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Economic Viability of Brewery Spent Grain as a Biofuel

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Economic Viability of Brewery Spent Grain as a Biofuel

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Abstract

This report summarizes an investigation into the technical feasibility and economic viability of use grain wastes from the beer brewing process as fuel to generate the heat needed in subsequent brewing process. The study finds that while use of spent grain as a biofuel is technically feasible, the economics are not attractive. Economic viability is limited by the underuse of capital equipment. The investment in heating equipment requires a higher utilization that the client brewer currently anticipates. It may be possible in the future that changing factors may swing the decision to a more positive one.

ACKNOWLEDGMENTS

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In addition, our study's business partners, Dana Koller of Kaktus Brewing Company, Keith and Kenneth Welch of Welch Boiler Service Company and Matt Allen of Mount Taylor Manufacturing provided invaluable assistance and guidance.

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1 EXECUTIVE SUMMARY

The Kaktus Brewing Company of Bernalillo, New Mexico generates 100 lb. of spent grain on a dry basis per brew cycle. A brew cycle takes approximately 2.0 hours and the company currently brews beer two to four times per week. At 400 lb. of spent grain each week, waste as spent grain mounts up.

1.1 Problem Description

The company presently uses the waste as feedstock for their own livestock and donates the majority to local farmers. Their other option is simply to throw it away, a decidedly ecologically unfriendly and potentially costly option. Other feedstock providers to local farmers are beginning to view micro-brewery waste as competition and are beginning to ask for regulation of this source. Such regulations will inevitably increase the cost of disposal. This issue applies to all micro-breweries in New Mexico and possibly the whole United States. The Kaktus Brewing Company is thus looking for alternative uses for the spent grain. One option may be using spent grain as boiler fuel.[1,2,3,4]

The beer brewing process involves heat soaking select mixtures of grain and other minor constituents between room temperature and 100 ºC (212 ºF) for up to two hours. The Kaktus Brewing Company currently uses electric brew vats for this and the cost of electric energy is a major cost of brewing beer for the company. The brewery's vats already have a jacket through which water or steam can circulate. Conversion to a steam based brew system would be straightforward. This possibility provides the question to be answered by this paper:

Can the savings in reduced electricity costs offset the initial cost to install a steam/hot water heating process fueled by waste grain?

As discussed in Section 0, the answer is, regrettably, not obviously. It is technically feasible and even reasonable to use spent grain as a fuel source. However, the cost to convert the Kaktus Brewing Company system is too high to offset savings from reduced electricity consumption in a reasonable time frame.

Installation of the simplest hot water system will cost approximately $12,500 in 2017. This system will offset the use of nearly 5500 kWh of electricity per year. These savings in electricity over a 25 year period is equivalent in 2017 dollars to $5500. In other words the electrical cost savings will offset only slightly less than half of the initial hot water system costs. This comparison is based on current brewery production rates.

Economics improve if production rates go up without increasing brewery plant size.   If beer production were to increase from 4 brews per week to 24, the theoretical maximum, then the $12,500 initial cost would result in a savings of $20,000 in 2017 dollars, more than enough to offset the initial capital outlay. In fact, the project would pay for itself in 10 years.

This still leaves two important outstanding questions. First, could Kaktus Brewing Company sell that much beer? Second, will the assumptions made in this analysis remain in place over the ten years it predicts will take to break even? Experience says that they inevitably will not. Thus the secondary question is: will any change in assumptions move in the direction to improve the economics or move to make them worse. These questions left to be answered by potential investors.

The investigation also looked into the possible use of pelletizing spent grain as a means improving economics. On review, this option adds to boiler operating costs through the added cost to process the grain. This added cost reduces the savings and makes payout less attractive. Answering the above economic questions required answers to several technical questions first.

1. Is spent grain a viable boiler fuel?
    a. What is the composition of the waste grain?
    b. How much energy is available from the fuel?
    c. The grain is wet from the brew process. How does this affect energy conversion?
    d. How much energy does a brew cycle require?
2. What would a spent grain burning system look like?
    a. How complex does it have to be?
    b. What is the cost of such a system?
    c. How do savings in operating costs offset up front capital outlay?

Section 2 addresses the first half of these questions. Section 2.1 summarizes tests run at Sandia to determine the energy available from the grain. Based on this energy, some assumptions can be made regarding grain composition. Section 2.2 describes the combustion model used to estimate energy conversion. This section addresses such issues as the impact of wet grain on combustion and the relationship between firebox temperature and energy conversion. Section 2.3 provides the basis for estimating energy requirements for the brew process. Finally, Section 2.4 provides a summary of the default assumptions for the numerous secondary variables involved in a combustion process. The basic conclusions that come from Section 2 are that combustion is possible and that such parameters as water and firebox temperature do not materially affect the result.

Three potential heating system configurations are summarized in Section 3. These three include a hot water system similar to that used in hot water baseboard heating systems for homes and two small boiler systems, one designed to burn spent grain directly and one designed to use pellets. Only the hot water system was costed and subjected to an economic analysis. The results of this analysis was so conclusive that subjecting the other two obviously more expensive systems to further analysis would not have been cost effective.

2 TECHNICAL MODELS

2.1 Laboratory Measurements of Heat of Combustion and Water Content

Based on published papers, spent grain will be predominantly cellulose ($C_6H_{10}O_5$), a woody material with a residual of glucose ($C_6H_{12}O_6$).[2] In theory, the brewing process will have converted all of the glucose into beer. However, some indeterminate amount will be left.

The Appendix in Section 0 contains an email summary of the enthalpy of combustion for spent grain obtained from Kaktus Brewing Company. The results are summarized in *Table-1*.

Table-1: Result of Heat of Combustion Calculation

ΔT (°C)	mass (g)	Δh_c (cal/g)
1.1222	0.1334	4561.0
1.0613	0.1285	4477.6
	average	4519.3
	std. dev.	59.0

The enthalpy of combustion was measured using a bomb calorimeter where the grain was burned at high pressure in pure oxygen and the temperature rise of a fixed mass of water and metal (the calorimeter itself) is measured. The resulting temperature rise is a direct measure of the energy of combustion. Given the small temperature rise of the experiment (~1 °C), all water created or included in the experiment returns to the liquid phase. Consequently, we can assume that the device measures gross heating value where water condenses to a liquid. The result, based on the average is -4519 cal/g (-8130 Btu/lb) which slightly higher than reported gross heating values of cellulose, -4170 cal/g (-7510 Btu/lb). [6] This difference is attributed to the presence of some residual quantity of more energetic glucose in the sample.

The amount of residual glucose will vary significantly depending on the brew process. Some brews may even result in no glucose residuals at all. Consequently subsequent analyses assume the grain is composed of pure cellulose. This is the conservative assumption. With pure cellulose, the amount of energy available for conversion is lowest resulting in higher estimates of fuel mass requirements.

The assumption of pure cellulose simplifies the chemical reactions to the models shown in equations 1 and 2.

With the decision to base further analysis on pure cellulose, the energy of formation used in combustion calculations will be -963 kJ/mol. The negative sign indicates the material will give off energy when it burns.

The spent grain burned almost completely with insufficient ash to measure. See the Appendix, Section 0.

Sandia also measured the amount of water left in spent grain when it comes directly from the brew vat. See the Appendix Section 0. At its wettest, spent grain contains 2.0 lb. water per lb. of dry grain.

2.2 Combustion Model

Figure 1 contains a schematic of the mass and energy flows in the boiler system under consideration here.

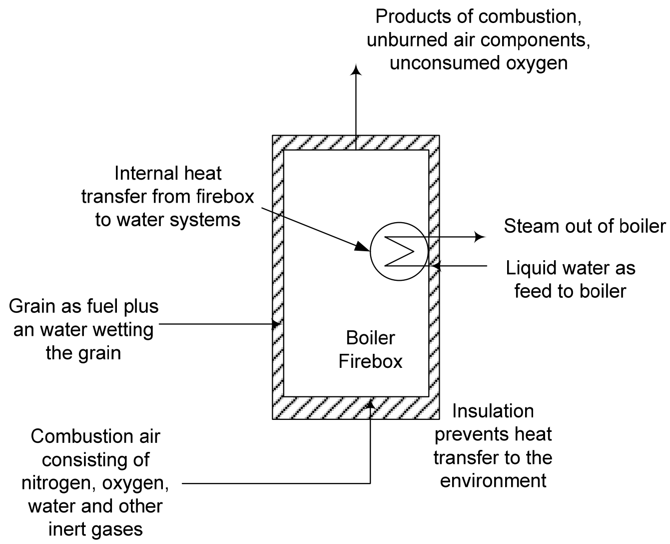

Figure 1: Boiler system free body diagram

In this system, grain as fuel enters the boiler where it combines with air. Oxygen in the air reacts with the grain causing it to burn, to decompose and heat up. This released heat transfers to the water in the boiler, heating it and potentially converting it to steam. Products of combustion, any unconsumed oxygen and all of the other constituents of air (nitrogen, argon, carbon dioxide) are then exhausted from the boiler system to the atmosphere.

Testing has shown that the spent grain from the brewing process can be conservatively modeled as cellulose. In its simplest form, combustion of pure cellulose in pure oxygen can be depicted with this chemical reaction:

$$C_6H_{10}O_5 + 6O_2 \Rightarrow 6CO_2 + 5H_2O \qquad 1$$

Reality is more complex. The grain is wet from the brewing process. Combustion occurs with air, which contains nitrogen, water and other compounds as well as oxygen. Reacting compounds' energy depends on its state as a liquid, solid or gas. Finally, in order to obtain complete combustion, the process will occur with excess oxygen.

Combustion of cellulose including all of the above follows this slightly more complex relationship:

$$\begin{aligned} \underbrace{xC_6H_{10}O_5(s) + nH_2O(l)}_{Wet\ Fuel} + \underbrace{x \cdot R_m Air(v)}_{Oxidizer} \Rightarrow & \underbrace{6xCO_2(v) + 5xH_2O}_{Products\ of\ Combustion} \\ & + \underbrace{nH_2O}_{Water\ with\ Grain} \\ & + \underbrace{x\left(z_{O_2}R_m - 6\right)O_2}_{Remaining\ O_2} \\ & + \underbrace{x \cdot R_m air_{lessO_2}}_{Other\ Constituents\ of\ Air} \end{aligned} \qquad 2$$

In English, x moles per unit time of cellulose ($C_6H_{10}O_5$) as a solid that is wet with n moles of liquid water combines with $x \cdot R_m$ moles of air as a vapor to form carbon dioxide (CO_2) and more water vapor. The reaction leaves $x\left(z_{O_2}R_m - 6\right)$ moles of oxygen unconsumed and $x \cdot R_m$ moles of those components of air (nitrogen, argon, etc.) that rode along with the combustion process without participation. The parameter R_m represents the molar oxygen to fuel ratio (units moles O_2/Moles dry fuel). The parameter z_{O_2} is the molar fraction of oxygen in air (approximately 21% depending on the air's humidity). All components on the right side of equation 2 are vapors.

