NABEER-Design

De-alcoholization of Beer Using Selective Membrane Reverse Osmosis

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Letter of Transmittal

To interested clients,

Amid increasing state excise duties on alcoholic beverages, a general shift towards healthier lifestyles and increased disposable income among families, the demand for non-alcoholic beverages is increasing. NA-BEER set out to develop an economic and optimized process for the de-alcoholization of beer. Federal and State Excise duties add a significant cost to the sale of alcoholic beverages in the United States. State excise duties can range between 20 cents per gallon in California to about $1.05 /gal in Alabama. For a production scale as large as 90,000 barrels per year (BPY), in states like Alabama, the de-alcoholization of beer can amount to generating around $3,00,000 per year in revenue.

An investment in this process can generate an internal rate of return (IRR) values of 15% at 67,447 Barrels per year produced in state of Alabama. This value was 71,700 BPY in the state of Georgia. This process is not lucrative in states like California, Florida, and Texas because of their low excise duties on beer. However, amid increasing state budget deficits, excise duties for these states are likely to increase in the coming years, especially because of increased government spending in the wake of pandemics like COVID-19.

In this paper, we discuss simulation and optimization of non-alcoholic beer production via reverse osmosis. We then develop equations to determine the number of BPY of beer that must be produced in order to reach various minimum IRRs in the states of Alabama and Georgia, where this process is likely more profitable. We also provide recommendations for equipment size and recommendations for future research to tune this process for specific breweries and beers.

Abstract

The high demand of non-alcoholic beverages is clearly seen today. Non-alcoholic (NA) beer can be produced from beer using reverse osmosis (RO), a membrane separation technique. NA beer has the advantage of being free from state excise duties. During the dealcoholizing process, the beer first goes through a pre-concentration step to reduce the volume of the feed beer by passing it through membrane modules. Then, there is a diafiltration step where the alcohol is washed out, further reducing the alcohol content in the beer. The beer can also be adjusted further by adding water to achieve the desired alcohol content.

In this paper, we examined ways to simulate the process using Python, ASPEN, and Excel and use design heuristics to determine the appropriate equipment. We optimized the process based on membrane area, the feed flow rate to the membrane, the amount of each batch feed and the recycling ratio. An optimal time necessary to dealcoholize one batch, combined with the batch feed amount, determines the annual production.

With the help of our simulation, utility costs and equipment costs were determined through appropriate heuristics. With the information attained, we used an economic analysis to determine the minimum capacity of NA beer needed. For the 5-year plant life, we used a 5-year MACRS depreciation schedule. We determined that at least 67,447 BPY were required to return at least 15% IRR on the invested capital costs in the state of Alabama, with the values of BPY being 70,834 in the state of Georgia. We determined relationships between IRR and BPY for each state and found that increasing the BPY linearly increases the %IRR for any given state. However, the operation was found to be nonprofitable in California, Florida or Texas.

Through the results of our optimization, we recommend running this plant at a temperature of 5℃ with pumps operating at no higher than 40 psi for the integrity of the membrane being used. The membrane used is CA995-PE, which is highly selective to water and ethanol. One batch process takes about 1.6 hours. Further analysis might be necessary to tune the process for different beers to preserve taste and texture in this process.

Contents

1. Introduction

The overall goal that NA-Beer Design Inc. set out to solve was the design of a process to generate non-alcoholic (NA) Beer. In the US, beverages with less than 0.5% ethanol by volume are considered exempt from federal and state excise duties on alcoholic beverages. NA-Beer referred to in this report is therefore less than 0.5% ethanol by volume. The primary challenge was to determine the minimum capacity in Barrels Per Year (BPY) of NA-Beer that would result in at least 15% IRR on invested capital. A secondary challenge was to optimize the process and add equipment such that operating costs are minimized. In order to do so, we created a process flow diagram of a semi-batch process for the de-alcoholization of beer. The process was a semi-batch membrane reverse osmosis/diafiltration process simulated using a combination of software to optimize process parameters and reduce costs. Simulated annual cost of the process under different size of the equipment and operating conditions allows us to estimate IRR from the net present value (NPV) calculation of the plant over 5 years.

The Revenue generated from NA beer is higher because it is free of federal and state excise taxes, therefore any revenue generated from this process was assumed to be the tax advantage from selling NA beer over Alcoholic Beer. The client requested an estimate of the IRR of this process in Alabama, Georgia, Florida, Texas and California. The brewery was designed to produce at least 60,000 BPY, with a limiting capacity of up to 90,000 BPY.

