GEO-HEAT CENTER

Oregon Institute of Technology, Klamath Falls, Oregon 97601 541/885-1750 FAX 541/885-1754

John W. Lund, Director
Andrew Chiasson
Tonya "Toni" Boyd
Debi Carr

January 31, 2007

The Geo-Heat Center conducted an evaluation of using geothermal energy in ethanol production. This work has been funded and completed under Midwest Research Institute, National Renewable Energy Laboratory (NREL) Task Order No. KLDJ-5-55052-01, "*Feasibility Studies and Life-Cycle Cost Analysis*", Task 3, "*Williston Geothermal Feasibility Study*".

Project Background

This Task Ordering Agreement (TOA) was submitted by the Williston Economic Development Partnership with the intent of receiving technical assistance in evaluating the feasibility of using geothermal energy in ethanol production in a proposed plant to be located near Williston, North Dakota. The original concept was to use geothermal fluids from deep, petroleum exploration and/or production wells.

The Geo-Heat Center met with parties interested in the project in Portland, OR in early January 2006. Attendees of this meeting included a geologist from the North Dakota Geological Survey, a research scientist from the Williston Research Extension Center of the North Dakota State University, and the executive director of the Williston Economic Development Partnership. The main project developer (chairman of Premier Bioenergy) also participated in the meeting by telephone.

One of the main outcomes of the Portland meeting was the realization of the necessity to obtain energy balance details of each step in the ethanol production process. This level detail is essential in a feasibility analysis because each plant is project-specific, and the project developer (Premier Bioenergy) was proposing to produce ethanol with much less energy than typical. This improved process would impact the required geothermal fluid temperature and flow rate. In addition, a detailed plant process would allow for analysis of using geothermal energy in a "part-load" configuration, should geothermal fluid temperature and/or flow rate be inadequate to meet the entire load.

During the course of this TOA project, Premier Bioenergy's priority in utilizing geothermal energy in ethanol production shifted from Williston, ND to Ritzville, WA – an area of no known geothermal resource. This decision was evidently based on factors other than energy. Premier Bioenergy met with Geo-Heat Center staff in early June 2006 to discuss project status and details, and it was re-iterated and agreed that process details of the plant were necessary, but these design details have not been made available.

Objectives and Scope

The original objective of this TOA was to provide a feasibility study for using geothermal energy in ethanol production in a proposed plant to be located near Williston, North Dakota. However, as described above, the developer's priorities and plant location had changed over the course of the project and the original objective of the TOA had to be modified.

To remain consistent with the original intent of this project, the Geo-Heat Center conducted a generalized feasibility study that could apply to any ethanol plant considering the use of geothermal energy in the production process. Thus, the modified TOA objective was to develop a spreadsheet design tool that could be used to analyze the economics of a potential ethanol project once a geothermal resource was characterized.

Overview of Ethanol Uses and Production

Ethanol is also referred to as ethyl alcohol or grain alcohol. According to BBI (2003), ethanol's primary uses in the U.S. are: as an octane extender for gasoline; as a clean-air gasoline additive in the form of an oxygenate; as a product to foster rural economic development; and as a domestic fuel source to aid in the reduction of U.S. dependence on imported oil. Ethanol blended fuels currently represent more than 12% of U.S. motor gasoline sales, and ethanol blends of up to 10% are approved under the warranties of all the major automobiles sold in the U.S.

At the time of completion of this report, there are currently about 100 ethanol plants in the U.S., producing over 4.2 billion gallons of ethanol annually (www.bbiethanol.com/). Over 20 new plants are planned or are under construction, with an estimated combined annual production of over 1.1 billion gallons of ethanol. As of 2003, approximately 95% of U.S. fuel ethanol was manufactured from corn (BBI International, 2003).

Ethanol Production Process and Energy Requirements

Prior to examining the feasibility of utilizing geothermal energy in ethanol production, it is necessary to detail the process, along with the associated energy and temperature requirements at each step. There are basically eight steps in the ethanol production process as summarized below and shown schematically in Figure 1.

1. Milling: The corn (or barley or wheat) is first processed through hammer mills, which grind it into a fine powder the industry refers to as "meal".

2. Cooking and Liquefaction: The meal is then mixed with water and enzymes, which passes through cookers where the starch is liquefied. Cooking is generally accomplished at temperatures of 150-180^{o}F (65-80^{o}C). The meal is exposed to a high temperature stage of 250-300^{o}F (120-150^{o}C) for a short period of time to reduce bacterial growth in the mash.