The amount of water associated with the fuel represents an important parameter. Water with the grain requires heating also which drains away energy that could be used to power a brewing process. This liquid water vaporizes during the combustion process, sapping more energy as latent heat from the combustion process. In fact, if enough water coexists with the grain, it cannot support combustion at all. As *Figure 2* shows, the amount of energy that can be extracted from the burning of cellulose drops to zero as the amount of water approaches 4.7 pound water per pound of dry cellulose.

The combustion equation above assumes that the amount of water present with the grain is sufficiently low to allow combustion. This is a reasonable assumption as simple tests run at Sandia show that the grain will hold approximately 2.0 pounds of water per pound of dry grain, well below the 4.7 pound/pound limit of *Figure 2*.

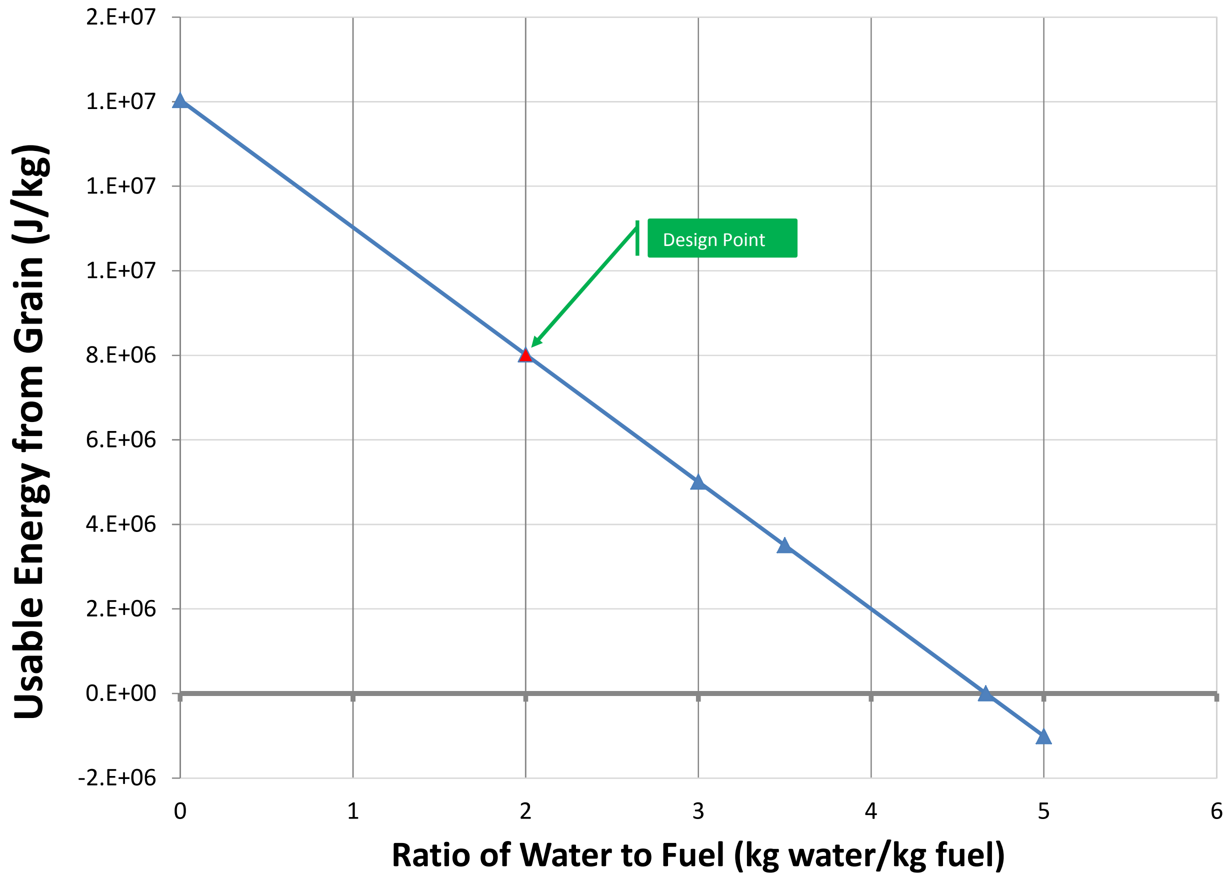

Figure 2: Impact of Wet Fuel on the Combustion Process

Humidity, or moisture in the air, has the same effect on combustion as does moisture in the grain. However, atmospheric water is already vaporized and the amount of water the air can hold is relatively small. As a consequence, the impact of humidity on the combustion process is secondary.

Assume a well-insulated boiler so that all energy leaving the boiler system does so by entering the water/steam. Modeling the heat transfer from the firebox to the steam as a heat flux, $\dot{Q}$, the energy balance for the firebox is

$$-\dot{Q} = \sum_{reactants} \dot{m}_r h_r - \sum_{products} \dot{m}_p h_p \quad (3)$$

The minus sign on the heat flux term is included to maintain the thermodynamics convention that energy leaving a system is negative. The energy exported from the firebox to the steam system equals the difference between the energy brought into the system via the grain and the air less the energy that leaves the system as products of combustion.

Table 2 contains a typical calculation for this brewery system. The data in this table corresponds to a brewing cycle using wet grain at 2.0 lb. H_2O/lb. dry fuel, a load of 45,000 kW (0.154 MBtu/h) with 25% relative humidity, and 80% excess air.

Table 2: Typical Overall Energy Balance

Description	Mass Rate (kg/s)	Enthalpy (J/kg)	Extension (W)	
Reactants				
$C_6H_{12}O_6$ as solid	0.00571	-5,939,209	-33,933	
Water in Fuel as liquid	0.00114	-16,051,054	-183,407	
Air as vapor	0.05263	-6,812	-359	
Total Reactants	0.06977		**217,698**	
Products (as vapor)				
CO2	0.00930	-8,751,799	-81430	
H2O	0.00317	-13,041,756	-41,393	
Air	0.04586	200,260	9,144	
Water in Fuel	0.01143	-13,041,756	--149,019	
Total of Products	0.06977	-3,765,351	**-262,698**	
Net to Boiler Water			**-45000**	W
			-154000	Btu/h

In this example, 0.00571 kg/s (0.0126 lb/s) of grain combines with 0.05263 kg/s (0.116 lb/s) air to form carbon dioxide and water to provide 45,000 W (154,000 Btu/h) energy to a boiler.

Default assumptions for this paper will be discussed in more detail below. One important default that will be discussed now is the firebox temperature. The firebox temperature equals the exhaust temperature of the products of combustion. The hotter this exhaust stream, the more energy it removes from the system to exhaust to atmosphere. In other words as the firebox temperature rises, the boiler system becomes less efficient. The chart in *Figure 3* quantifies this discussion. One can see the drop in recoverable energy with increasing temperature.

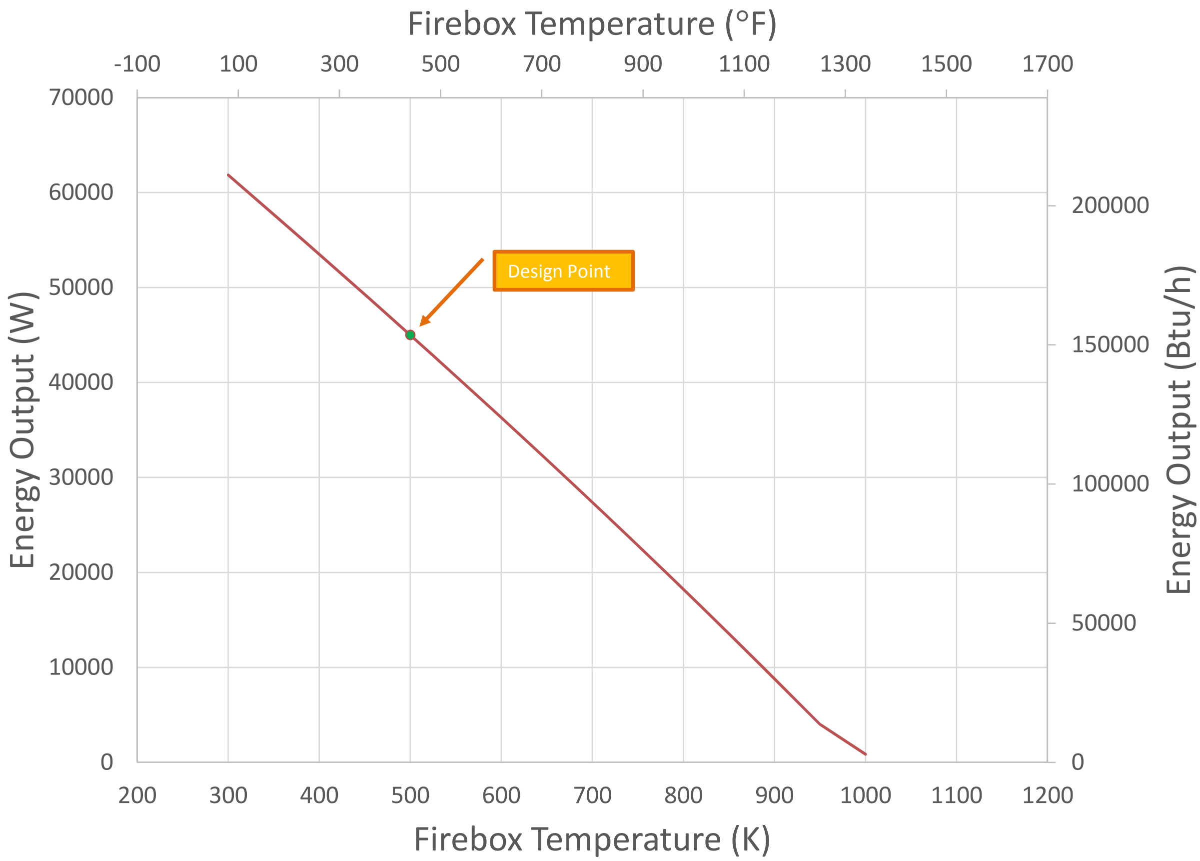

Figure 3: Relationship between Energy Output and Firebox Temperature

The next section will raise the questions of overall energy consumption for a brew cycle, peak versus average energy consumption and the energy available in the spent grain relative to a brew cycle's total energy demand. The chart in *Figure 4* begins that discussion. The graph shows the relationship between a brew cycle's energy demand and the rate at which it must consume grain. Recall that a brew cycle at Kaktus Brewery produces approximately 100 pounds of spent grain and that a cycle lasts approximately 2 hours. In other words, a cycle produces about 50 lb/h of grain. At a wet fuel ratio of 2.0 lb water per lb dry fuel, grain as a fuel can produce slightly more than 50 kW over the two hours of a brewing cycle. At 3 lb H2O per lb dry grain, the rate of energy production drops to approximately 33 kW. Ultimately, with dry fuel, a 50 lb/h burn rate can generate 90 kW. As is reported later, all three of these example rates are well above the actual average energy requirements of a brew cycle.