2. Results

2.1 Process Flow Diagram (PFD)

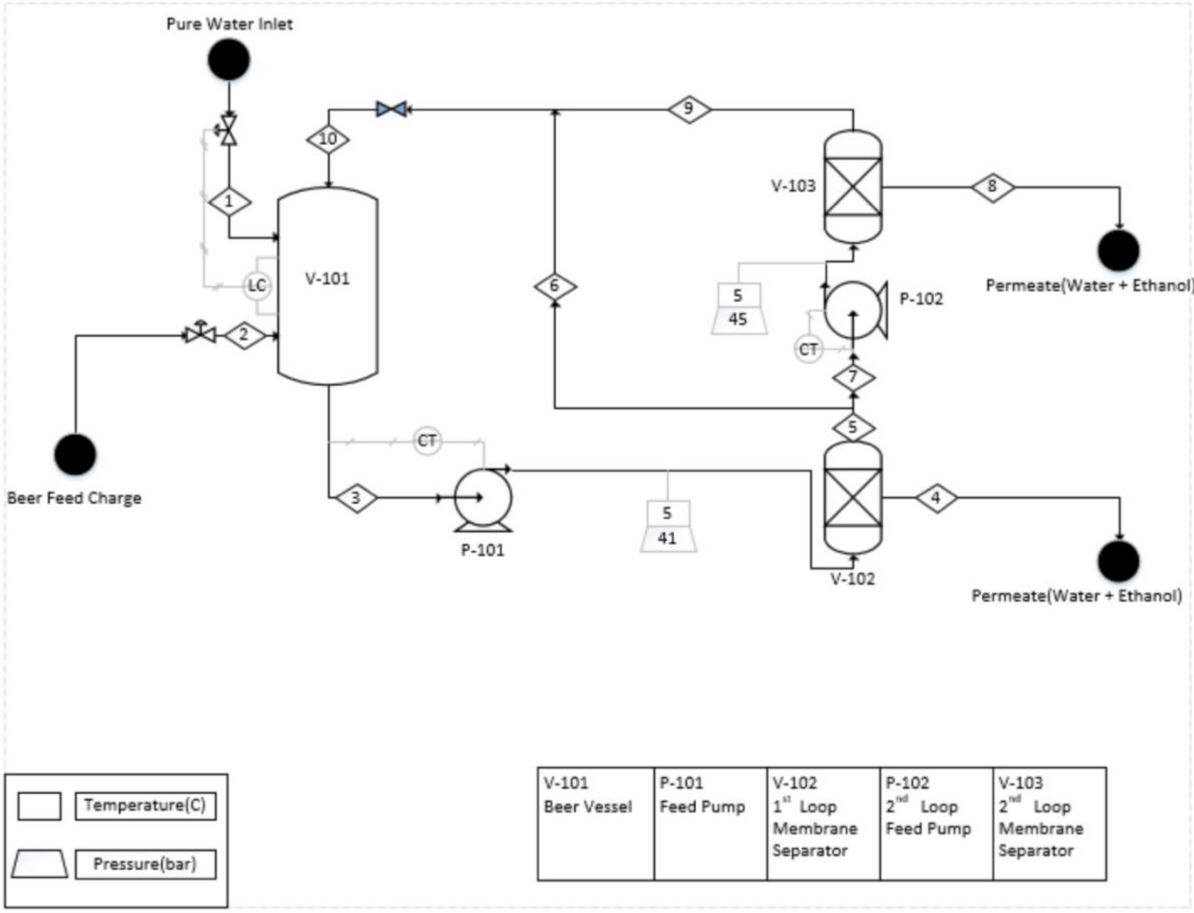

Figure 1.0: Process Flow Diagram

The process flow diagram in Figure 1.0 illustrates our semi-batch process. The beer vessel is initially charged with beer by stream 2. After the vessel is fully charged, flow in stream 2 would stop by the closing of the valve. Then, the process to generated NA beer begins. The feed beer goes through two membrane RO steps (V-102 and V-103), where the beer is cross-flowed through a spiral-wound selectively permeable membrane CA995-PE from Alpha Laval. It was assumed that the permeates through the membranes (Streams 4, 8) were comprised purely of ethanol and water. The resulting weak aqueous ethanol solution could then be repurposed within the facility. The retentate streams (Streams 5, 9) are pumped back into the feed tank for several passes through the membrane units. Beer in the feed tank is diluted with deionized water (Stream 2) in a diafiltration step to compensate for the volume lost to the concentration step. Given this process was semi-batch and required several passes of the beer through the membrane, a concentration profile for ethanol in the feed tank (V-101) was created, which decreased over time. A concentration profile for the optimized process producing 69,995 BPY is shown in Figure 1.1 in Section 2.2.

2.2 Stream Flow Tables

Production capacities were chosen randomly within the range between 60,000 BPY and 90,000 BPY. At those randomly chosen production capacities, Python was used to simulate and to optimize the batch processes per production capacity. Of the chosen production capacities, 69,994 BPY had a net positive cash flow for states, such as Alabama and Georgia. Thus, all of the figures in the Results section correspond to a production capacity of 69, 994 BPY. A specific production capacity will impact the concentration profile and flow rates in all streams for snapshots in time. Nonetheless, a similar trend exists for all the production capacities. Pumps will raise the pressure of inlet streams to the membrane separators by 40-45 bar to keep the driving force of RO constant (see Discussion for details). Initially, the permeate rates are high. For example, at 69, 994 BPY, the permeate rates are around 77.86 k mol/h of water and 1.08 k mol/h of ethanol in the first membrane separator and 77.86 k mol/h of water and 1.13 k mol/h of ethanol in the second separator. However, the flow of ethanol permeate will decrease over time as the concentration of ethanol in the feed tank decreases. Shown in Figure 1.1 is a concentration profile of ethanol in the beer vessel during the batch process. Please refer to the Appendix A to view other concentration profiles. Two snapshots in time, t = 0 and t = end, were used to generate the stream tables shown in Tables 1.1 and 1.2 respectively. It is important to note that stream 2 is not included in the stream tables. As mentioned earlier, stream 2 only functions to charge the beer vessel and does not participate in the semi-batch process.