3. Saccharification: The process of saccharification involves transferring the mash from the cookers where it is cooled, and a secondary enzyme (glucoamylase) is added to convert the liquefied starch to fermentable sugars (dextrose).

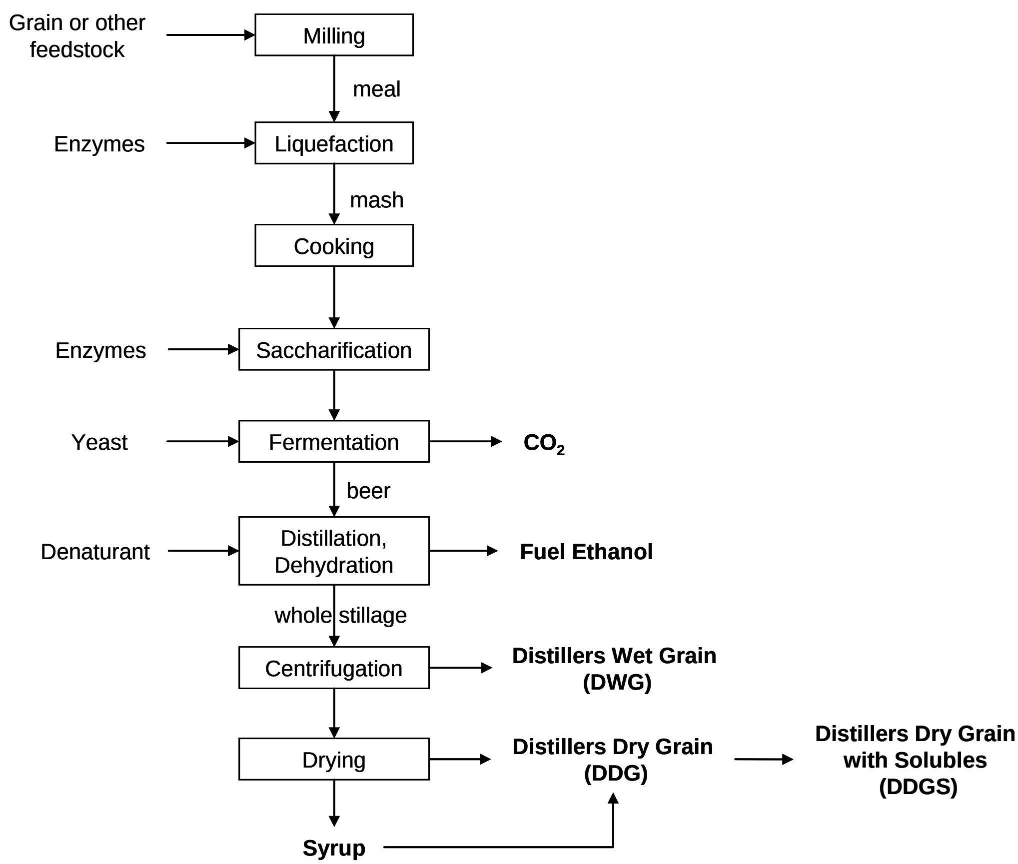

Figure 1. Process schematic of ethanol production using the dry milling process.

4. Fermentation: Yeast is then added to the mash to ferment the sugars to ethanol and carbon dioxide. Using a continuous process, the fermenting mash will be allowed to flow, or cascade, through several fermenters until the mash is fully fermented. In a batch fermentation process, the mash stays in one fermenter for about 48 hours before the distillation process is started.

5. Distillation: The fermented mash, now called "beer," at this stage contains about 10% alcohol, as well as non-fermentable solids from the corn and the yeast cells. The mash is then pumped to the continuous flow, multi-column distillation system where the alcohol is removed from the solids and the water. Ethanol boils at a temperature of 173^{o}F (78.3^{o}C) at sea level pressure, allowing the distillation separation of the ethanol from water, which boils at 212^{o}F (100^{o}C) at sea level. The alcohol will leave the top of the final column at about 95% purity (190 proof), and the residual mash, called stillage, gets transferred from the base of the column to the co-product processing area.

6. Dehydration: The alcohol from the top of the column is then passed through a dehydration system where the remaining water is removed. At this point, distillation has diminishing effect, and the remaining water must be removed chemically. Most commercial ethanol plants use a molecular sieve to capture the remaining water in the ethanol. The alcohol product at this stage is called anhydrous ethanol and is approximately 200 proof.

