91,344.00	1.1	\$100,478.40
Pervaporation Membrane	\$2,095,192.00	1.1	\$2,304,711.20
Pervaporator Condenser	\$52,067.00	1.1	\$57,273.70
Evaporator	\$12,553,345.57	1.1	\$13,808,680.12
Evaporator Condenser	\$411,272.00	1.1	\$452,399.20
Centrifuge	\$1,606,869.03	1.1	\$1,767,555.93
Dryer	\$23,564,194.43	1.1	\$25,920,613.87
Turbine	\$3,605,000.00	1.1	\$3,965,500.00
Boiler	\$23,000,000.00	1.1	\$25,300,000.00

Installation, including insulation and painting (35% of purchased equipment cost)	\$31,040,028.65
Instrumentation and controls, installed (25% of purchased equipment cost)	\$22,171,449.03
Piping, installed (30% of purchased-equipment cost)	\$26,605,738.84
Electrical, installed (30% of purchased equipment cost)	\$26,605,738.84
Buildings, process and auxiliary (40% of purchased equipment cost)	\$35,474,318.45
Service facilities and yard improvements (40% of purchased equipment cost)	\$35,474,318.45
Land (6% of purchased-equipment cost)	\$5,321,147.77
Direct Costs	\$182,692,740.03
Engineering and supervision (15% of direct costs)	\$27,403,911.00
Construction expense and contractor's fee (15% of direct costs)	\$27,403,911.00
Contingency (8% of fixed-capital investment)	\$14,615,419.20
Indirect Costs	\$69,423,241.21
Fixed Capital Investment (Direct+Indirect Cost)	\$252,115,981.24
Total Capital Investment	\$296,607,036.75

Raw Material	Cost/ (bu,kg,gal,hr etc)(\$/?)	Annual Consumption or Production (bu,gal,lb,hr,etc)	Annual Cost (\$/yr)
Corn	\$3.35	71836800	\$240,653,280
Chemical, Enzymes, Yeast	\$0.07	200000000	\$13,400,000
Denaturants	\$2.69	1000000.00	\$2,690,000.00
Ethylene Gylcol	\$0.49	254209	\$124,562.20
Total Raw Materials			\$256,867,842.20

Utilities			
	Usage (lb/hr)	Usage (1000 kg/yr)	Cost
Reboiler-LP1	340,000.00	1351875.97	\$23,090,041.54
Reboiler-HP1	70,000.00	278327.41	\$4,753,832.08
Reboiler-LP2	340,000.00	1351875.97	\$23,090,041.54
Reboiler-HP2	250,000.00	994026.45	\$16,977,971.72

Total	1,000,000.00	\$67,911,886.89
Auxiliary Steam		\$13,582,377.38

Electricity	Number	Total Usage	Cost
Pumps	7	4233600	\$211,680.00
Hammer Mills	3	12787200	\$639,360.00
Centrifuge	2	3870720	\$193,536.00
Vacuum Pump	6	1328026	\$66,401.30
Dryer	1	38655360	\$1,932,768.00
Total			\$3,043,745.300
Auxiliary Electricity			\$913,123.590

Make-up Water

Total Utilities		\$85,451,133.162
Raw Material	Annual Consumption or Production (bu,gal,lb,hr,etc)	Annual Cost (\$/yr)

Corn	71836800	\$240,653,280
Chemical, Enzymes, Yeast	200000000	\$13,400,000
Denaturants	1000000.00	\$2,690,000.00
Total Raw Materials		\$256,743,280.00

Estimated Total Product Cost (E- TPC)		\$513,486,560.00
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Utilities		
Operating Labor	1% of E-TPC	\$5,134,865.60
Directory		
Supervisions	18% of Operating Labor	\$924,275.81
Engineering		
Support	4 positions @ \$80,000 x 1.6 benefits	\$512,000.00
Utilities	Calculated	\$85,451,133.16
Maintanance and Repairs	5% of Fixed Capital Investment	\$11,463,726.28
Operating Supplies	15% of Maintanance and Repairs	\$1,719,558.94