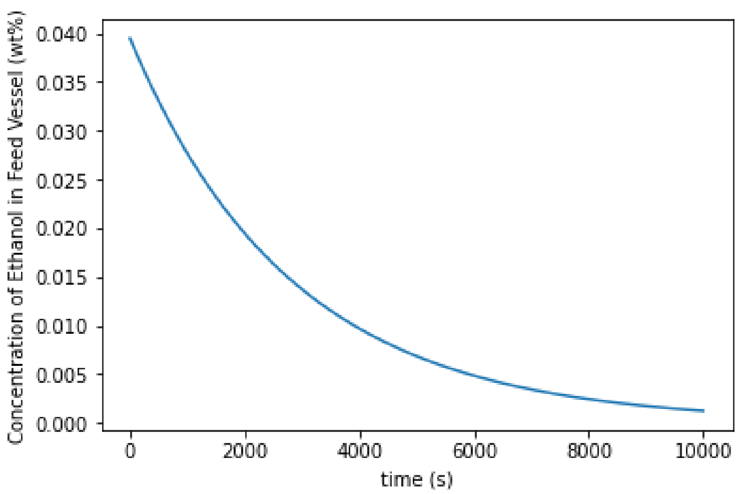

Figure 1.1: Concentration of Ethanol by weight in the feed beer vessel. A concentration of wt% 0.00394 corresponds to a 0.5 volume% of Ethanol.

Table 1.1: Stream table for the beginning of the batch process (t = 0s)

Stream Number	**1**	**3**	**4**	**5**	
Pressure (bar)	1	1	1	1	
Temperature (°C)	5	5	5	5	
Liquid fraction	1	1	1	1	
Mass flow (kg/h)	4776.09	3240.00	1476.18	1763.82	
Mole flow (kmol/h)	255.90	264.69	78.94	185.75	
Component flowrates (kmol/h)					
Ethanol	0.00	4.31	1.08	3.23	
Water	255.90	259.38	77.86	181.52	
Solutes	0.00	1.00	0.00	1.00	
Stream Number	**6**	**7**	**8**	**9**	**10**
Pressure (bar)	1	1	1	1	1
Temperature (°C)	5	5	5	5	5
Liquid fraction	1	1	1	1	1
Mass flow (kg/h)	88.19	1675.63	1476.62	199.02	287.21
Mole flow (kmol/h)	9.29	176.46	78.99	97.48	106.77
Component flowrates (kmol/h)					
Ethanol	0.16	3.07	1.13	1.94	2.10
Water	9.08	172.45	77.86	94.59	103.66
Solutes	0.01	0.99	0.00	0.99	1.00

Table 1.2: Stream table for end of batch process (t = 5763s)

Stream Number	**1**	**3**	**4**	**5**	
Pressure (bar)	1	1	1	1	
Temperature (°C)	5	5	5	5	
Liquid fraction	1	1	1	1	
Mass Flow (kg/h)	4776.09	3240.00	1476.18	1763.82	
Mole Flow (kmol/h)	252.81	170.15	77.97	92.18	
Component flowrates (kmol/h)					
Ethanol	0.00	2.78	0.11	2.67	
Water	252.81	166.73	77.86	88.87	
Solutes	0.00	0.64	0.00	0.64	
Stream Number	**6**	**7**	**8**	**9**	**10**
Pressure (bar)	1	1	1	1	1
Temperature (°C)	5	5	5	5	5
Liquid fraction	1	1	1	1	1
Mass Flow (kg/h)	88.19	1675.63	1476.62	199.02	287.21
Mole Flow (kmol/h)	4.61	87.57	77.97	9.60	14.21
Component flowrates (kmol/h)					
Ethanol	0.13	2.54	0.11	2.42	2.56
Water	4.44	84.43	77.86	6.57	11.01
Solutes	0.006	0.634	0.00	0.634	0.64

2.3 Manufacturing Cost Summary

In this report, our net profit is determined as the amount of cost saved by avoiding state excise duties. This is not exactly "revenue." However, it is a net increase in cash flow compared to the base case, where alcoholic beer was sold directly without the dealcoholizing process. The cost of manufacturing and other capital investments are also in terms of the extra amount to pay for building the dealcoholizing process system. It is important to note that we are assuming the price of the alcoholic beer to be equal to the price of the NA beer.

The cost of waste treatment, if we were to dispose all the permeate streams, was extremely high. As a result, we seek for an alternative solution: the permeate streams would be recycled back to the beer production facility and diluted with water, acting as a solvent in the yeast fermentation step. This could also potentially reduce the amount of yeast or the time required to produce certain volume of beer. Thus, in this case, we simply disregarded the cost of waste treatment.

Table 1.3: Yearly Revenue Per State at 69,994 BPY.