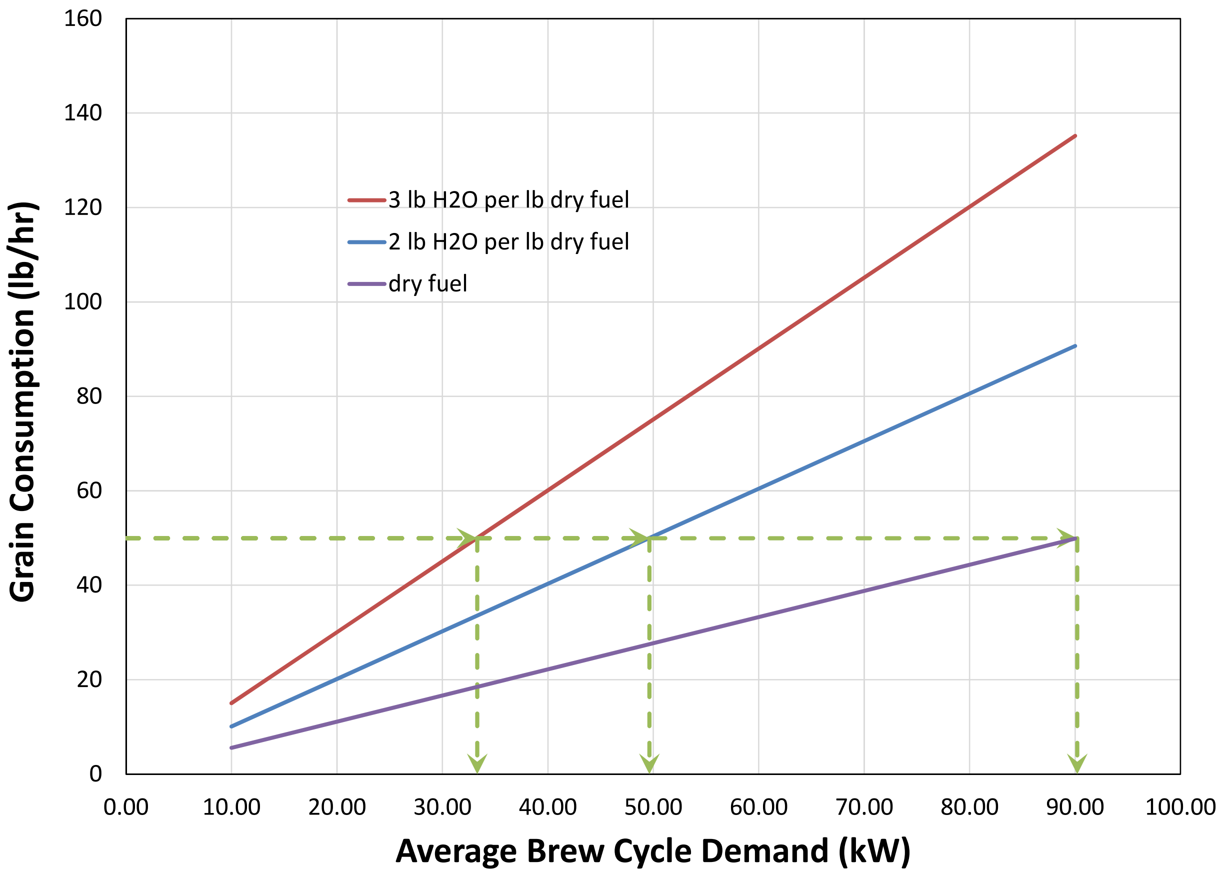

Figure 4: Grain Consumption vs. Average Cycle Power Demand

In reality, an operator may choose to leave the boiler on low fire for extended lengths of time and still have plenty of fuel. At a energy rate of 20 kW, a reasonably wet fuel (2.0 lb/lb) could expect to consume less than 20 lb/h of grain. At this rate, the grain produced from one brew cycle would last 5 hours.

2.3 Brew Vat Energy Consumption Model

The basic brewing process is to submerse select grains in cold water, then to heat the water in stages allowing different enzymes to work on the grain sugars at each temperature. Actual temperatures and soak times determine beer's taste and are consequently closely guarded by brew masters. The process outlined in *Figure 5* is a generic one based on interviews with Kaktus Brewing Company personnel. It is designed to provide a reasonable estimate of brewing energy needs. The soaking grain starts at room temperature (25 °C) and is immediately heated to 62 °C where it is held for 1200 seconds (20 minutes). The brew is then heated to 72 °C and held for an additional 20 minutes. Additional plateaus may be required depending on the brew master's recipe. Ultimately the whole brew is brought to boiling temperature and boiled for one hour.

Time to raise brew temperature between plateaus is assumed to be 400 seconds. At the elevation of the Kaktus brewery, boiling occurs at approximately 95 °C.

A brewing process consumes most of its energy during the periodic heating events. During the plateaus, the only energy required is to make up for any heat lost to the environment. Energy demand during heating depends strongly on the rate at which the brew master wishes to transition between plateaus. Notice, for example, that the greatest energy demand of 88-90 kW occurs during initial heating from 25 °C to 62 °C projected to occur in 400 seconds.

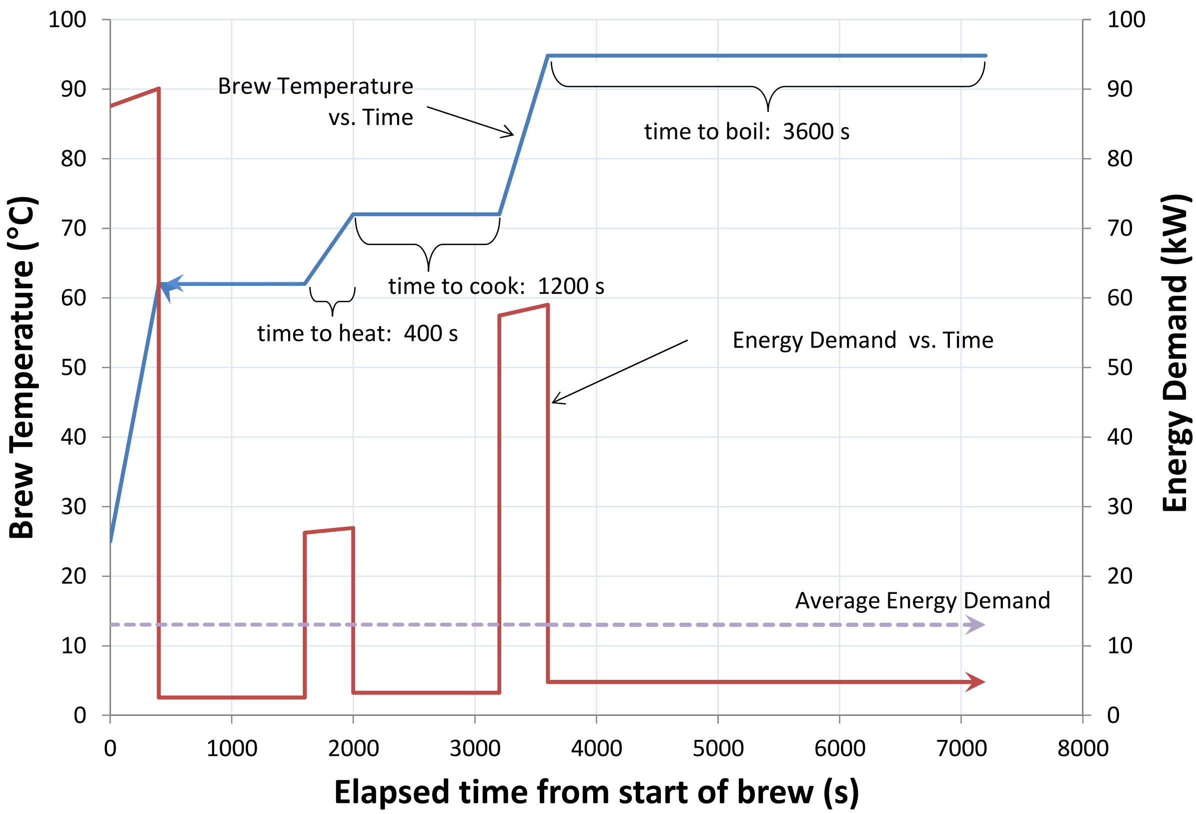

Figure 5: Typical Brew Process

Compare this 90 kW demand to the cycle average of 13 kW. The brewing process laid out in *Figure 5* has a peak demand of 90 kW which occurs for only 400 seconds.

The difference is so great that some adjustment should be possible. See for example the brew cycle depicted in *Figure 6*. This process uses half of the previous cycle's peak, or 45 kW, for the peak demand sizing criteria. This reduction in peak demand extends the heating time from 400 seconds to 800 seconds. The graphs in *Figure 6* reflect a brew process in which all energy demands were adjusted to peaks at or slightly below 45 kW. Heat-up times vary accordingly.