7. Denaturing: Ethanol to be used for fuel is then denatured with a small amount (2-5%) of a product (usually gasoline) to make it unfit for human consumption.

8. Co-Products: There are two main co-products created in the production of ethanol: carbon dioxide and distillers' grain. Carbon dioxide is given off in significant quantities during fermentation, and many ethanol plants collect this carbon dioxide, clean it of any residual alcohol, compress it, and sell it for use in carbonated beverages or in the flash freezing of meat. Distillers' grain is sold in two forms: distillers' wet grain (DWG) and distillers' dried grain (DDG). Both are high in protein and other nutrients, and are a highly valued livestock feed ingredient. DWG seems to be preferred by dairy and beef cattle (BBI International, 2003), but if a cattle feed lot is not within 100 miles of the ethanol plant, storage and transportation can become problematic. DDG requires a high amount of input energy to dry the grain to 10-12% moisture. The main advantage of DDG over DWG is better "flowability" and longer storage life. Some ethanol plants also create a "syrup" that contains some of the leftover materials, and can be sold as a separate product in addition to the distiller's grain, or combined with it to form so-called "distillers' dried grain with solubles" (DDGS).

Ethanol is also made from a wet-milling process. Many of the larger ethanol producers use this process, which also yields many other products, such as high fructose corn sweetener.

According to BBI International (2003), about 85% of the ethanol plants in the U.S. use natural gas as a source of thermal energy. The remainder use propane, fuel oil, or coal. In general, about 20,000 to 40,000 Btu of energy is required to produce a gallon of ethanol and associated co-products. The highest energy requirements are needed when dry distillers grain is a co-product.

Geothermal utilization opportunities exist in three stages of the production process: cooking, distillation, and drying of the distillers grain. In addition, geothermal energy could be used for space heating.

Economic Analysis

A spreadsheet tool was developed for the energy and economic analyses of a hypothetical ethanol plant considering the use of geothermal energy. The model consists of three worksheets for evaluating the feasibility of an ethanol project, where the heat source is conventional fossil fuel and/or geothermal energy. The worksheets are:

- Energy Consumption,
- Cost Analysis, and
- Life-Cycle and Sensitivity Analysis

The use of each of the worksheets and the information they contain is described in the following subsections.

Energy Consumption: The *Energy Consumption* worksheet (Figure 2) contains all the details of the energy requirements and energy costs to produce ethanol on a peak hour and an annual basis. The sections of the spreadsheet are: Process Description, Heating Load, Systems, and Annual Energy Cost.

	Value	Units	% of Cost Conv.	% of Cost Geo.	Comments
PROCESS DESCRIPTION					
Annual ethanol plant capacity	10,000,000	gal			
Energy requirement per gallon	30,000	Btu/gal			A typical range is 20,000 to 40,000 Btu/gal. Higher energy requirements are necessary for dry distillers grain byproduct.
Annual number of days of operation	350	days/year			
Hours per day of operation	24	hrs/day			
Hours per year of operation	8,400	hrs/year			
HEATING LOAD					
Peak Load	35,714,286	Btu/hr			
Annual Load	3.00E+11	Btu			
	87,924,971	kWh			
SYSTEMS					
Geothermal					
% Peak Load Geothermal	75%				
Peak heating required	26,785,714	Btu/hr			
Well pumping head	150	ft			
Required capacity of production well(s)	1,339	gpm			Based on a temperature drop of 40°F
Number of pumping wells	2				
Well pump motor size	72	hp			
Process flow rate	1,339	gpm			For preliminary estimates, enter same as geothermal side
Process flow head losses	150	ft			For preliminary estimates, enter same as geothermal side
Process pump motor size	72	hp			
Conventional					
Conversion efficiency	0.85				
Supplemental heating required	8,928,571	Btu/hr			
Electrical Requirements					
Electrical energy per gallon of ethanol	0.8	kWh			Typically about 0.8 kWh of electricity is used to make 1 gal. of ethanol (BBI, 2003).
ANNUAL ENERGY COST					
Conventional energy cost rate	$0.80	/therm			
Electricity rate	$0.050	/kWh			
Conventional					
Electrical energy cost	$400,000		12.4%		
Heating energy cost	$2,823,529		87.6%		
TOTAL	**$3,223,529**		100%		
Geothermal					
Electrical energy cost	$400,000			33.7%	
Well pump energy cost	$53,428			4.5%	
Circulating pump energy cost	$26,714	$480,142		2.3%	
Remaining heating energy cost	$705,882			59.5%	
	$1,186,025			100%	
Annual Savings w. Geothermal	**$2,037,505**				
	63.2%				