State	Amount Saved in Excise Duties ($/gal)	Profit per Barrel	Yearly Revenue at 69,994 BPY
Alabama	1.05	32.55	$2,278,305.02
Georgia	1.01	31.31	$2,191,512,45
California	0.2	6.2	$433,962.86
Texas	0.2	6.2	$433,962.86
Florida	0.48	14.88	$1,041,510.87

Table 1.4: Raw Material Cost at 69,994 BPY. The raw materials cost for the feed beer and the NA beer cancel out, except for the additional DI water needed to produce NA beer.

Flow rate of water [kg/hr]	Operating hours [hr/day]	DI water [$/1000 kg]	Cost of DI Water
5040	20	1	$36,792.00

Table 1.5: Cost of Utilities at 69,994 BPY. The utilities cost for the feed beer and the NA beer cancel out, except for the electrical utilities needed to power the pumps.

Power of pump 1 [kW]	Power of pump 2 [kW]	Rate of electricity [$/kWh]	Operating hours [hr/day]	Cost of Electricity
6.53	4.90	$0.06	20	$5,002.81

Table 1.6: Cost of Operating Labor. The operating labor for the feed beer and the NA beer cancels out, except for the additional labor needed to operate the reverse osmosis units.

N_{np}	N_{OL}	Operating Labor	Labor Cost
2	2.60	12	$714,960

Table 1.7: Cost of Manufacturing. Determination of FCI_{GR} and reverse osmosis equipment costs are explained in Section 2.4, Investment Summary.

69,994 BPY	
Area of Membrane [m^2]	90.90
Cost of Membrane	$18,180.00
Cost of Housing	$4,545.00
Total Membrane Cost	$22,725
FCI_{GR}	$361,000
C_{OL}	
N_{np}	2
N_{OL}	2.60
Operating Labor	12
Labor Cost	$714, 960
C_{UT}	
Power of pump 1 [kW]	6.53
Power of pump 2 [kW]	4.90
Rate of electricity [$/kWh]	$0.06
Operating hours [hr/day]	20
Cost of Electricity	$5,002.81
C_{RM}	
Flow rate of water [kg/hr]	5040
Operating hours [hr/day]	20
DI water [$/1000 kg]	1
Cost of DI Water	$36,792.00
$COM_d = 0.18 * FCI_{GR} + 2.73 * C_{OL} + 1.23 * (C_{UT} + C_{RM})$	$2,068,228.41

2.4 Investment Summary

An estimation of upfront capital to construct a reverse osmosis plant was determined by the program, CAPCOST. Pricing for the individual membrane units were \$200 per m^2 for the membrane and \$50 per m^2 for the housing (1). Depending on the production capacity of the reverse osmosis plant, FCI_{GR} will change to accommodate the capacity. For example, if the production capacity was 90,000 BPY, the size of the beer vessel, the power required for the pumps, and the size of the membrane will either increase or decrease for fulfill the production rate. Shown below in Table 1.8 is the FCI_{GR} for 69,994 BPY.

Table 1.8: FCI_{GR} for 69,994 BPY

Add Equipment

Edit Equipment

Remove All Equipment

Unit Number	100
CEPCI	397

User Added Equipment

Pumps (with drives)	Pump Type	Power (kilowatts)	# Spares	MOC	Discharge Pressure (barg)	Purchased Equipment Cost	Bare Module Cost
P-101	Centrifugal	6.53	1	Stainless Steel	41	\$ 6,850	\$ 49,500
P-102	Centrifugal	4.9	1	Stainless Steel	46.1	\$ 6,320	\$ 47,200

Vessels	Orientation	Length/Height (meters)	Diameter (meters)	MOC	Demister MOC	Pressure (barg)	Purchased Equipment Cost	Bare Module Cost
V-101	Horizontal	4.67	1.56	Stainles Steel		10	\$ 9,910	\$ 114,000

User Added Equipment	Description	BMF_0	Actual BMF	Purchased Equipment Cost	Bare Module Cost
V-102	Membrane Separator	1	1	\$ 22,725	\$ 22,725
V-103	Membrane Separator	1	1	\$ 22,725	\$ 22,725

Total Bare Module Cost \$ 210,700

Total Module Cost: \$ 302,000.00

Total Grassroots Cost: \$ 361,000.00

2.5 Equipment Summary

The semi-batch process consists of a feed vessel for beer and additional vessels for membrane separation. The membrane separators are shown here as vessels that are designed to withstand pressures around 40-50 psi and acidic solutions, making stainless steel an ideal material of construction. Additional design heuristics and optimizations were used to evaluate the dimensions of the feed tank. The pumps were designed to withstand pressures of around 40-50 psi.