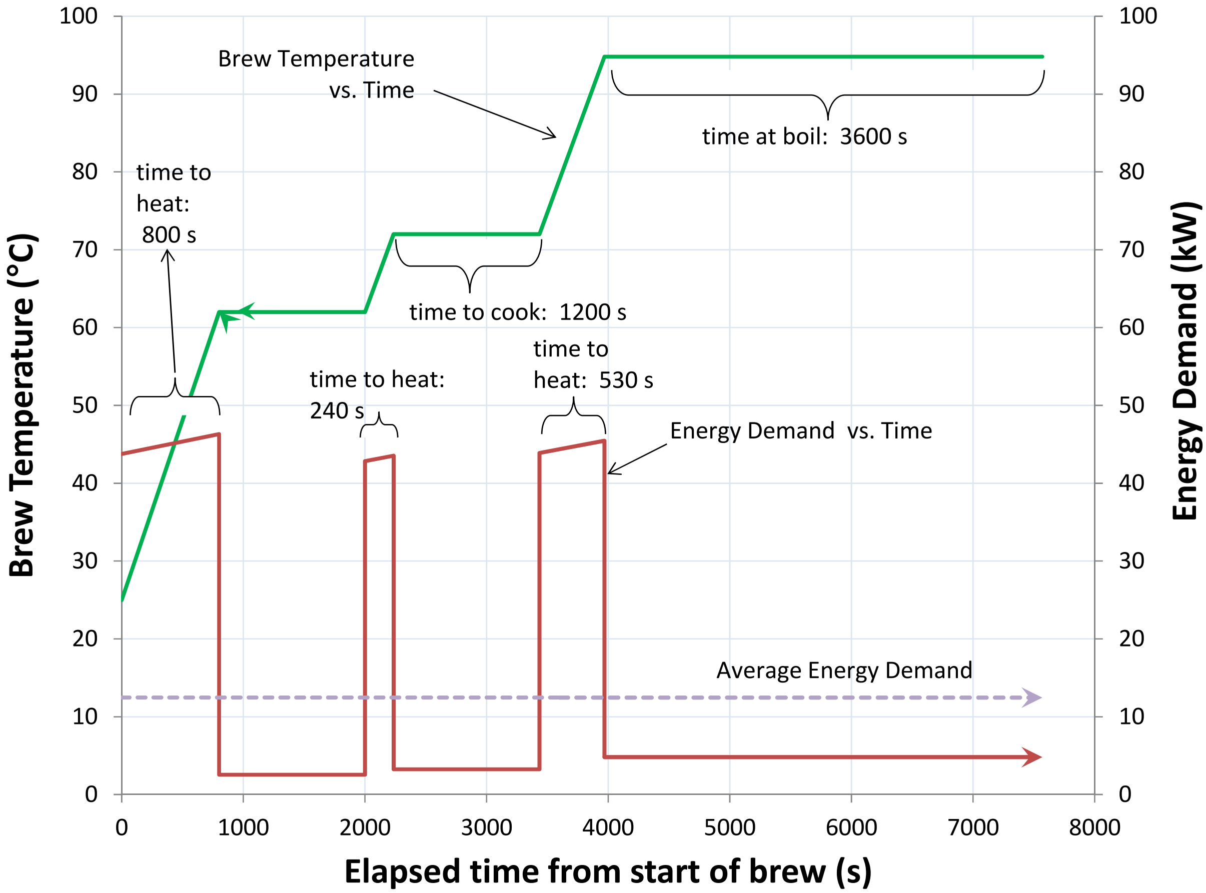

Figure 6: Brew Process with Adjusted Heat Up Times

Notice that this change has minimal effect on the average energy demand. The process of *Figure 6* will be used for sizing equipment in subsequent sections.

2.4 Default Conditions

Table-3 lists those parameters included in the model but normally held constant in an analysis. Values are provided in both metric (SI) and United States Customary (USC) units.

Table-3: Default Conditions

Parameter	Value SI	Value USC
Ambient Temperature	298.15 K	77 °F
Boiler Stack Temperature	500 K	440 °F
Ambient Pressure	0.84 bara	12.1 psia
Atmospheric Relative Humidity	25%	
Combustion System Excess Air	80%	
Water in Grain	1.5 kg H2O/kg dry fuel	1.5 lb H2O/lb dry fuel

Water in grain is based on a short study conducted at Sandia and documented in Appendix XX. The study involve collecting wet grain in a clean drum.

3 SYSTEM MODELS

This section describes three potential boiler/hot water system configurations. These three systems include a hot water system similar to that used in home hot water baseboard heating systems and two small boiler systems, one designed to burn spent grain directly and one designed to use pellets.

3.1 Hot Water System

Refer to the process schematic in *Figure 7*. The system shown there is a very economical one that uses hot water in lieu of steam. *Table 4* contains a Heat and Material Balance for this simplest system. Some important facts regarding this option include the following:

1. This scheme helps reduce cost by avoiding the need for a fired pressure vessel certification,
2. While the system is automatically stoked, the relatively small hopper need manual filling,
3. Similarly, the system will require manual ash removal (limited because of the low ash content of spent grain)
4. Heated water is open to atmosphere via the atmospheric vent. This avoids the need for a fired pressure vessel stamp
5. Atmospheric vent maintains a backpressure via an elevated open chamber above the heater
6. The Trim Cooler is small and allows long term operation even after brew cycle quits
7. Trim cooler is rudimentary, consisting of finned tubes without a fan. The cooler is there to provide cooling whenever the brew vat is offline. It may be left out if the operator chooses not to keep the boiler on line after brewing.

In addition to being the lowest cost system, it has the advantage of being simple and a good starting point from which Kaktus Brewing Company or others can safely and conveniently build experience.

3.1.1 Schematic and Heat and Material Balance

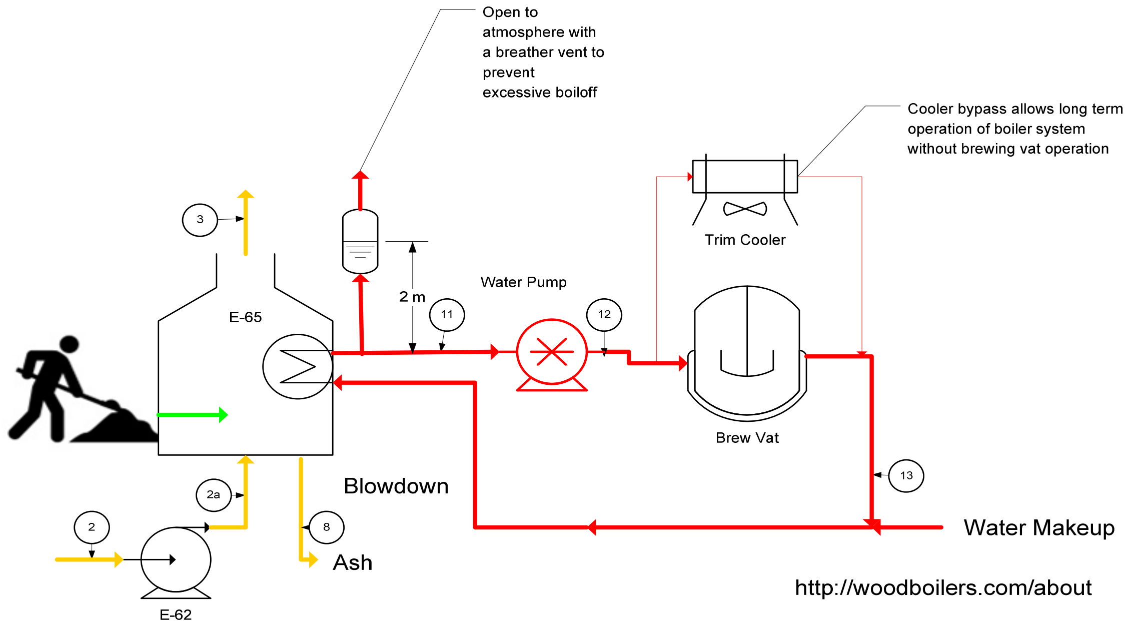

Figure 7: Minimum Cost Hot Water System

Table 4: Heat and Mass Balance for Hot Water Option

Stream ID	Units	1	2	2a	3	8		11	12	13
Description		Wet Grain	Intake Air	Combu stion Air	Exhaust	Grate Ash		Hot Water	HP Water	Return
Temperature	K	298.15	298.15	327.54	500	Hot		373.86	373.87	353.15
Pressure	bara	0.840	0.840	0.840	0.840	atm		1.040	1.730	1.17793
Enthalpy	kJ/kg	(10,924)	(6)	23	(2,938)			(15,648)	(15,648)	(15,758)
Phase		solid	vapor	vapor	vapor	solid		sat. liquid	sat liquid	liquid
Dry Grain Mass Rate	kg/s	0.00459	-	-	-	-		-	-	-
Water Mass Rate	kg/s	0.00689	-	-	0.0062	-		0.4076	0.4076	0.4076
Air Mass Rate	kg/s	-	0.0367	0.0367	0.0320	-		-	-	-
Ash Mass Rate	kg/s	0.00023	-	-	2.30E-04	.0002		-	-	-
CO2 Mass Rate	kg/s	-	-	-	0.0065	-		-	-	-
Total Mass Rate	kg/s	0.01171	0.0367	0.0367	0.0449	0.0002		-	-	-

Heater Capacity 45000 W with a circulation rate of 6.75 gal/min. Typical furnaces that can burn grain (see *Figure 8*) will cost on the order of $3500.00

Figure 8: Typical Hot Water Heating System [7]

The water pump has a design pressure rise is 10 psi to accommodate high flow rate through the brewing vat jacket system. See the family of head curves in *Figure 9*. A 10 psi pressure rise across the pump equates to 24 feet of flowing fluid. At 6.75 gal/min and 24 feet rise, the curve for a pump type 0011 (curve 3) works well.

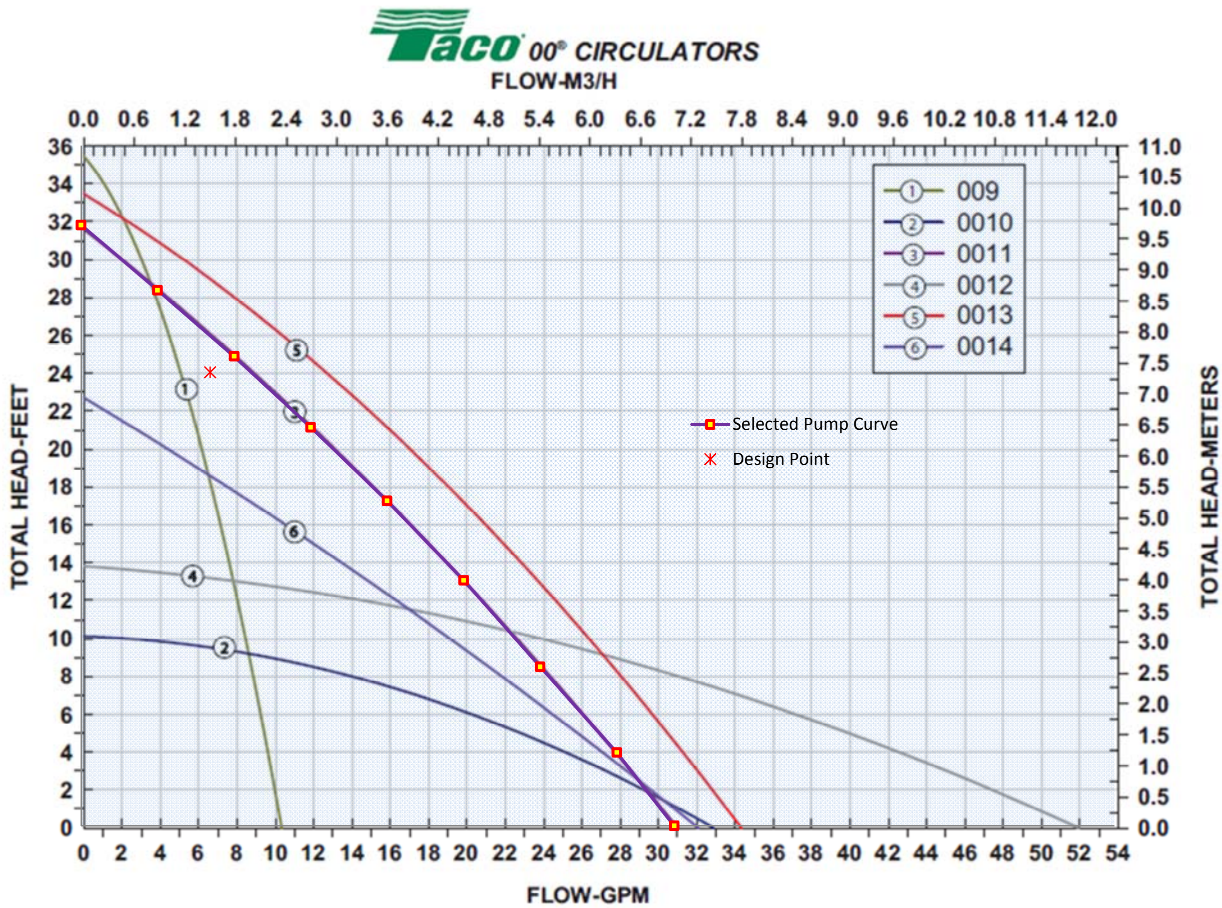

Figure 9: Typical Water Pump Curve (Source: https://www.taco-hvac.com/uploads/FileLibrary/100-2.3.pdf)

This particular pump costs approximately $250.

