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Low-Temperature Geothermal Resources for District Heating: An Energy-Economic Model of West Virginia University Case Study

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ABSTRACT

Low-temperature geothermal energy has recently gained more attention as a possible use of geothermal energy in geographic areas that are not typically associated with geothermal energy use. The attractive features of low-temperature geothermal utilization include, but are not limited to its stable, baseload energy output, low environmental impact, and the renewability of the resource. West Virginia University (WVU) presents itself as a possible attractive location for the expansion of geothermal resource utilization within the eastern United States due to the elevated temperatures in the eastern counties of West Virginia recently identified by the work of Frone, Richards, and Blackwell at Southern Methodist University (SMU) [Blackwell et al., 2010]. WVU has an extensive district heating system that supplies the campus buildings at the 30,000-student university with steam for both heating in the winter and steam for a distributed system of absorption chillers for cooling in the summer.

This paper presents a feasibility analysis of the WVU case study using both energetic and economic analyses to assess scenarios of the potential integration of geothermal energy in an eastern-US district heating system. Process simulations have been performed using Aspen Plus to simulate the steam distribution system based on the current distribution pipeline on the WVU campus. The flow pattern, including the temperature, flow rate, and pressure of geothermal hot water is optimized to determine a number of design parameters for the geothermal system. These design parameters include the number of geothermal injection and production wells, the potential use of auxiliary heating equipment using natural gas, and the system of injection wells. The objective function for the optimization of the system is the Equivalent Annual Operating Cost, which includes the initial investment in the cost of drilling and fluid distribution equipment, as well as the operation and maintenance costs. Additionally, for comparative purposes, the cost of the heat per kWh_{th} delivered is estimated.

KEYWORDS: Low-temperature, direct-use, district heating

INTRODUCTION

Geothermal energy is one of the significant sustainable energy resources which can satisfy people's increasing demand for energy. In most cases, a geothermal system has a fluid circulating in it, absorbing heat from hot rocks underground and giving heat to another fluid at surface. With concerns of how hot the circulating fluid can be, the geothermal systems are categorized into two kinds: electricity generation and district heating. Generally speaking, at acceptable drilling depth, the geothermal fluid with a temperature higher than 150°C can be used for electricity generation, and that with a temperature lower than 150°C can be used for district heating [Erdogmus et al., 2006].

In the United States, according to the annual energy report by Energy Information Administration in 2010, the residential and the commercial sectors share 22.6% and 18.6% of the total energy consumption [EIA, 2011]. Further study shows that space heating, water heating, and air conditioning contribute 70% of the total residential energy consumption [EIA, 2011]. About 30% of the total commercial energy consumption is used for spacing heating [EIA, 2011]. This means 21.4% of total energy consumption is used for such low temperature end-use regarding to residential and commercial sectors. Considering certain heating and air conditioning in industrial sector, this low temperature end-use may contribute up to 25% of the total energy consumption. The most common fuels used for space heating in US are natural gas, electricity, and propane [EIA, 2011]. In this paper, we focus on the potential use of geothermal energy in an on-campus district heating system. We examine the potential for substituting geothermal energy for conventional fossil fuels. The United States Geological Survey (USGS) has estimated the geothermal energy can provide 60,000 MW_{th} for direct use. Comparing with the estimated direct use in 2005, 617 MW_{th} [Green & Nix, 2006], there is much can be done to develop geothermal energy.

Recent work of Frone, Richards, and Blackwell at Southern Methodist University (SMU) has identified West Virginia (WV) as a geothermal hot spot, as warm as 200°C and as shallow as 5 km [Blackwell et al., 2010]. The hotter region extends from north central WV, in Monongalia County, where WVU is located, to southeast WV, in Greenbrier County. WVU has an extensive district heating system that supplies the campus buildings at a 30,000-student university with steam for both heating in the winter and steam for a distributed system of absorption chillers for cooling in the summer. The size of the energy-consuming population and the dense arrangement of the campus buildings, in conjunction with the existing steam pipelines make WVU a perfect case-study location for direct use of geothermal energy. With the assistance of WVU facilities management, the flow rate of hot geothermal water was estimated based on the current steam use [WVU, 2011]. An Aspen Plus model consisting of the hot water distribution system, the heat exchangers used for building heating, and absorption chillers used for cooling was built to simulate the dynamic heating and cooling system over the full 12-month operating cycle. Finally, the Equivalent Annual Operating Cost (EAOC) and the cost of the heat per kWh_{th} were calculated for further comparative purposes.