Table 1.9: Major Equipment Summary for 69,994 BPY

Vessels **V-101** Horizontal Stainless Steel L = 1.56 m D = 4.67 m Maximum pressure: 10 bar g	
V-102 Membrane: CA995-PE Membrane Operating Area = 90.90 m^2 Stainless Steel Spiral Wound	**V-103** Membrane: CA995-PE Membrane Operating Area = 90.90 m^2 Stainless Steel Spiral Wound
Pumps **P-101 A/B** Centrifugal/electric drive Stainless Steel Power required = 6.53 kW 85% efficient Discharge Pressure = 41 bar	**P-102 A/B** Centrifugal/electric drive Stainless Steel Power required = 4.90 kW 85% efficient Discharge Pressure = 46 bar

2.6 Cash Flow Diagram (CFD)

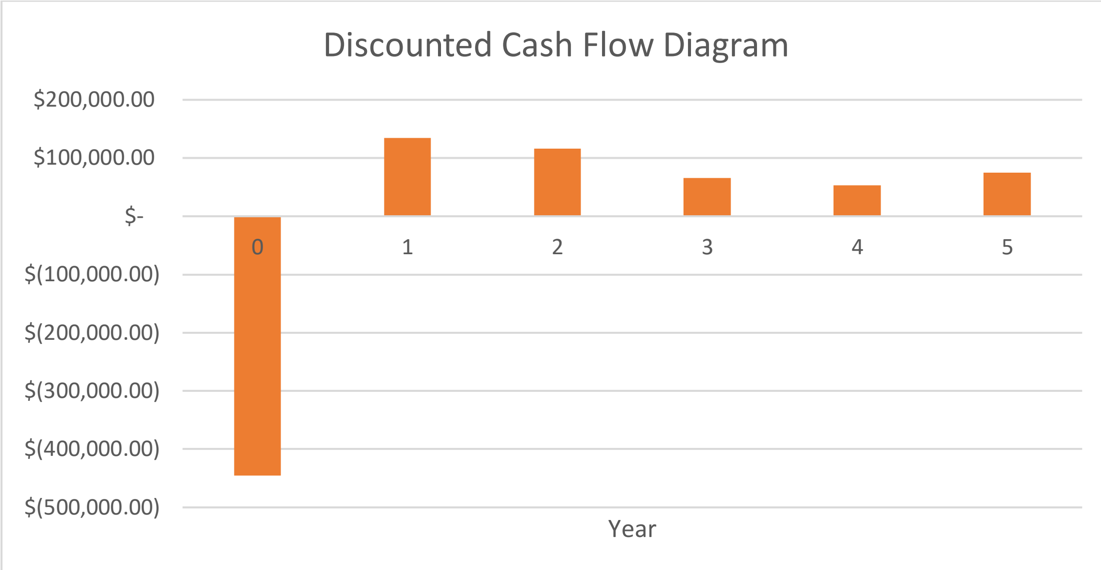

Figure 1.2: Discounted CFD at 69,994 BPY for Alabama

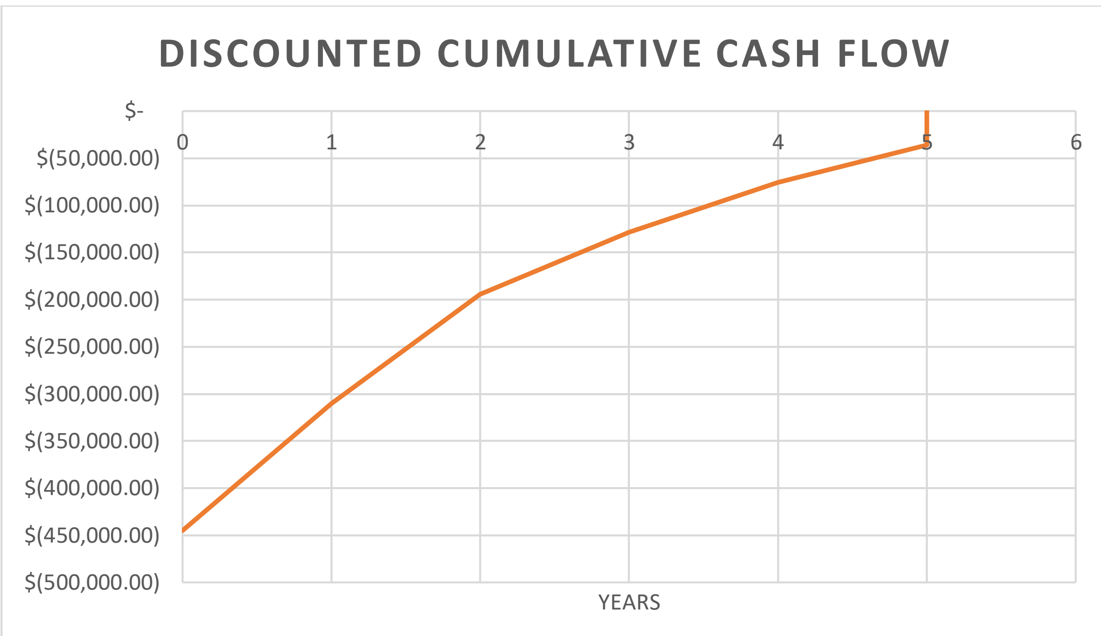

Figure 1.3: Discounted Cumulative CFD at 69,994 BPY for Alabama

As shown in Figure 1.2 and Figure 1.3, the production of 69,994 BPY of NA beer was profitable. The revenue, $2,278,305.02, exceeded the cost of manufacturing, which was $2,068,228.41. Goal seek was used on Microsoft Excel to determine the IRR corresponding to this production capacity. At this production capacity, the IRR was 26.22%.