For the bypass cooler, a simple water to air convection type heat exchanger like that shown in *Figure 10* will suffice. This equipment costs $127 to $150. Notice that this system is basic and includes no protection other than manual draining and covering for protection from freeze during cold weather.

Figure 10: Simple Heat Exchanger (source: http://www.outdoorfurnacesupply.com)

3.1.2 Cost Estimate

Estimating method is based on a typical process engineering process used for conceptual design of chemical plants.[8] The system starts with raw equipment cost, C_p, the cost of major equipment FOB the factory. These initial costs can be obtained via phone conversations with vendors, internet cost data or from capital cost information taken from the same reference. The estimating process then applies a bare module cost factor, F_{BM}, that accounts for foundations, pipe and connections plus instrumentation. Total direct cost is the extension of equipment cost times bare module factor, $C_{BM} = C_p*F_{BM}$. Bare module factors are provided by the reference and may include factors to account for material, pressure and other similar cost factors. These extended bare module costs, when summed, provide the total direct cost of a set of process equipment. Additional overhead costs, like engineering, shipment, cost of money, contingency and other home office costs are added to direct costs to provide an estimate of the total project capital cost.

Table-5: Hot Water System Initial Cost Estimate

	Equipment Cost	**FBM**	**Direct Capital Cost Installed**
Boiler	$3500	2.0	$7000
Pump	250	3.5	875
Trim Cooler	150	3.0	450
Total Direct Cost	$3900		$8325
	% of Direct		
Engineering	15%		1250
Other Home Office	15%		1250
Contingency	20%		1670
			$12495
		Say	**$12500**

The total estimated cost for this project is $12,500.

3.1.3 Discounted Cash Flow Analysis for Hot Water System

The problem with capital investments is that one must spend a lot of money early in the project life to reap benefits in later years. One can argue that the money is worth more to an investor early because the project loses the interest on the invested funds until the project begins earning returns. One way to address this time dependent value of money is to discount later years back to the initial year of the project. Many methods exist to discount funds. The one used here employs a factor based on the amount of interest that money would earn if it began reaping benefits immediately. *Table 6* contains some of the parameters used in this discounted cash flow analysis.

Table 6: Discounted Cash Flow Parameter Values

Description	Value	Units
Start Year	2017	
Duration	25	years
Brew Frequency	4	Brews/wk
Power Consumption	13	kW/brew
Brew Duration	2	h
Inflation Rate	3%	Per Year
Rate of Return	5%	Per Year
O&M Rate	3%	per cent of Capital
Incremental Cost Power	0.107591	/kwh
Incremental Cost Power	0.128645	/kwh (Summer Rate)

Currently, Kaktus Brewery brews two vats of beer on Tuesday and two on Thursday for a total of four brews per week. Based on *Figure 5*, each brew consumes an average of 13 kW and lasts 2 hours. This project estimates annual inflation will trend at about 3% per year. This is high, but inflation should increase as the economy improves. The analysis assumes that Kaktus could earn 5% per year on money it invests. This may appear low, but is conservative. A rough rule of thumb for process equipment like boilers is that operating and maintenance (O&M) annual costs run from 2 to 3% of initial capital costs. [9] This analysis used the higher range of this number. The local electric company has published a two tier rate structure for medium sized commercial businesses that accounts for increased usage during summer months. The schedule for this rate basis in contained in the Appendix, Section 0.

Table 7 contains the discounted cash flow analysis for the base case in which we do nothing, continuing to brew beer with the electrical system currently used.

Table 7: Discounted Cash Flow – Base Case

		Cost						
Year		Power	O&M	Capital	Total Annual Cost	Discount Factor	Cost Discounted to 2017	Disc. Cash Flow
2017	0	-273	0	0	-273	1.0000	-273	-273
2018	1	-281	0	0	-281	0.9524	-268	-541
2019	2	-290	0	0	-290	0.907	-263	-804
2020	3	-298	0	0	-298	0.8638	-257	-1061
2021	4	-307	0	0	-307	0.8227	-253	-1314
2022	5	-316	0	0	-316	0.7835	-248	-1562
2023	6	-326	0	0	-326	0.7462	-243	-1805
2024	7	-336	0	0	-336	0.7107	-239	-2044
2025	8	-346	0	0	-346	0.6768	-234	-2278
2026	9	-356	0	0	-356	0.6446	-229	-2507
2027	10	-367	0	0	-367	0.6139	-225	-2732
2028	11	-378	0	0	-378	0.5847	-221	-2953
2029	12	-389	0	0	-389	0.5568	-217	-3170
2030	13	-401	0	0	-401	0.5303	-213	-3383
2031	14	-413	0	0	-413	0.5051	-209	-3592
2032	15	-425	0	0	-425	0.481	-204	-3796
2033	16	-438	0	0	-438	0.4581	-201	-3997
2034	17	-451	0	0	-451	0.4363	-197	-4194
2035	18	-465	0	0	-465	0.4155	-193	-4387
2036	19	-479	0	0	-479	0.3957	-190	-4577
2037	20	-493	0	0	-493	0.3769	-186	-4763
2038	21	-508	0	0	-508	0.3589	-182	-4945
2039	22	-523	0	0	-523	0.3418	-179	-5124
2040	23	-539	0	0	-539	0.3256	-175	-5299
2041	24	-555	0	0	-555	0.3101	-172	-5471
		-9953					-5471	

The negative signs used in *Table 7* designate costs, or money leaving the enterprise.

Discounting for this project was carried out for 25 years, beginning in 2017 and ending in 2041. During this period, no investments were made and the brewery will have spent a total of $9953 for electricity to brew beer. This $9953 in dollars of the day represents a constant annual electricity consumption with inflation. This amount when discounted would equate to $5471 dollars in the year 2017.

Table 8 contains the discounted cash flow analysis for this hot water case. Power costs are now zero, being replaced by the hot water heating system, the cost of which is detailed in*Table-5*.

Table 8: Discounted Cash Flow – Hot Water Case

		Operating Cost						
Year		Power	O&M	Capital Cost	Total DoD	Discount Factor	Discounted	
2017	0	0	-375	-12500	-12875	1	-12875	-12875
2018	1	0	-386		-386	0.9524	-368	-13243
2019	2	0	-398		-398	0.907	-361	-13604
2020	3	0	-410		-410	0.8638	-354	-13958
2021	4	0	-422		-422	0.8227	-347	-14305
2022	5	0	-435		-435	0.7835	-341	-14646
2023	6	0	-448		-448	0.7462	-334	-14980
2024	7	0	-461		-461	0.7107	-328	-15308
2025	8	0	-475		-475	0.6768	-321	-15629
2026	9	0	-489		-489	0.6446	-315	-15944
2027	10	0	-504		-504	0.6139	-309	-16253
2028	11	0	-519		-519	0.5847	-303	-16556
2029	12	0	-535		-535	0.5568	-298	-16854
2030	13	0	-551		-551	0.5303	-292	-17146
2031	14	0	-567		-567	0.5051	-286	-17432
2032	15	0	-584		-584	0.481	-281	-17713
2033	16	0	-602		-602	0.4581	-276	-17989
2034	17	0	-620		-620	0.4363	-271	-18260
2035	18	0	-638		-638	0.4155	-265	-18525
2036	19	0	-658		-658	0.3957	-260	-18785
2037	20	0	-677		-677	0.3769	-255	-19040
2038	21	0	-698		-698	0.3589	-251	-19291
2039	22	0	-719		-719	0.3418	-246	-19537
2040	23	0	-740		-740	0.3256	-241	-19778
2041	24	0	-762		-762	0.3101	-236	-20014
Totals			-13673		-26173		-20014	

As the table shows, this project will have spent by 2041 $13,673 on O&M alone, more than was spent in the base case for electricity. This O&M combined with the initial capital cost amounts to a discounted sum that would equal $20,014 in 2017. The base case, with the use of electricity in lieu of spent grain, easily is the more economical alternative.

The problem here comes from the underutilization of capital investments. The brand new boiler stands idle too much of the time. Our analysis so far assumes 4 brews per week for a total of 8 hours out of a total of 48 hours assuming 8 hour days and counting Saturday. Within these hours, Kaktus Brewery could make as many as 24 brews in a week. This extrapolation to more beer production blithely assumes that Kaktus could sell this increased beer production – a far from proven assumption. Using this highly optimistic assumption, *Figure 11* contains a graph that plots the discounted cash flow for both cases: the High Beer Sales Base Case and the Hot Water Case.