BACKGROUND

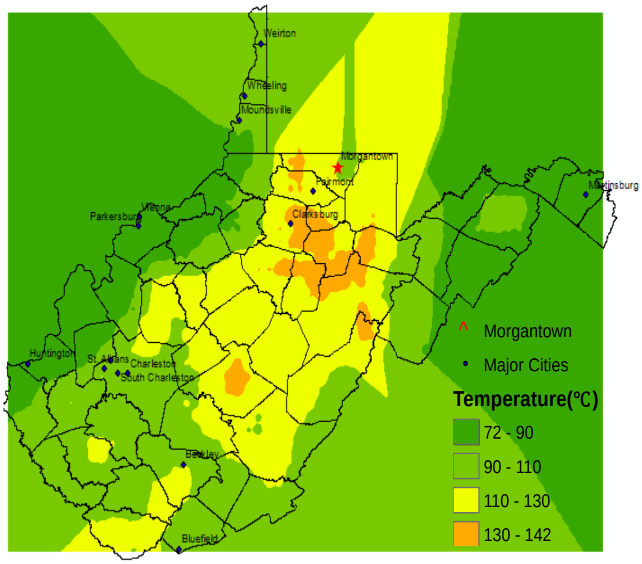
West Virginia University has three main campus, Health Sciences, the downtown main campus and the Evansdale campus, which houses engineering, agricultural sciences, and education. The Health Sciences campus is equipped with its own heating system, including two 600 hp Cleaver-Brooks boilers, rated at 25.1 MMBtu/hr each. The downtown campus primarily uses steam directly through the buildings. It would not likely be economical to replace the steam system with geothermal hot water since all the buildings heating utilities would be changed. Hence, only the Evansdale campus is considered at this time. Most buildings on this campus use a steam/water heat exchanger system. The saturated steam is delivered to each building by the steam distribution pipelines and exchange heat with water which circulating through the building radiation system. As long as the steam pipelines allow a sufficient flow rate to deliver the necessary heat, it is reasonable to replace the steam by geothermal hot water without a significant facility change.

In addition to issues of sustainability, there may be potential economic advantages to the use of geothermal energy in the WVU district heating system.

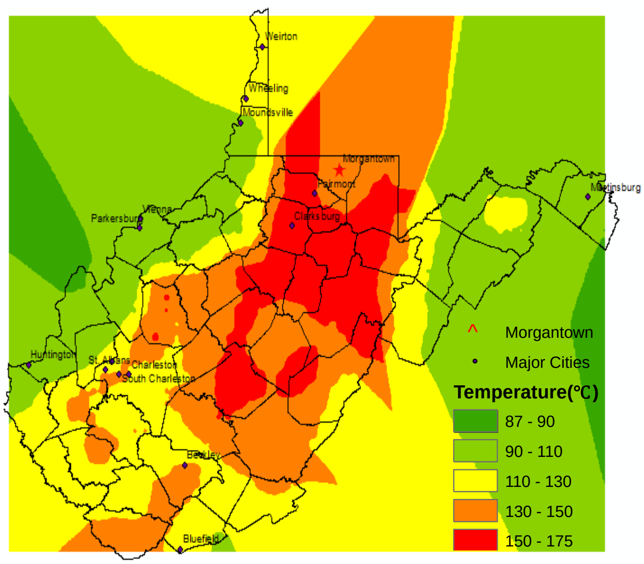
The existing pipeline map and the current steam usage detailed to each building were provided by WVU facilities management. The campus is served by an 8'' high pressure pipeline from Morgantown Energy Associates (MEA). The main stream enters from the northeast of the campus and is reduced to 125 psi, 140°C saturated steam then distributed throughout the campus. The campus main steam line is 10'' pipeline with 1 psi drop per 100 feet of the pipe length. The sub-stream pipe size varies with the heating load of different building, usually ranging from 4'' to 8''. The length of the pipe is based on field measurement and calculation from the map. This pipeline distribution will be used in Aspen Plus model to help model the geothermal hot water transfer.