Figure 2. *Energy Consumption worksheet for the ethanol plant model (note red fonts are user input, black and green fonts are calculated values, blue fonts are user comments).*

The first section (*Process Description*) of the *Energy Consumption* worksheet contains user-input information that describes the ethanol process in terms of annual gallons produced and the amount of energy required per gallon. According to BBI (2003) small plants produce about 5 million gallons per year, whereas large plants can produce up to 100 million gallons per year. For this feasibility study, a plant producing 10 million gallons per year was assumed. Also in this section, the annual hours of operation are entered.

The second section (*Heating Load*) of the spreadsheet computes the peak hourly heating load and the annual heating load. As detailed modeling of the physics of ethanol production is beyond the scope of this project, these loads are computed from data entered in the *Process Description* section.

In the third section (*Systems*), the details of the heating system are specified and computed. The main input parameter is the fraction of the process that uses geothermal energy. This fraction is highly dependent on temperatures and flow rates of a geothermal resource and on the level of design detail that goes into a plant. For example, a relatively high temperature resource (i.e. over 250^{o}F) could meet all the loads necessary, depending on the well yields. Conversely, a resource with fluid temperatures on the order of 190^{o}F might require special engineering of heat transfer equipment and systems in order to handle part-load conditions. For this study, we assumed an ethanol plant with a split of 75% geothermal energy and 25% natural gas.

In the *Systems* section, the user also enters the details of the geothermal well, and the required flow rate is computed from the peak hour load. These values are used to compute annual electrical energy consumption.

The fourth and final section (*Annual Energy Cost*) of the *Energy Consumption* worksheet, is where energy consumption of a conventional and geothermal ethanol plant are computed. The user enters the conventional energy cost rate and the electricity rate. Conventional energy sources included in the spreadsheet are natural gas, propane, or heating oil. For this feasibility study, we assumed natural gas as the conventional heating energy at a rate of $0.80/therm. The average electricity rate was estimated at $0.05/kWh.

As seen in Figure 2, for an ethanol plant producing 10 million gallons per year, the annual energy cost of a conventional natural gas ethanol plant is $3.22 million, while the annual energy cost of a 75% geothermal, 25% natural gas ethanol plant is $1.19 million. Thus, the 75% geothermal plant provides an annual energy savings of 63.2%, or $2.04 million over a 100% natural gas plant.

<u>Cost Analysis:</u> The *Cost Analysis* spreadsheet (Figure 3) contains all the details of the cost considerations for an ethanol plant project. The costs considered include initial costs, annual costs, gross annual income, and periodic costs, each of which is described below. Taxes are not considered.

The first section of the *Cost Analysis* worksheet is where the initial costs are specified. The initial costs are subdivided into *Design & Engineering* costs and *Equipment & Installation* costs. As seen in Figure 3, line items are provided in the *Design & Engineering* section for site assessment and investigation, plant design, and construction oversight. These items, meant to be costs incurred regardless of the heat source, were not considered specifically for this stage of the feasibility study. Rather, a typical 5% of the plant construction cost was assumed.

The *Equipment & Installation* section includes all associated costs for the plant, land purchase, and geothermal equipment (including geothermal exploration costs and final well drilling). For the 100% natural gas ethanol plant, only plant costs and land acquisition costs are considered. Plant costs are estimated from data provided by BBI (2003), which are shown graphically in Figure 4. It was assumed that adequate land could be acquired for $150,000. Geothermal exploration costs, including exploratory drilling and consulting services of a professional geologist, are estimated at $1 million. As a suitable geothermal resource will likely be located in a remote area, additional construction costs of utilities and services will be incurred. These costs are estimated at $1.5 million. Final well installation costs are estimated at $1.5 million, with a total drilling footage of 10,000 ft. Note that this drilling quantity can include any number of supply and injection wells totaling 10,000 ft. All other geothermal equipment costs are shown in Figure 3. The incremental cost of the geothermal ethanol scenario above the conventional is approximately $4.57 million or 21.6% for the 10 million gallon capacity plant examined here.