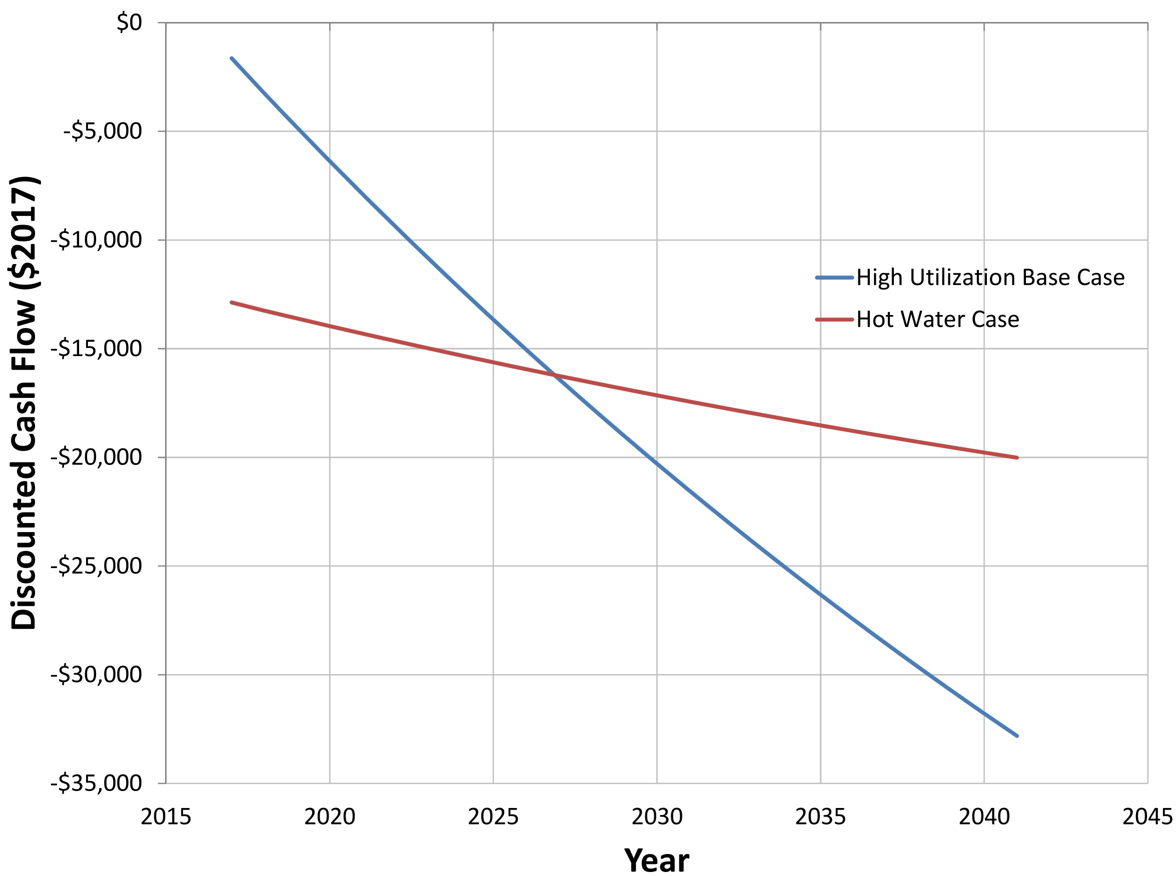

Figure 11: High Utilization Case Comparison

In this high utilization case, the project would begin to profit, would break even, ten years from initiation in 2027. Waiting 10 years to break even would appear to present an unacceptably high risk.

The risk with models like this discounted cash flow analysis is that it involves the assumptions implicit in *Table 6*, as well as other assumptions regarding the constancy of methods and amounts. The longer a project extends, the greater the probability that an assumption within the model will break down. The skill in using such a model comes in establishing the gut feel about whether the most likely model failures will improve or make worse the resulting economics.

3.2 Premium Grain Burning System

A second and more expensive potential process is drawn schematically in

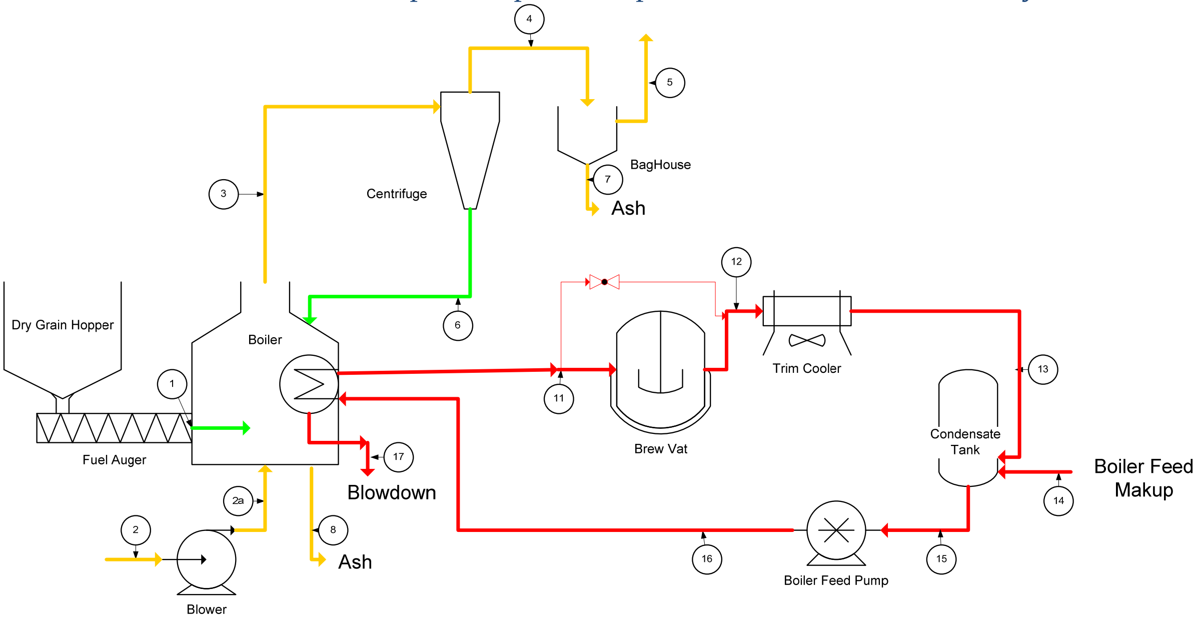

Figure 13 with a heat and material balance in *Table 9*. This system is more complex than the hot water system described in Section 3.1. This new system includes the following features:

1. Steam generating boiler
2. Automatic fuel stoking
3. Fluidized bed burner system
4. Centrifugal particulates filter with ember return to firebox
5. Ash baghouse to extract ash from exhaust
6. Steam system protected by relief valves(not shown)
7. Steam system blowdown with Makeup based on 1% blowdown

The boiler size would be at a minimum 45 kW (154,000 Btu/h). This specification is based on the data plotted in *Figure 4*. This figure shows a higher maximum boiler requirement of 90 kW. The thinking in specifying a lower rating is that the maximum is a one-time spike that can be accommodated by a combination of longer heat times at lower power and operation of the boiler at above design for short periods.

The boiler would discharge at a pressure of 1.29 bara (6.5 psig) at a rate of 0.0191 kg/s (0.302 gal/m).

The blower for the boiler air feed can create a pressure rise of 0.235 bar (3.41 psi) in order to lift and fluidize the bed of burning grain. With an air demand of 0.0526 kg/s (418 lb/h), the blow will require a 1.88 kW (2.52 hp) driver.

The high pressure fluidized bed burner will create carryover of ash and burning embers in the burner exhaust. Consequently, the system will require a centrifugal separator to return embers to the firebox plus a bag filter system to remove ash from the exhaust before venting.

The boiler system will operate under pressure. As a consequence, the brewing vat will require relief valve protection to avoid overpressure and damage or potentially rupture.

Boiler water will accumulate dissolved solids with time. Boilers of this size and capacity should maintain a total dissolved solids (TDS) level of 2500 ppm. [ulrich] Assuming as a worst case scenario (e.g. during startup) that feedwater to the boiler comes 100% from makeup and that makeup comes from the reverse osmosis system already installed at the brewery. Dissolved solids in the makeup will be on the order of 25 ppm.[ulrich] Based on *Figure 12*, blowdown rate will be 1% of makeup. This is a closed system, so makeup will be intermittent.

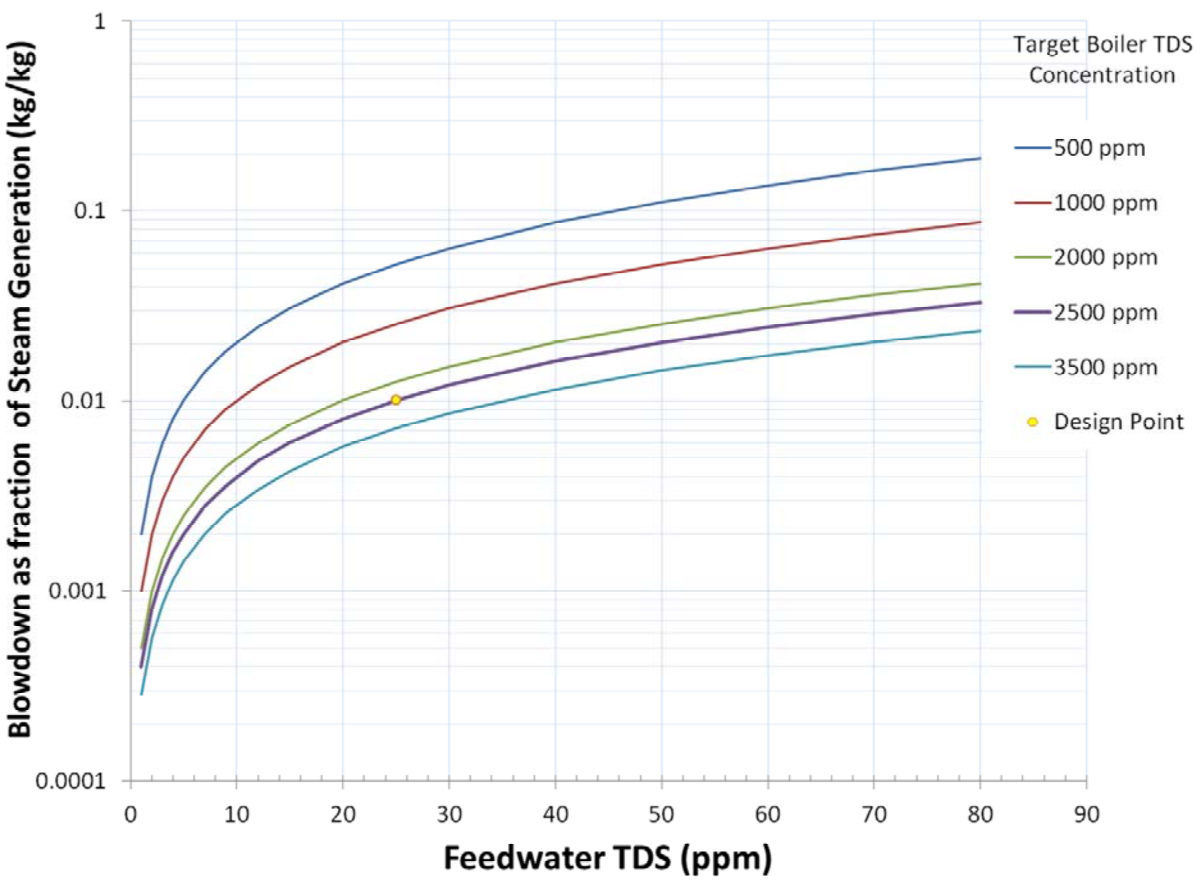

Figure 12: Blowdown Estimating Curve

The boiler feed pump requires a pressure rise of 0.350 bar (5 psi). With the above specified 0.0191 kg/s flow rate, boiler feed pump power will be 1.4 W (0.00185 hp).