2.7 Minimum Production for specified IRR in Alabama

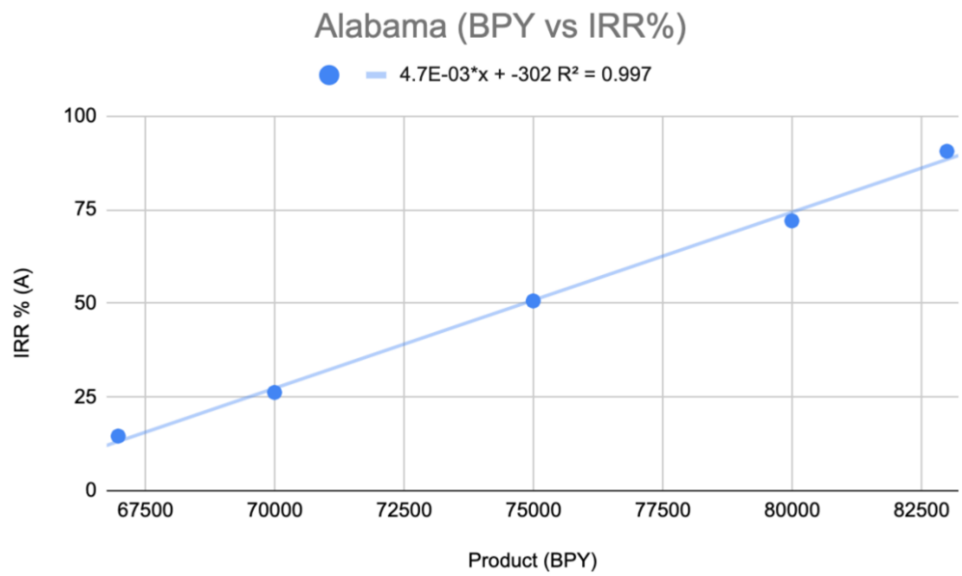

Figure 1.4: Correlation between BPY and IRR% for Alabama. R_2 suggests a highly linear relationship.

A cost analysis was conducted at 66,000 BPY, 70,000 BPY, and other corresponding points in Figure 1.4. A linear fit was generated in order to determine the production needed to return 15%, 20%, 25%, 30%, and 35% IRR on invested capital. Table 1.10, shown below, displays the required BPY to achieve the specific IRR values. These values were calculated from the linear fit equation.

Table 1.10: Required capacities of NA beer to provide IRR's of 15%, 20%, 25%, 30% and 35%

IRR (%)	Minimum BPY (Alabama)
15	67,447
20	68,511
25	69,575
30	70,639
35	71,703

2.8 Minimum Production for specified IRR in Georgia

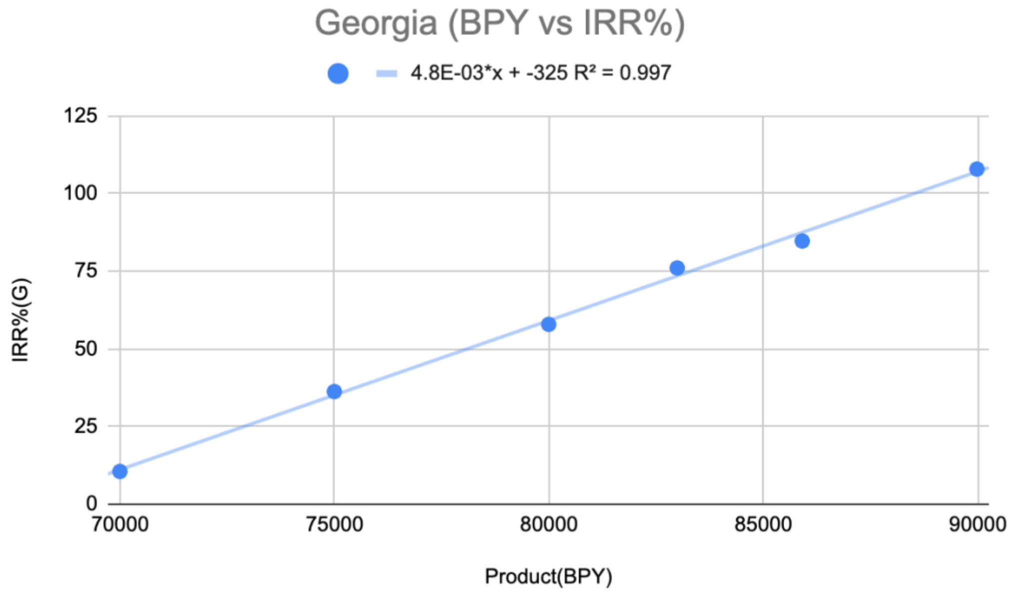

Figure 1.5: Correlation between BPY and IRR% for Georgia. R2 suggests a highly linear relationship.

A cost analysis, conducted in a similar fashion to the cost analysis of Alabama, generated the linear fit displayed in Figure 1.5. The corresponding capacities required to provide IRR's of 15%, 20%, 25%, 30% and 35% was calculated from the linear fit equation and is shown in Table 1.11 below.