The steam usage of each building is the average from the steam metering system over the past few years. Additionally, the university's master plan was consulted to account for future building. It is used for steam estimation for new buildings, based on the energy use for different building type and the total area of each building. All the buildings were taken into considered and the building type included classroom (25-50 Btu/hr/Ft^2), green house (25 Btu/hr/Ft^2) and library (20 Btu/hr/Ft^2).

In 2010, West Virginia was shown to be a geothermal hot region based on the work by SMU [Blackwell et al., 2010]. Seven temperature maps, based on data provided by Frone, Richards, and Blackwell, at underground depth of 3.5 km to 9.5 km, with an interval of 1 km, were generated by ArcGIS. ArcGIS is a geographic information system software which stores different kinds of geographic information in different layers and can analysis, manage or custom data between different layers. The Inverse Distance Weight method was used to interpolate the original points data to the whole area of West Virginia. Based on the temperature vs. depth estimations, a drilling depth of 3.5 km to 4.5 km will likely be deep enough to produce geothermal fluid between 110°C to 140°C. It is assumed that the temperature changes linearly with the depth between 3.5 km and 4.5 km. Using this assumption, the temperature gradient near WVU was calculated to be 26.44°C/km between 3.5 km to 4.5 km. Figure 1 shows the temperature map at depth of 3.5 km and 4.5 km.



(a)



(b)

Figure 1: Temperature Maps (in °C) of WV at Depth of 3.5 km (a) and 4.5 km (b)

MODELING APPROACH

In order to simulate a year-round steam usage scenario, the total geothermal hot water flow rate was first estimated. Then the Aspen Plus models for heat exchangers and absorption chillers using geothermal hot water were built. At last energy and economic evaluations were performed for a feasibility analysis.

Geothermal Hot Water Consumption

The geothermal hot water is the connection between a geothermal reservoir system and a geothermal direct use system. After the flow pattern of the geothermal hot water is determined, the number of the geothermal injection and production wells is determined based on the total flow rate. The drilling depth will be calculated based on the temperature requirement of the geothermal hot water. Since the current actual steam usage by each building is known, the total flow rate of geothermal water is calculated using the equation:

$$[m(C_P\Delta T+\lambda)]_{\text{steam}}=[m\,C_P\Delta T]_{\text{water}} \qquad (1)$$

Based on a general quality of a geothermal reservoir, the inlet geothermal hot water is 140°C and the outlet is 80°C using a heat exchanger without pressure drop. With the total steam usage for the Evansdale campus, the flow rate of the geothermal hot water is about 582,804 lbs/hr, or about 74 kg/s. The detailed estimation by each building is provided in Appendix 1.

Aspen Plus Model of Heating System

The heating system model consists of the pipelines, the heat exchangers and the stream splitting nodes. It is based on the steam schematic of the Evansdale campus, which provides the length, the inner diameter and pressure drop of each pipe. The overall heat transfer coefficient to simulate the heat loss during distribution is calculated by equation:

$$\frac{1}{U_i}=\frac{1}{\dfrac{1}{h_i}+\dfrac{1}{h_0}\dfrac{D_i}{D_0}+\dfrac{w}{k}\dfrac{D_i}{D_0}} \qquad (2)$$

Where:

$$h_i=\frac{0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}\,k}{D_i}\text{, for turbulent flow}$$

$$D_L=\frac{D_0-D_i}{\ln\left(D_0/D_i\right)}$$

h_o = heat transfer coefficient of air
k = thermal conductivity of steel
D_o, D_i, w are based on standards of steel pipes

Several stream splits are used in the model to separate stream into different buildings feeds. No pressure drop through the splits is assumed. The split fraction is calculated by the ratio of the downstream building heat load and the upstream heat load. Detailed calculation sheets regarding heat transfer coefficients and split fractions are provided in Appendix 2.