The trim cooler is small with a need to dissipate only 10 kW (34,150 Btu/h). This equates to a bare tube area of approximately 0.6 m^2 (6.5 ft^2).

3.2.1 Cost and Economic Analysis

A final cost estimate was not pursued for this option. The increase in capital equipment will drive capital cost up without a parallel drop in operating cost as a consequence the relatively unattractive economics of the hot water system will be worse for this higher cost system.

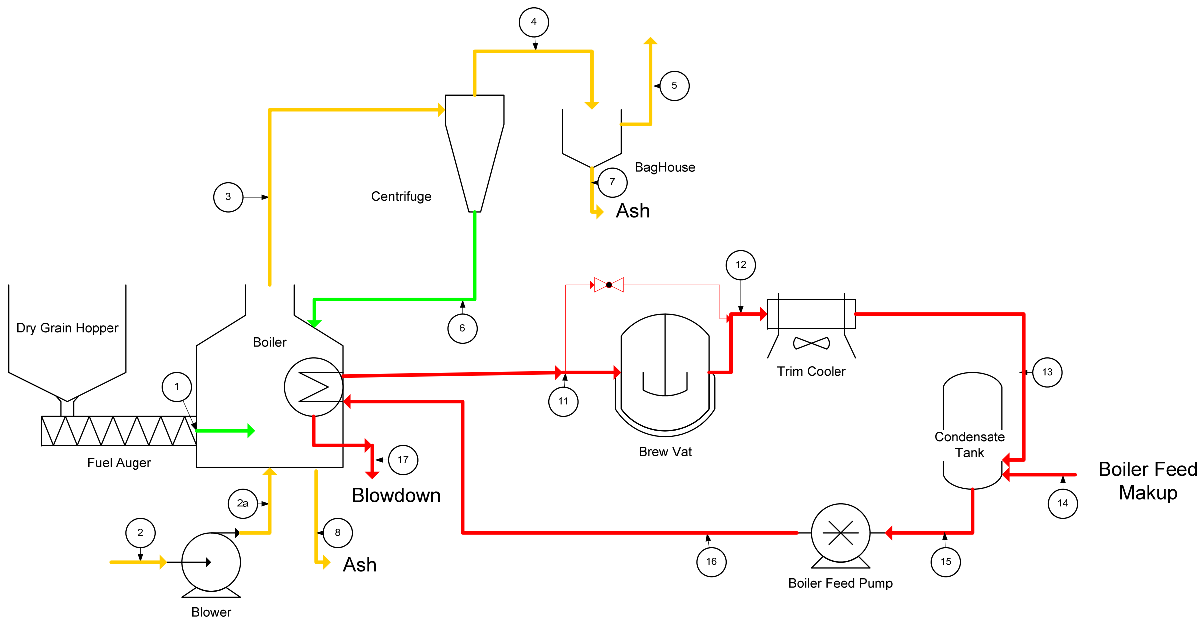

Figure 13: Premium System Grain Burning Process Sketch

Table 9: Premium Grain Burning System Heat and Material Balance

Stream ID		1	2	2a	3	4	5	6	7	8	11	12	13	14	15	16	17
Description	Units	Wet Grain	Intake Air	Comb Air	Exhaust 1	Exhaust 2	Exhaust 3	Reflux	Airborne Ash	Grate Ash	Steam	Steam/Liq	Condensate	Makeup	LP Boiler Feed	Boiler Feed	Blow down
Temperature	K	298.2	298.2	327.5	500	500	500	500	500	Hot	373.2	373.2	363.2	298.2	354.3	354.3	373.2
Pressure	bara	0.8404	0.8404	1.075	0.8404	0.8404	0.8404	0.8404	0.84	atm	1.289	1.151	1.013	0.84	0.9382	1.289	1.289
Enthalpy	kJ/kg	-12680	-6812	28.3	-3765	-3765	-3765	nom			-13290	-15650	-12770	-14580	-12790	-12790	-12750
Phase		solid	vapor	vapor	vapor	vapor	vapor	vapor	vapor	solid	solid	0	liquid	liquid	liquid	liquid	liquid
Dry Grain	kg/s	0.005713	0	0	0	0	0		0		0	0	0	0		0	0
Water	kg/s	0.01143	0	0	0.0146	0.0146	0.0146		0		0.01906	0.01906	0.01906	0.000191	0.01926	0.01926	0.000191
Air	kg/s	0	0.05263	0.05263	0.04586	0.04586	0.04586		0		0	0	0	0		0	0
Ash	kg/s	0.000285			0.000286	0.000286			Nominal	0.000286	0	0	0	0		0	0
CO_2	kg/s	0	0		0.009304	0.009304	0.009304				0	0	0	0		0	0
Total	kg/s	0.01743	0.05263	0.05263	0.07005	0.07005	0.06977	nom	0	0.000286	0.01906	0.01906	0.01906	0.000191	0.01926	0.01926	0.000191

3.3 Premium Pellet Burning System

The third potential process investigated is shown in *Figure 14* with the heat and material balance in *Table 10*. This system is similar on the steam side to the system described in Section 3.2. However, it is slightly simpler on the burner side. This system would take pellets formed from spent grain as fuel. Pellets will not generate the small particulates that would come with burning grain in a fluidized bed system. Without these small particulates the need for flue gas treatment, specifically the centrifuge and the bag house, goes away.

This new system includes the following features:

1. Steam generating boiler
2. Automatic fuel stoking
3. Steam system protected by relief valves(not shown)
4. Steam system blowdown with Makeup based on 1% blowdown

The boiler size would be at a minimum 45 kW (154,000 Btu/h). This specification is based on the data plotted in *Figure 4*. This figure shows a higher maximum boiler requirement of 90 kW. The thinking in specifying a lower rating is that the maximum is a one-time spike that can be accommodated by a combination of longer heat times at lower power and operation of the boiler at above design for short periods.

The boiler would discharge steam at a pressure of 1.29 bara (6.5 psig) at a rate of 0.0191 kg/s (0.302 gal/m).

The blower for the boiler air feed can create a pressure rise of 10 inches of water or 0.248 bar (3.61 psi) in order to ensure air flow to the firebox. With an air demand of 0.0526 kg/s (418 lb/h), the blower will require a 0.9 kW (0.267 hp) driver.

The boiler system will operate under pressure. As a consequence, the brewing vat will require relief valve protection to avoid overpressure and damage or potentially rupture.

Boiler water will accumulate dissolved solids with time. Boilers of this size and capacity should maintain a total dissolved solids (TDS) level of 2500 ppm. [ulrich] Assuming as a worst case scenario (e.g. during startup) that feedwater to the boiler comes 100% from makeup and that makeup comes from the reverse osmosis system already installed at the brewery. Dissolved solids in the makeup will be on the order of 25 ppm.[ulrich] Based on *Figure 12*, blowdown rate will be 1% of makeup. This is a closed system, so makeup will be intermittent.

The boiler feed pump requires a pressure rise of 0.350 bar (5 psi). With the above specified 0.0191 kg/s flow rate, boiler feed pump power will be 1.4 W (0.00185 hp).

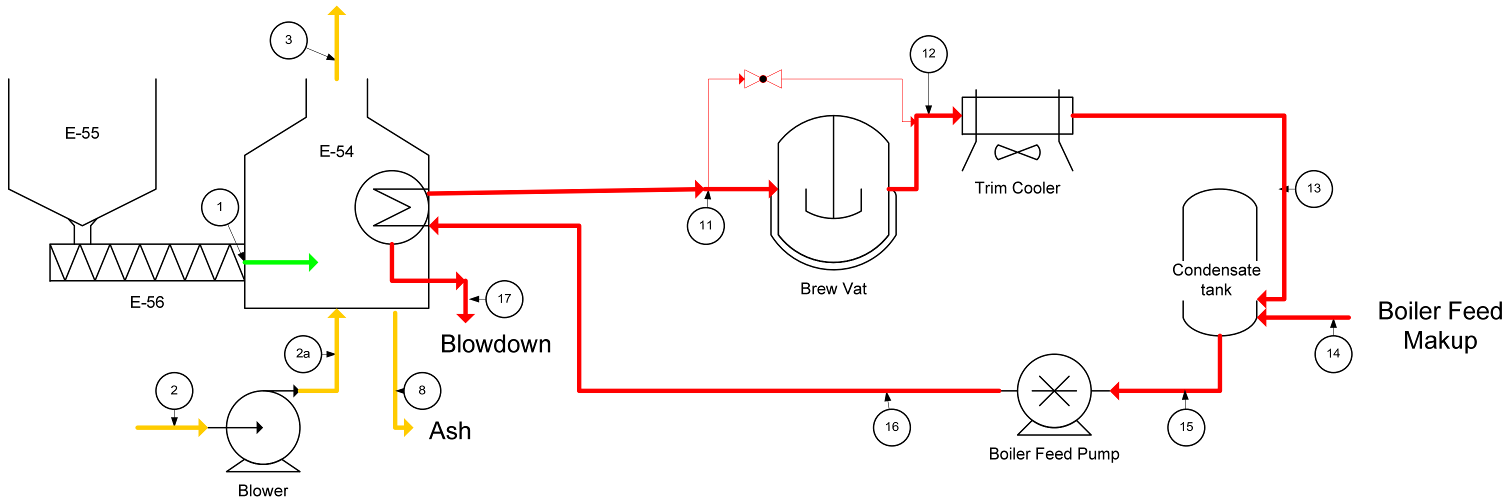

Figure 14: Premium Pellet Burning System Process Sketch

Table 10: Premium Pellet Burning System Heat and Material Balance

Stream ID		1	2	2a	3	8	11	12	13	14	15	16	17
		Wet Grain	**Intake Air**	**Comb Air**	**Exhaust 1**	**Grate Ash**	**Steam**	**Steam/Liq**	**Conden-sate**	**Makeup**	**LP Boiler Feed**	**Boiler Feed**	**Blowdown**
Temperature	K	298.2	298.2	327.5	500	Hot	373.2	373.2	311.2	298.2	311	311	373.2
Pressure	bara	0.84	0.8404	0.84	0.84	atm	1.289	1.151	1.013	0.84	0.9382	1.289	1.289
Enthalpy	J/kg	-12680	-6.812	28.3	-3765		-13290	-15650	-14490	-14580	-14.49	-14490	-12750
Phase		solid/liq	vapor	vapor	vapor	solid	sat vapor	vap/liq	subcooled	subcooled	subcooled	subcooled	subcooled
Dry Grain	kg/s	0.005713	0	0	0		0	0	0	0		0	0
Water	kg/s	0.01143	0	0	0.0146		0.01906	0.01906	0.01906	0.000191	0.01926	0.01926	0.000191
Air	kg/s	0	0.05263	0.05263	0.04586		0	0	0	0		0	0
Ash	kg/s	0.0002857			0.0002857	0.0002857	0	0	0	0		0	0
CO_2	kg/s	0	0		0.009304		0	0	0	0		0	0
Total	kg/s	0.01743	0.05263	0.05263	0.07005	0.0002857	0.01906	0.01906	0.01906	0.000191	0.01926	0.01926	0.000191