Table 1.11: Required capacities of NA beer to provide IRR's of 15%, 20%, 25%, 30% and 35%

IRR (%)	Minimum BPY (Georgia)
15	70,834
20	71,875
25	72,917
30	73,959
35	75,000

2.9 Minimum Production for specified IRR in Florida, Texas, and California

Estimated fixed capital cost and cost of manufacturing are the same among all states. However, in states of Florida, Texas and California, the "revenue" from selling NA beer, which is the annual product amount multiplied by the state excise duties, is much less than the cost of manufacturing per year. In these scenarios, the process fails to earn a positive net profit, so that no positive IRR exists as a solution. If the company insists on producing NA beer in these states, we highly recommend that the NA beer produced be transported (introducing extra fee) and sold in Alabama or Georgia.

3. Discussion

3.1 Python

While Hysys software, like ASPEN, provide certain methods for simulation of batch processes, simulating the entire process using ASPEN can be especially difficult. For example, there was no built-in membrane separator in ASPEN. To simulate such a unit, it is required for the users to learn Fortran. Thus, our team chose Python as the simulation software of choice for the membrane osmosis process. Python allows the membrane osmosis process to be modeled as a semi-batch process using differential equations. These equations will be discussed below. Using Python, it was easier to obtain a time-dependent concentration curve for the beer vessel.

3.1.1 Assumptions

Several assumptions had to be made while simulating the semi-batch process for ease of calculation. First, we assumed that no solutes in the original beer (aromatics, salts and proteins) were lost in the permeate. All solutes remained in the retentate. Secondly, since osmotic pressure in the solution is proportional to the mole concentration of solutes, the osmotic pressure on the retentate side can be estimated as:

$$\pi_R = \frac{M_{solute,F}}{M_{solute,R}}\pi_F = \frac{\dot{V}_R}{\dot{V}_F} \approx \frac{\dot{M}_R}{\dot{M}_F}$$

This equation then allowed us to determine the osmotic pressure difference $\Delta\pi = \pi_R - \pi_F$ backwards after simulation, while the flux was designed to be constant (see following section).

3.1.2 Governing Equations

The key equation of the RO process is below:

$$J_i = k_i(\Delta P - \Delta\pi)$$

where J_i is the permeate flux of species i (water or ethanol) across the membrane, k_i is the permeability of species i, ΔP is pressure drop across the membrane and $\Delta\pi$ is the difference in osmotic pressure on both sides. The quantity $\Delta P - \Delta\pi$ is identified as the “driving force” of the separation. Using the assumptions stated above, we determined that $\Delta\pi$ is proportional to the concentration of other solutes and with a base case of 5.7 bar for non-dealcoholized beer, estimated from a study on NA beer production (2). The permeability is also estimated to be $1.25 \times 10^{-5}\ g/(cm^2 \cdot s \cdot bar)$ for water based on their experimental results. The permeability of ethanol is approximated from the that of water using the following equation:

$$k_E = k_W x_E(1 - R_E)$$

where x_E is the mass fraction of ethanol in the feed solution and R_E is the rejection rate of ethanol for CA995-PE membrane from experimental data (2). Under the conditions of $\Delta P \approx 40\ bar$ and $T = 5°\text{C}$, R_E is 0.1. The mass flow rate of each species across the membrane could then be calculated by the product of flux and membrane area.

Mass balances are used to obtain stream information through Python simulation.

Overall mass balance on the feed tank at steady state:

$$\frac{dm}{dt} = \dot{M}_1 + \dot{M}_{10} - \dot{M}_3 = 0$$

$$\frac{d(x_E \cdot m_0)}{dt} = \dot{M}_6 x_5 + \dot{M}_9 x_9 - \dot{M}_3 x_E$$

Where m_0 is the initial batch feed amount and x_E is the mass fraction of ethanol in the tank.

Mass balance on the first membrane separator:

$$\dot{M}_3 x_E = \dot{M}_4(1 - R_E)x_E + \dot{M}_5 x_5$$

Mass balance on the second membrane separator:

$$\dot{M}_7 x_5 = \dot{M}_8(1 - R_E)x_5 + \dot{M}_9 x_9$$

The above three equations are combined together and simulated in python to solve for the continuous change in mass composition of ethanol in the feed tank. After optimizing membrane area, feed amount, feed to the first membrane separator and the recycle ratio, other stream variables were calculated and summarized in stream tables.

Optimization was carried out by recalculating the time taken for a batch of feed beer to reach a concentration of 0.5% beer by volume. The parameters varied were calculated through a for loop and a minimum was determined.

3.2 ASPEN

Pump efficiencies were simulated in ASPEN, disregarding the solute components since they are very little in amount and treating the streams as ethanol-water binary mixtures. We used the following inputs: pressure increase, flow rate, and compositions of stream 3 and stream 7 (see Table 1.12). The above quantities were all averaged over the operating time interval until the ethanol concentration reaches the desired value of 5% v/v (3.95% w/w). This is done in Python with numpy.trapz() method to integrate the desired quantity along the time of operation and then divide by the that time. We set the pump efficiency to 85% as a common value. The thermodynamic method used is UNIQUAC, a subset of NRTL, because it is a variant of the Wilson method that takes into account partial miscibility and differently sized particles.