	Unit	Quantity	Unit Cost	Amount	TOTALS	% of Cost Conv.	% of Cost Geo.	Comments
INITIAL COSTS								
Design & Engineering								
Site assessment, investigation	hr		$100	$0				
Plant design	hr		$100	$0				
Construction oversight	hr		$100	$0				
				$1,000,000		4.7%	3.9%	For now, assume approx. 5% of plant cost
Equipment & Installation								
Conventional								
Ethanol plant	lump	1	$20,000,000	$20,000,000		94.6%	77.8%	See Figure 4 of this report for an estimate
Land purchase	acre	10	$15,000	$150,000		0.7%	0.58%	
Additional Geothermal								
Resource Exploration	lump	1	$1,000,000	$1,000,000			3.89%	Exploration drilling + geologist's time
Services to remote area	% of plant	5%	$20,000,000	$1,000,000			3.89%	Roads, water, sewage, etc. (5% of plant cost)
Utilities to remote area	miles	10	$50,000	$500,000			1.94%	Power lines, natural gas pipeline
Well Drilling	total ft	10,000	$150	$1,500,000			5.83%	Approx. $100-$150/ft
Well flow testing	lump	1	$5,000	$5,000			0.02%	
Horizontal transfer piping	ft	1,000	$50.00	$50,000			0.19%	Approx. $25 - $100/ft
Well pump bowl assembly	stage	22	-	$52,110			0.20%	Costs from equations in design handbook
Well head & column	depth ft	300	-	$38,800			0.15%	Costs from equations in design handbook
Well pump motor + VFD	hp	72	-	$17,738			0.07%	Costs from equations in design handbook
Circulating pumps	hp	72.47	$500	$36,236			0.14%	Approx. $250 - $1,900/hp
Plate heat exchangers	ft^2	1,488	$12.50	$18,601			0.07%	Approx. $10 - $20/$ft^2$
Fittings, valves, controls	lump	1		$150,000			0.58%	Assume 10% of well drilling costs preliminarily
Process heat exchange coils	MBtu/hr	26,786	$7.50	$200,893			0.78%	Approx. $5 - $10/Mbtuh
				$24,719,378				
Total: Conventional					$21,150,000	100%		
Total: Geothermal					$25,719,378		100%	
Incremental Geothermal Cost					*$4,569,378*			
					21.6%			
ANNUAL COSTS						% of Cost Conv.	% of Cost Geo.	
Energy use - conventional				$3,223,529		22.3%		
Energy use - geothermal				$1,186,025			9.6%	
Maintenance - Conv.	per gal.	10,000,000	$0.02	$200,000		1.4%	1.6%	
Additional Maintenance - Geo.	lump	1	$15,000	$15,000			0.1%	Well maintenance
Labor	per gal.	10,000,000	$0.10	$1,000,000		6.9%	8.1%	
Feedstock + chemicals	per gal.	10,000,000	$1.00	$10,000,000		69.3%	80.6%	
Total: Conventional					$14,423,529			
Total: Geothermal					$12,401,025			
ANNUAL INCOME								
Ethanol	per gal.	10,000,000	$1.50	$15,000,000				
Distillers grain	per gal.	10,000,000	$0.30	$3,000,000				
CO_2	per gal.	10,000,000	$0.05	$500,000				
Total Sales Income					$18,500,000			
PRE-TAX PROFITS						Per Gal.		
Conventional					$4,076,471	$0.41		
Geothermal					$6,098,975	$0.61		
PERIODIC COSTS or INCOME	Years							
Well refurbishing	5			$25,000				Enter costs as POSITIVE, income NEGATIVE
Well pump replacement	15			$163,485				Enter costs as POSITIVE, income NEGATIVE

***Figure 3**. Cost analysis worksheet for the ethanol plant model (note red fonts are user input, black and green fonts are calculated values, blue fonts are user comments).*

The *Annual Costs* section includes all costs associated with ethanol production, and the user enters unit costs in terms of $/gallon of ethanol produced on an annual basis. For this feasibility study, relative values for this section were taken from BBI (2003). For both plants, the greatest annual cost item is that associated with acquiring the feedstock (typically corn) and related chemicals and enzymes. For the conventional natural gas ethanol plant, energy costs account for 22.3% of total annual costs, while only 9.6% of the total annual cost is attributed to energy use in the 75% geothermal, 25% natural gas ethanol plant scenario. For the geothermal case, an additional well maintenance cost was assumed at $15,000, or 0.1% of the annual costs.