3.3.1 Cost and Economic Analysis

A final cost estimate was not pursued for this option. The increase in capital equipment will drive capital cost up. In addition, the use of pellets will increase the operating costs. The increased capital cost over the marginally economic hot water system combined increased operating costs a parallel drop in operating cost as a consequence the relatively unattractive economics of the hot water system will be worse for this higher cost system

4 REFERENCES

1. U.S. Patent Office; Spent Grain Fuel Product and Process; Pub No.: US2013/0055622 A1; Mar7.2013
2. Porametr Arromdee, Vladimir I. Kuprianov; Combustion of peanut shells in a cone-shaped bubbling fluidized-bed combustor using alumina as the bed material; Applied Energy 97 (2012) 470-482
3. Chien-Song Chyang, Feng Duan, Shih-Min Lin, Jim Tso; A study on fluidized bed combustion characteristics of corncob in three different combustion modes; Bioresource Technology 116 (2012) 184–189
4. Ana M. Celaya, Amanda T. Lade, Jillian L. Goldfarb; Co-combustion of brewer's spent grains and Illinois No. 6 coal: Impact of blend ratio on pyrolysis and oxidation behavior; Fuel Processing Technology 129 (2015) 39–51
5. Dr. E.A. Richards, P.E; *FUEL ENERGY FROM PROCESS WASTE BIOMASS*; http://my.execpc.com/~drer/cornfuel.htm
6. Ralph S. Jessup and Edward 1. Prosen; *Heats of Combustion and Formation of Cellulose and Nitrocellulose (Cellulose Nitrate)*; U. S. Department of Commerce National Bureau of Standards, Research Paper RP2086. Volume 44, April 1950.
7. TARM Biomass; Multiheat Brochure; 3/2007
8. Ulrich, G. D., Vasudevan, P. T.; Chemical Engineering Process Design and Ecomomics A Practical Guide 2nd Edition; Process Publishing; 2004; ISBN 0-9708768-2-3.
9. Branan, C; Rules of thumb for Chemical Engineers, Fifth Edition; Elsevier; 2012.

APPENDIX A: SANDIA MEASUREMENTS

Appendix A.1: Sandia Measurements

Appendix A.1.1: Laboratory Measurements of Heat of Combustion

Morrow, Charles W

From: Lindgren, Eric
Sent: Tuesday, November 24, 2015 8:08 PM
To: Carlson, Rachel L
Cc: Morrow, Charles W
Subject: Re: Quick scoping run

Thanks for the runs. These are right in the ballpark of my literature value of 4452 cal/g.

Is there any note of the moisture loss on drying?

Monday try adding back 20% and 40% moisture and run them again. I think the will burn but we will probably get back the same cal value.

Thanks again and have a good Thanksgiving!

Eric

Sent from my iPhone

On Nov 24, 2015, at 3:10 PM, Carlson, Rachel L <rlcarl@sandia.gov> wrote:

> Eric,
>
> I had the pressing lab make a few pellets of your sample after drying it at 50C for 4 hours. The value from those runs in cal/gram is:
>
> **Spent Grain**
>
> | Temp Rise in Celsius | mass (g) | EE | |
> |---|---|---|---|
> | 1.1222 | 0.1334 | 543.077 | 4561.0 |
> | 1.0613 | 0.1285 | 543.077 | 4477.6 |
> | | | avg | 4519.3 |
> | | | std dev | 59.0 |
>
> If you still want to pursue adding water back into the sample and re-running those samples I could do a few runs on Monday. I am not positive the material will actually combust with the liquid water added, but I can give it a try. Please let me know.
>
> -Rachel

Appendix A.1.2: Field Measurement of Water Content

Morrow, Charles W

From:	Brito, Roxanne
Sent:	Wednesday, November 11, 2015 2:31 PM
To:	Lindgren, Eric; Morrow, Charles W
Cc:	Koenig, Greg John; Chavez, William R; QASPR_DRT
Subject:	Biofuel Dry

All,

The Biofuel weights are as follows:

Barrel Empty: 21.23lbs
1/3 Full WET Biofuel: 142.31lbs
1/3 Full DRY Biofuel: 61.67lbs

The Barrel was opened at 5:18pm on 11/3/15, and was weight scanned at 5:47pm on 11/3/15.

The DRY weight was taken at 2:15 11/11/15

-Roxanne

Roxanne J. Brito
SIP General Technical-Col
Phone: (505)-284-9606
Email: rbrito@sandia.gov
Bldg. 823/4228

Appendix A.1.3 Biofuel Ash Content

Morrow, Charles W

From:	Carlson, Rachel L
Sent:	Wednesday, December 02, 2015 9:27 PM
To:	Morrow, Charles W
Cc:	Lindgren, Eric
Subject:	Re: Quick scoping run

The samples burned fairly completely, with just traces of black residue left over as well as some water. I did not weight the pans after the test as the residues seemed negligible. Had there been visible ash, I would have weighed it and included as it would indicate incomplete combustion.

-Rachel

From: Morrow, Charles W
Sent: Wednesday, December 2, 2015 9:12 AM
To: Carlson, Rachel L
Cc: Lindgren, Eric
Subject: RE: Quick scoping run

Thanks. Did you by chance measure the residual ash post test?

APPENDIX B: PNM SCHEDULE 2A

RECEIVED
DEC 30 2011
NM PUBLIC REGULATION COMMISSION

PUBLIC SERVICE COMPANY OF NEW MEXICO
ELECTRIC SERVICES

20TH REVISED RATE NO. 2A
CANCELING 19TH REVISED RATE NO. 2A

SMALL POWER SERVICE

APPLICABILITY: The rates on this Schedule are available for single- and three-phase service for commercial, business, professional, small industrial loads and shared residential wells. Service will be provided under this schedule if at least one of the following two conditions are met: 1) Customer's on-peak kW must be less than an estimated 50 kW for at least 3 months during the next 12 continuous months or less than an actual 50 kW for at least 3 months during the previous 12 continuous months, or 2) Customer's consumption must be less than an estimated 15,000 kWh for at least 3 months during the next 12 continuous months or less than an actual 15,000 kWh for at least 3 months during the previous 12 continuous months. All service shall be delivered at a single service location to be designated by the Company.

Service will be furnished subject to the Company's Rules and Regulations and any subsequent revisions. These Rules and Regulations are available at the Company's office and are on file with the New Mexico Public Regulation Commission. These Rules and Regulations are a part of this Schedule as if fully written herein.

TERRITORY: All territory served by the Company in New Mexico.

TYPE OF SERVICE: The type of service available under this Schedule will be determined by the Company and will be supplied at a single service location and would normally be one of the following:

(1) 120/240 volt single-phase (overhead up to 85kW or underground up to 140kW), or

(2) 240 volt delta three-phase (overhead only; up to 50 kW), or

(3) Combination of 120/240 volt single-phase and 240 volt delta three-phase (overhead only; combined load not to exceed 75 kW; neither the single-phase nor the three-phase may exceed 50 kW), or

(4) 120/208 volt three-phase grounded Y overhead transformer (up to 50kW),

(5) 120/208 volt three-phase grounded Y from a padmount transformer,

(6) 277/480 volt three-phase grounded Y from a padmount transformer, or

(7) 277/480 volt three-phase from an overhead transformer (up to 125 kW).

Note: 240 volt three-phase service is not available from underground distribution systems.
Refer to the Company's Rules and Regulations for further details pertaining to availability of other voltages and special services. Where service is furnished at different locations, a separate bill will be rendered for each meter location.

Advice Notice No. 437

Gerard T. Ortiz
Executive Director, NM Retail Regulatory Services
GCG#513676

EFFECTIVE

JAN 31 2012

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BY FO Case # 10-00086-UT

For each service location the Company reserves the right to use either a single combination meter or separate single- and three-phase meters in which event the meter readings will be added arithmetically and a single bill under the above rates will be rendered to the customer.

Three-phase service will be supplied only on a 12-month continuous and nonseasonal basis.

Metering will normally be done at the secondary voltage. The Company reserves the right to meter in the most practical manner, either primary or secondary voltage.

NET RATE PER MONTH OR PART THEREOF FOR EACH SERVICE LOCATION: The rate for electric service provided shall be the sum of A, B, C, D, E, and F:

IN THE BILLING MONTHS OF:	June, July and August	All Other Months
(A) CUSTOMER CHARGE: (Per Metered Account)	$8.46/Bill	$8.46/Bill
(B) ENERGY CHARGE: All kWh per Month	$0.1286451/kWh	$0.1075914/kWh

(C) ADDITIONAL TRANSFORMER CAPACITY: Customers in this category may be given the option of installing separate metering and wiring to serve the fluctuating or intermittent load where it is used regularly in their business. Necessary transformer capacity will be provided by PNM for this service. In the event a separate service or transformer installation or additional transformer capacity is required for fluctuating loads, such service, unless otherwise provided for in the rate schedules will be metered and billed separately; the minimum charge will be on a 12-month basis at the rate of $1.50 per month per kVA of capacity required, but not less than $10 per month. The Customer's wiring to such equipment causing the need for additional transformer capacity shall be installed in a continuous length of rigid conduit or Company-approved cable.

(D) FUEL AND PURCHASED POWER COST ADJUSTMENT: The above rates are based upon a base fuel cost for energy approved in NMPRC Case No. 10-00086-UT. For this tariff, base rate is $0.0213613 per kWh, effective for fuel and purchased power expenses incurred beginning August 21, 2011.

All kWh usage under this tariff will be subject to a Fuel and Purchase Power Cost Adjustment Clause ("FPPCAC") factor calculated according to the provisions in PNM's Rider 23.

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BY FTO Case #10-00086-UT

Advice Notice No. 437

Gerard T. Ortiz
Executive Director, NM Retail Regulatory Services
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Sandia National Laboratories