Table 1.12. Inputs to APSPEN for pump efficiency calculation

Pump 1 flow (g/s)	P1 Pressure Increase (bar)	S1 ethanol (mass %)	Pump 2 flow (g/s)	P2 Pressure Increase (bar)	S2 ethanol (mass %)
1100	40	0.0153	596.6	44.7	0.0166
1300	40	0.0153	811.3	43.3	0.0163
1000	40	0.0153	536.3	44.8	0.0166
1500	40	0.0153	1038.6	42.5	0.0160
1400	40	0.0153	967	42.5	0.0160
1400	40	0.0153	994.7	42.24	0.0160
800	40	0.0153	426.2	44.89	0.0167
1500	40	0.0153	1142.7	41.7	0.0158

3.3 CAPCOST

3.3.1 Pumps

Centrifugal pumps are commonly used in the industry for low viscosity fluids, such as water. In comparison to positive displacement pumps, centrifugal pumps also require lower maintenance costs due to its simplicity of moving parts (3). Thus, we chose to use centrifugal pumps for our RO process.

Power inputs for each pump was obtained by ASPEN. Refer to Section 3.2 for more details. The discharge pressure per pump was predetermined by the process. The material of construction was stainless steel.

3.3.2 Beer Vessel

The beer vessel was designed according to heuristics. As stated by Turton et. al., "liquid drums are usually horizontal" (4). The optimal length to diameter ratio is 3 (4). To be cautious, the volume of the vessel was designed so that the initial feed fills the half the total volume. Once the volume was determined by the feed charge, the length and diameter were found by Solver. Similar to the pumps, the material of construction was stainless steel.

3.3.3 Membrane Vessels

Membrane cost was estimated from Vane's study on a vapor stripping permeation process to separate alcohol-water mixture (1). The cost of membrane housing was estimated to be \$50 /m2, and the installation and replacement (every three years) of the membrane cost \$200 /m2. As shown in the results section, the membrane units were entered under user-defined. CAPCOST did not have cost correlations for RO units. Both the bare module factors, base and actual, were assumed to be 1. Thus, the purchase cost was equal to the bare module cost.

3.4 Cash Flow Diagram Analysis

For the purposes of determining the raw material costs, revenue and cost of manufacturing for this process, it was assumed that this process operates in extension to an existing beer plant. Thus, all values were determined by subtracting a renovated beer + RO plant by the base case beer plant. This method of approach allows us to only need to account for the costs associated with building and maintaining the RO processing plant. Moreover, we assumed that the selling price of NA beer is the same as that of alcoholic beer to only have a "revenue" of state excise taxes.

For the cash flow analysis, there were several assumptions made. Defined by the problem statement, the plant life would be 5 years. Thus, we chose to have a 3 year Modified Accelerated Cost Recovery System (MACRS). Table 1.13 provides the depreciation schedule for MACRS method for a 3-year recovery period.

Table 1.13: Depreciation Schedule for MACRS Method for a 3-Year Recovery Period

Year	Depreciation Allowance (% of Capital Investment)
1	33.33
2	44.45
3	14.81
4	7.41

The taxation rate was assumed to be 40%. The working capital was assumed to be 17% of the FCI_{GR} (4). The cost of land and salvage value was scaled off the FCI_{GR} using textbook values. Land value was assumed to be 5.78% of FCI_{GR}. Salvage value was assumed to be 8.66% of FCI_{GR}.

4. Conclusions

We conclude that the operation is only financially feasible in the states of Alabama and Georgia. In Alabama, the minimum amount of beer produced for IRR of 15% is 67,447 BPY. Meanwhile the state of Georgia requires at least 70,8304 BPY. For higher values, the IRR increases linearly as a function of BPY with 35% IRR at 75,000 BPY in Georgia and 71,703 BPY in Alabama. For states of California, Georgia and Texas, they fail to break even on this process due to low state excise duties.

5. Recommendations

We recommend that prior to implementing this process to pre-existing breweries, further research and experiments must be conducted. There were many assumptions made in this analysis that may not be applicable in a plant setting. For example, we assumed the permeance of every solute, besides ethanol and water, through the membrane to be zero. Additionally, the osmotic pressure drop across the membrane was determined from existing experimental data. These assumptions detract the accuracy of our analysis. Instead, it would be more beneficial to perform experiments and tune the process parameters based on the particular beer to be dealcoholized. Doing so will allow the exact composition of the beer to be known, thus parameters like the molar concentration of every component, osmotic pressure drop, and permeate flux, can be more accurately estimated. This is essential as it will provide a more accurate estimate of the amount of DI water required in the process, leading to a more realistic cost value. More importantly, we can then determine the permeance of other components that might permeate through the membrane, potentially causing a loss of taste and texture which may impact the quality and sales of the product.

Finally, membrane separation processes can cause a loss of carbonation within the beer. This loss of carbonation was not taken into account in our analysis. The beer produced might require additional carbonation to restore the original flavor.

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