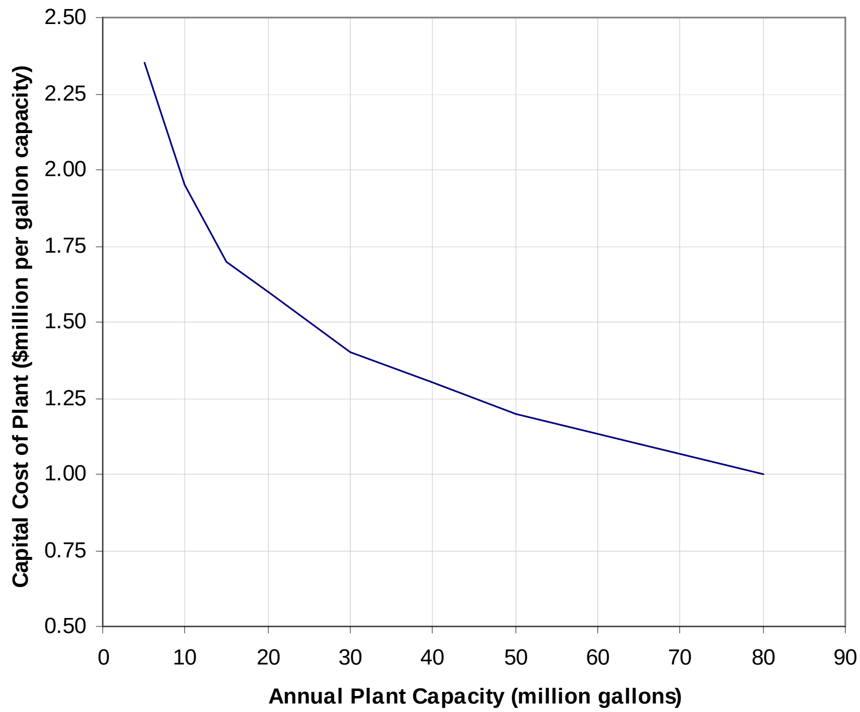

Figure 4. *Capital cost of an ethanol plant versus annual plant capacity (data taken from BBI, 2003).*

The *Annual Income* section includes all revenues generated from ethanol production, and the user enters unit values in terms of $/gallon. For this feasibility study, relative values for this section were taken from BBI (2003). Income is generated through sale of ethanol, CO_2, and some type of distillers grain. As described previously, the distillers grain is sold as animal feed and can be wet, dry, or mixed with solubles. For the ethanol plant scenario considered here, gross sales of $18.5 million are realized.

The next section, *Pre-Tax Profits,* calculates profits before taxes. For the scenarios examined here, the conventional natural gas ethanol plant yields an annual profit before taxes of approximately $4.1 million, while the 75% geothermal, 25% natural gas ethanol plant yields an annual profit before taxes of approximately $6.1 million. This results in a pre-tax profit margin of $0.41/gal. for the conventional plant and $0.61/gal. for the geothermal scenario.

The final section of the *Cost Analysis* worksheet is where *Periodic Costs or Income* are entered. Here, only geothermal periodic costs of well re-furbishing and geothermal well pump replacement costs are considered. These are taken into account in the life-cycle cost analysis described next.

<u>Life-Cycle Cost and Sensitivity Analysis:</u> Thirty-year life-cycle economics are compared on this worksheet using a present value comparison. Given the uncertainty of the cost items, a sensitivity

analysis was conducted in order to observe the effects of various cost items on the present value. The items varied in the sensitivity analysis were: natural gas costs, energy required per gallon of ethanol, fraction of energy provided by geothermal, geothermal initial costs, ethanol market price, feedstock price, and electricity costs. Results of the sensitivity analysis are shown in Figure 5. Present values are expressed as a ratio of the geothermal scenario to the conventional scenario. A discount rate of 8% was assumed.