Laboratory Charges	15% of Operating Labor	\$770,229.84
Patents and Royalties	3% of E-TPC	\$15,404,596.80
Fixed Charges	10% of E-TPC	\$51,348,656.000
Depreciation	10% of Machinery and Equipment and 2% of Buildings	\$8,710,302.787
Local Taxes	2% fo fixed Capital Investment	\$4,585,490.511
Insurance	0.6% of Fixed Capital Investment	\$1,375,647.153
Rent	10% of Buildings	\$3,226,038.069
Plant Overhead Cost	10% of E-TPC	\$51,348,656.000
Administrative Cost	15% of Operating Labor Supervision and Maintanance	\$2,628,430.153
Distribution and Selling Cost	2% of E-TPC	\$10,269,731.200
Research and development Cost	5% of E-TPC	\$25,674,328.000
Financing (interest)	5% of Total Capital Investment	\$13,486,736.80
Total Annual Utilities		\$294,034,403.10
Manufacturing Cost		\$550,777,683.10
Total Annual Operating Cost		\$605,855,451.41
Total Annual Cost		\$60,585,545.14
Cost Per Gallon		\$3.03

Unit	Sale Price (\$)	Delivery factor	Total Price (\$)
Grains Receiving and Storage	\$9,678,530.43	1.1	\$10,646,383.47
Liquefaction and Saccharification	\$15,087,120.96	1.1	\$16,595,833.06
Fermentation	\$29,889,579.27	1.1	\$32,878,537.20
Common Support System	\$4,839,265.22	1.1	\$5,323,191.74
Rolling Stock and Shop Equipment	\$1,059,188.53	1.1	\$1,165,107.39

Start-up cost	\$2,086,993.70	1.1	\$2,295,693.07
Spare Parts Cost	\$156,916.82	1.1	\$172,608.50
Beer Column 1	\$1,122,440.00	1.1	\$1,234,684.00
Beer Column 2	\$936,049.00	1.1	\$1,029,653.90
Beer Column 3	\$1,122,440.00	1.1	\$1,234,684.00
Rectifying Column 1	\$1,823,031.00	1.1	\$2,005,334.10
Rectifying Column 2	\$893,656.00	1.1	\$983,021.60
Solvent Recovery Colum	\$518,058.00	1.1	\$569,863.80
Condensers/Reboilers	\$13,516,266.00	1.1	\$14,867,892.60
Vacuum Pumps	\$300,000.00	1.1	\$330,000.00
CO2 Scrubber	\$457,102.00	1.1	\$502,812.20
9 Slurry Pumps	\$1,000,000.00	1.1	\$1,100,000.00
Vacuum Pump	\$91,344.00	1.1	\$100,478.40
Evaporator	\$12,553,345.57	1.1	\$13,808,680.12
Evaporator Condenser	\$411,272.00	1.1	\$452,399.20
Centrifuge	\$1,606,869.03	1.1	\$1,767,555.93
Dryer	\$23,564,194.43	1.1	\$25,920,613.87
Turbine	\$3,605,000.00	1.1	\$3,965,500.00
Boiler	\$23,000,000.00	1.1	\$25,300,000.00
Installation, including insulation and painting (35% of purchased equipment cost)			\$31,040,028.65
Instrumentation and controls, installed (25% of purchased equipment cost)			\$22,171,449.03
Piping, installed (30% of purchased-equipment cost)			\$26,605,738.84
Electrical, installed (30% of purchased equipment cost)			\$26,605,738.84
Buildings, process and auxiliary (40% of purchased equipment cost)			\$35,474,318.45
Service facilities and yard improvements (40% of purchased equipment cost)			\$35,474,318.45
Land (6% of purchased-equipment cost)			\$5,321,147.77
Direct Costs			\$182,692,740.03
Engineering and supervision (15% of direct costs)			\$27,403,911.00
Construction expense and contractor's fee (15% of direct costs)			\$27,403,911.00
Contingency (8% of fixed-capital investment)			\$14,615,419.20
Indirect Costs			\$69,423,241.21
Fixed Capital Investment (Direct+Indirect Cost)			\$252,115,981.24
Total Capital Investment			\$296,607,036.75