The geothermal water is not used directly to avoid potential corrosion and scaling in the distributed building radiator system. One solution to protect the inner building facilities, heat exchangers external to each building are added. Another solution that was considered is a centralized heat exchange process using a large heat exchanger and to distribute the fluid directly into buildings. This case differs with the existing heating system and the existing steam usage cannot be used. The heat exchangers added to each building are assumed without pressure drop, and the heat duty is based on the heating load of each individual building.

The main stream is initially set as 74 kg/s at 140°C and 58 psi, the same as the geothermal water calculation. The flow rate and temperature can be varied to examine different energetic and economic scenarios. The spent hot water is assumed to return back into reservoir regardless of the temperature.

The equipment cost is also calculated in this model. The pipelines are not included in the cost estimation because the existing pipelines will be used. The water cost including the initial geothermal reservoir circulating water and the annual water makeup due to water loss in reservoir is also not considered in the model. It is assumed that makeup water will be obtained from Monongahela River in close proximity to WVU. Therefore the majority of the capital cost is the cost of heat exchangers. The Aspen Plus model of heating system in Evansdale campus is provided in Appendix 3.

Aspen Plus Model of Absorption Chillers

There are two buildings on the Evansdale campus using water/lithium bromide absorption chillers, rated at a total of 5,265 kW_{th}. There are seven more buildings being constructed over the next few years, adding another 4,670 kW_{th} of cooling load. For this new construction, absorption chillers will be used if they are confirmed to be more economical. A single-effect water/lithium bromide absorption chiller is modeled by Aspen Plus using the geothermal hot water as the heat source [Somers et al., 2011] (Figure 2).

The model is a closed loop using water/LiBr as a circulating fluid and it provides cooling or refrigeration. The heat exchanger H2 is where the water/LiBr solution is heated by the geothermal water. Then it is separated into saturated steam and saturated liquid by the flash tank (DFLASH). The saturated steam (Stream 7) is condensed into liquid and goes through the valve (VALV2), which reduce the pressure significantly. The cooling is provided when the water evaporates into steam through evaporator (EVAP). The saturated solution (Stream 4) produces heat to preheat the water/LiBr solution in heat exchanger HOT-COLD before entering the flash tank. The cooled solution (Stream 6) mixes with the steam (Stream 10) from the evaporator and goes towards the flash tank again. Another heat exchanger H1 is added before the flash tank to desaturated the supersaturated steam leaving the flash tank. Stream 1 is set a tear stream in the Aspen Plus model to more easily converge the loop. There are several assumptions used in the model. 1) The pressure is considered constant through heat exchanger or flash tank except the pump and the valves. 2) The pump efficiency is 100%. To provide 9,935 kW_{th} of total cooling load from the evaporator, the heat duty of the heat exchanger H2 would need to be 13,550 kW_{th}, requiring 51 kg/s of geothermal hot water at 140°C. In this case, the geothermal hot water can be used both in summer and winter at a similar flow rate.