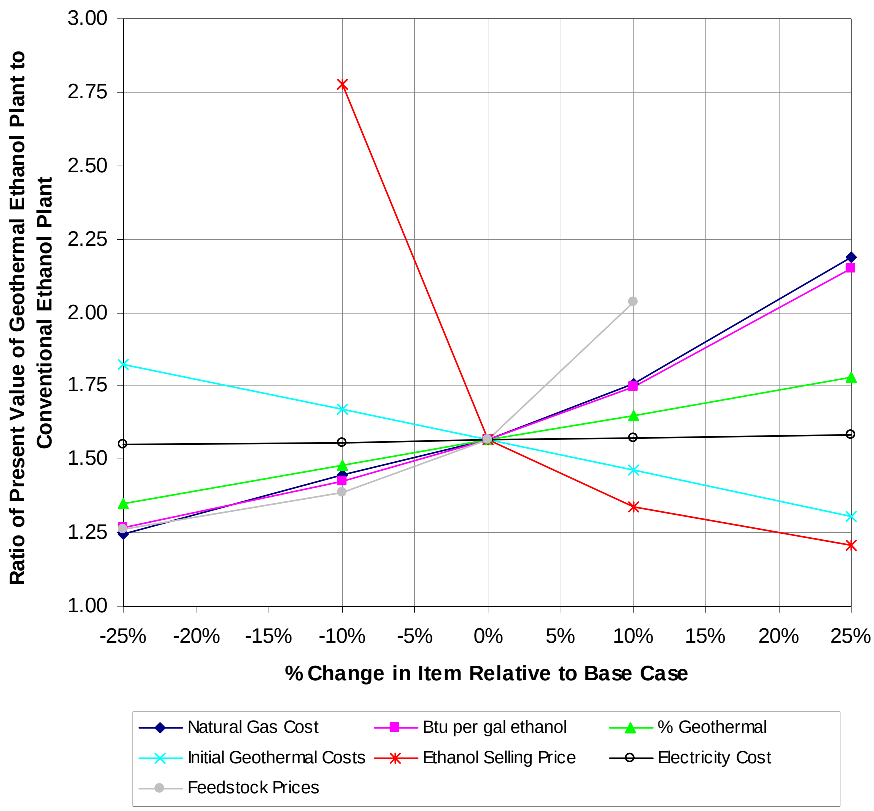

Figure 5*. Sensitivity analysis of various cost items on the present value of a geothermal ethanol plant relative to a conventional natural gas ethanol plant.*

A review of the data presented in Figure 5 shows that, for the base case described above, the geothermal case has a 54% greater present value than the conventional case. The most sensitive item to the present values is the ethanol selling price. As ethanol selling price is decreased, the ratio of the present value of the geothermal case to the conventional case rises dramatically as operating costs become very important. As the ethanol selling price is increased by up to 25%, the present value of the geothermal case relative to the conventional case decreases to about 1.2.

Following the market price for ethanol, the next most sensitive item on the project economics is the feedstock price. An increase in feedstock price of 10% increases the ratio of the present value of the geothermal case to the conventional case up to a value of 2. A further increase in the feedstock price up to 25% results in operating costs exceeding profits (and thus resulting in a negative present value) for the conventional case, while the geothermal case remains profitable.

Lowering the feedstock price has a similar effect to lowering the natural gas price and the energy required per gallon of ethanol, the next most sensitive items.

The next most sensitive items to the present value ratio, each having a nearly identical impact, are the natural gas price and the energy required per gallon of ethanol. Increasing each by 25% increases the ratio of the present value of the geothermal case to the conventional case to about 2.2. Decreasing these items by 25% has less of an impact, lowering the ratio of the present value of the geothermal case to the conventional case increases to about 1.25.

The next most sensitive item to the present value ratio is the initial geothermal cost, followed closely by the fraction of energy provided by geothermal. As the initial geothermal cost is decreased by 25%, the ratio of the present value of the geothermal case to the conventional case increases to about 1.8. Conversely, as the initial geothermal cost is increased by up to 25%, the ratio of the present value of the geothermal case to the conventional case decreases to about 1.25. When the fraction of energy provided by geothermal is increased by 25% (i.e. up to 93.75%), the ratio of the present value of the geothermal case to the conventional case increases to about 1.76. When the fraction of energy provided by geothermal is decreased by 25% (i.e. down to 56.25%), the ratio of the present value of the geothermal case to the conventional case decreases to about 1.35.

The project economics are relatively insensitive to the electricity cost.

Potential Barriers to Geothermal Utilization in Ethanol Production

Although the economics of utilization of geothermal energy can be quite attractive in ethanol production, some barriers to implementation have been identified. One of these is geothermal resource location. If the resource is far from ethanol markets and byproducts markets and/or remote from transportation infrastructure, economics of an ethanol project could become prohibitive.