Raw Material	Cost/ (bu,kg,gal,hr etc)(\$/?)	Annual Consumption or Production (bu,gal,lb,hr,etc)	Annual Cost (\$/yr)
Corn	\$3.35	71836800	\$240,653,280
Chemical, Enzymes, Yeast	\$0.07	200000000	\$13,400,000
Denaturants	\$2.69	1000000.00	\$2,690,000.00
Ethylene Glycol	\$0.49	254209	\$124,562.20
Total Raw Materials			\$256,867,842.20

Utilities			
Steam	Usage (lb/hr)	Usage (1000 kg/yr)	Cost
Reboiler-1-1	74000.00	294,231.83	\$5,025,479.63
Reboiler-1-2	74000.00	294,231.83	\$5,025,479.63
Reboiler-1-3	74000.00	294,231.83	\$5,025,479.63
Reboiler-2-1	126000.00	500,989.33	\$8,556,897.75
Reboiler-2-2	126500.00	502,977.38	\$8,590,853.69
Reboiler-3-1	130000.00	516,893.75	\$8,828,545.30
Total	604,500.00		\$41,052,735.63
Auxiliary Steam			\$8,210,547.13

Electricity	Number	Total Usage	Cost
Pumps	7	4233600	\$211,680.00
Hammer Mills	3	12787200	\$639,360.00
Centrifuge	2	3870720	\$193,536.00
Vacuum Pump	3	664013	\$33,200.65
Dryer	1	38655360	\$1,932,768.00
Total			\$3,010,544.650
Auxiliary Electricity			\$903,163.395

Total Utilities	\$53,176,990.797	
Raw Material	Annual Consumption or Production (bu,gal,lb,hr,etc)	Annual Cost (\$/yr)
Corn	71836800	\$240,653,280
Chemical, Enzymes, Yeast	200000000	\$13,400,000

Denaturants	1000000.00	\$2,690,000.00
Ethylene Gylcol	254209	\$124,562.20
Total Raw Materials		\$256,867,842.20
Estimated Total ProductCost (E-TPC)		\$513,735,684.40
Utilities		
Operating Labor	1% of E-TPC	\$5,137,356.84
Directory Supervisions	18% of Operating Labor	\$924,724.23
Utilities	Calculated	\$53,176,990.80
Engineering Support	4 positions @ \$80,000 x 1.6 benefits	\$512,000.00
Maintanance and Repairs	5% of Fixed Capital Investment	\$12,605,799.06
Operating Supplies	15% of Maintanance and Repairs	\$1,890,869.86
Laboratory Charges	15% of Operating Labor	\$770,603.53
Patents and Royalties	3% of E-TPC	\$15,412,070.53
Fixed Charges	10% of E-TPC	\$51,373,568.440
Depreciation	10% of Machinery and Equipment and 2% of Buildings	\$9,578,065.982
Local Taxes	2% fo fixed Capital Investment	\$5,042,319.625
Insurance	0.6% of Fixed Capital Investment	\$1,512,695.887
Rent	10% of Buildings	\$3,547,431.845
Plant Overhead Cost	10% of E-TPC	\$51,373,568.440
Administrative Cost	15% of Operating Labor Supervision and Maintanance	\$2,800,182.021
Distribution and Selling Cost	2% of E-TPC	\$10,274,713.688
Research and development Cost	5% of E-TPC	\$25,686,784.220
Financing (interest)	5% of Total Capital Investment	\$14,830,351.84
Total Annual Utilities		\$266,450,096.84
Manufacturing Cost	\$523,317,939.04	
Total Annual Operating Cost	\$575,649,732.94	
Total Annual Cost	\$57,564,973.29	
Cost Per Gallon	\$2.88	

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<sup>i</sup> Refer to Section 5.3  
<sup>ii</sup> Refer to Section 5.3