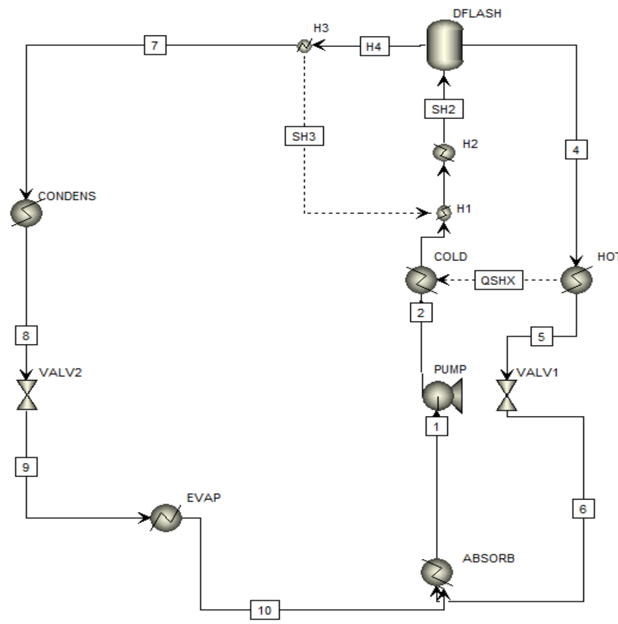


Figure 2: Aspen Plus Model of Single-Effect Absorption Chiller

RESULT AND DISCUSSION

The result of the Aspen heat system model shows that 74 kg/s of geothermal hot water at 140°C and 58 psi can satisfy every building's heating load when comparing to the recent usage data. Assuming a constant heating load and a fixed minimum temperature used in the buildings, the flow rate and the temperature of the hot water are inversely related. Using this Aspen model, the corresponding required flow rates were determined for a few reservoir temperatures. We assume that 80 kg/s is the maximum production rate of a geothermal well near WVU and 140°C is the maximum temperature that can be obtained at an acceptable drilling depth. Finally, 38°C is the minimum requirement for a flow's outlet temperature of a heat exchanger. As a result, 56 kg/s is the minimum flow rate at the maximum temperature of 140°C; and 108°C is the minimum temperature necessary at maximum flow rate of 80 kg/s. Therefore the six cases shown in Table 1 are used for economic evaluation.

Table 1: Cases of Heating System for Economic Evaluation

Case Number	Flow Rate (kg/s)	Temperature (°C)
1	56.0	140
2	60.5	132
3	64.0	127
4	67.4	121
5	72.0	116
6	80.0	108

As stated before, for cooling in the summer, 51 kg/s hot water at 140°C is needed in the absorption chiller for some of the campus buildings. In the event of more buildings using absorption chillers instead of electric chillers, the required flow rate of geothermal hot water is expected to increase in the range of 56 kg/s to 80 kg/s, which will make this project more economical.

Economic Evaluation

The assessment of this geothermal project is not only determined by energetic factors but by economic ones as well. Geothermal district heating system investment is characterized as a high initial investment and a relatively low operating and maintenance cost [Erdogmus et al., 2006].

The cost of drilling is a major cost component of any geothermal project. For a high-quality geothermal reservoir, the drilling cost may account for about 30% of the total capital cost; and with a low temperature gradient, as in this case, the drilling cost may contribute 65% of the capital cost [MIT, 2006]. For drilling cost estimations in this case study, the MIT Depth Depent (MITDD) drilling cost index is used [Augustine, 2009]. The index takes into consideration both the depth of a completed well and the year the well was finished, using the Joint Association Survey (JAS) database [American Petroleum Institute, 1976-2005]. The JAS database on Drilling Costs collects data from thousands of the oil and gas wells drilled in United States every year. The tabulated data show how drilling costs change over time and with depth (Figure 3).

In this paper, the drilling cost is determined from Figure 3 based on the drilling depth, which is calculated from the desired temperature and the temperature gradient, 26.44°C/km. The total drilling cost consists one injection well and one production well, and inflated to 2010 [Marshall & Swift, 2003-2010].

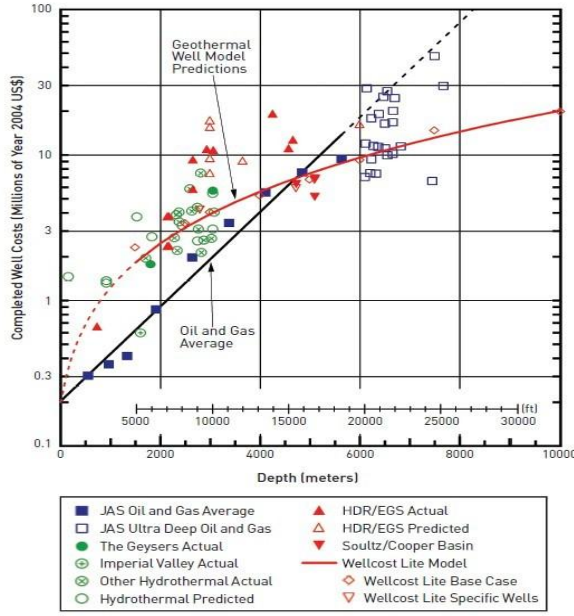


Figure 3: Completed geothermal and oil and gas wells costs as a function of depth in 2004 [MIT, 2006]