Another challenge in the use of geothermal energy in ethanol production is in the necessary plant design modifications. The majority of ethanol plants use low-temperature steam in their process, but geothermal fluids may be two-phase or single phase liquid, depending on the resource temperatures and pressures. This will require selection of different heat transfer equipment and modifications to the plant process design (relative to conventional), and will likely incur more design time and cost that may become prohibitive.

Finally, there could be some opportunities in ethanol plants for waste heat recovery that can negatively impact the economics of geothermal energy utilization. This might be the case where thermal oxidation is the best means of destruction of regulated volatile organic emissions and/or odors that could otherwise be released into the atmosphere. Thermal oxidation of air pollutants typically requires destruction temperatures over 1,000^{o}F, resulting in a significant amount of waste heat available for recovery and use in the ethanol production process.

Although some barriers do exist in further development of geothermal utilization in ethanol production, there are some advancements being made as well, particularly with regard to the use of lower temperature resources. New technologies in ethanol production are evolving through research that has been aimed at low-temperature, low-energy chemical process of extracting ethanol from many different types of organic materials.

Concluding Summary

The Geo-Heat Center has conducted an evaluation of using geothermal energy in ethanol production. This work has been funded and completed under Midwest Research Institute, National Renewable Energy Laboratory (NREL) Task Order No. KLDJ-5-55052-01, "*Feasibility Studies and Life-Cycle Cost Analysis*", Task 3, "*Williston Geothermal Feasibility Study*".

The original objective of this TOA was modified to conduct a generalized feasibility study that could apply to any ethanol plant considering the use of geothermal energy. As such, a spreadsheet design tool was developed that could be used to analyze the economics of a potential ethanol project once a geothermal resource was characterized. A hypothetical ethanol plant using a dry-milling process was analyzed for this feasibility study, producing 10 million gallons of ethanol on an annual basis. The energy fraction considered was 75% geothermal and 25% natural gas.

Some specific results of this study are as follows:

- According to BBI International (2003), about 85% of the ethanol plants in the U.S. use natural gas as a source of thermal energy. The remainder use propane, fuel oil, or coal. In general, about 25,000 Btu of energy is required to produce a gallon of ethanol, and the associated dry distillers grain requires an additional 12,700 Btu.
- As of 2003, approximately 95% of U.S. fuel ethanol was manufactured from corn.
- Geothermal utilization opportunities exist in three stages of the production process: cooking, distillation, and drying of the distillers grain. In addition, geothermal energy could be used for space heating.
    - Cooking is generally accomplished at temperatures of 150-180^{o}F (65-80^{o}C). The meal is exposed to a high temperature stage of 250-300^{o}F (120-150^{o}C) for a short period of time to reduce bacterial growth in the mash.
    - Distillation occurs at temperatures between the boiling point of ethanol (173^{o}F (78.3^{o}C) at sea level pressure) and the boiling point of water (212^{o}F (100^{o}C) at sea level).
    - Grain drying occurs at temperatures exceeding the boiling point of water
- For the base case examined here, the incremental cost of the 75% geothermal plant above the conventional is approximately $4.57 million or 21.6%.
- The estimated annual energy savings with the 75% geothermal plant is $2.04 million or 63.2%. Energy costs account for 22.3% of total annual costs for the conventional plant, while only 9.6% of the total annual cost is attributed to energy use in the 75% geothermal plant.
- The conventional ethanol plant yields an annual profit before taxes of approximately $4.1 million, while the 75% geothermal plant yields an annual profit before taxes of approximately $6.1 million. This results in a pre-tax profit margin of $0.41/gal. for the conventional plant and $0.61/gal. for the geothermal scenario.
- The present value of a 30-year life-cycle of the 75% geothermal plant is 1.54 times greater than the conventional plant.

- A sensitivity analysis of cost items on the present value, shows that project economics are most sensitive to: ethanol selling price, feedstock price, natural gas price, energy required per gallon of ethanol, initial geothermal cost, and fraction of energy provided by geothermal. Project economics are relatively insensitive to electricity cost.
- Some barriers to further development of geothermal energy utilization in ethanol production include: distance of the geothermal resource from markets and/or infrastructure; plant design modifications to account for two-phase or single-phase liquid geothermal fluids; and other waste heat recovery opportunities at an ethanol plant.
- New technologies in ethanol production are emerging that require lower temperature and lower energy per gallon, expanding possibilities for low-temperature geothermal energy utilization.

References

BBI International, 2003. *Ethanol Plant Development Handbook*, 4th Ed.