The equipment cost of the heat system is dominated by the cost of heat exchanger, which is determined by the economic evaluation function of the Aspen Plus model. The Aspen Plus model also gives the operating cost of the heating system (Table 2).

Table 2: Operating Cost and Total Direct Cost for Six Cases of the Heating System

Case Number	Operating Cost($ million/year)	Total Direct Cost†($ million)
1	1.22	4.92
2	1.22	4.93
3	1.22	4.94
4	1.22	4.97
5	1.22	4.98
6	1.22	5.00

†*Total Direct Cost: equipment cost and the material, labor cost (including installation)*

The operating cost doesn't change for all the cases and the total direct cost increases with the increase of the flow rate. That is because neither the increase of the flow rate nor the decrease of the temperature is large enough to influence the operating cost. And both of them may cause the change of size of heat exchangers, and then influence the material, labor cost. Additionally, the flow rate has larger influence factor than the temperature does based on the result of Table 2.

The absorption chiller model also gives the operating cost and the total direct cost, $2.39 million/year and $4.40 million respectively.

The geothermal reservoir is considered separately from the flow process plant. The initial investment is mainly the sum of the drilling cost and the direct cost of the flow process. As for the manufacturing cost, it is associated with a day-to-day operation of the system and it must be estimated before the feasibility of the project can be assessed. A detailed list of all the manufacturing cost considered in this project is shown in Table 3 [Turton et al., 2009].

Table 3: Factors Affecting Manufacturing Cost

Factor	Description
Direct Cost	
Operating Labor	Short as C_{oL}, one engineer is assumed here, averagely $70,000/year.
Direct Supervisory	Cost of administrative or support personnel, about $0.18C_{oL}$
Maintenance & Repair	About $0.06FCI$*
Operating Supplies	Cost of daily operation excluding raw material, about $0.009FCI$*
Fixed Cost	
Depreciation	Legal operating costs for tax purposes, about 0.1 *FCI**
Local Tax and Insurance	About 0.032 *FCI**
Factory Expenses	Payroll service, accounting, etc. About 0.708 C_{oL} +0.036 *FCI**
General Expenses	
Administration Costs	About 0.177 C_{oL} +0.009 *FCI**
Total	2.065 C_{oL} +$0.246FCI$*

**FCI: Fixed Capital Investment on plant-side, or the total direct cost.*

At this point, the initial investment including the plant-side total direct cost and the geothermal-side drilling cost is calculated. The annual operating cost is calculated taking into consideration every aspect of the day-to-day operation. The lifetime of this project is assumed to be 15 years and the capital cost of the project can be calculated (Table 4).

Table 4: Capital Cost Calculation ($ million)

Case	1	2	3	4	5	6
Drilling	16.82	15.09	14.35	12.86	12.37	10.88
Heating	4.92	4.93	4.94	4.97	4.98	5.00
Cooling	4.40	4.40	4.40	4.40	4.40	4.40
Initial	26.14	24.42	23.69	22.23	21.75	20.28
FCI	9.32	9.33	9.34	9.37	9.38	9.40
Manufacturing	2.45	2.45	2.45	2.46	2.46	2.47
Capital	62.89	61.17	60.44	59.13	58.65	57.33

The levelized cost of energy is calculated. The heating load and the cooling load is from the Aspen Plus model. Due to the slight difference of the temperature, the heating load doesn't change significantly. Two heating and cooling scenarios were considered: 180 days of heating with 180 days of cooling, and 90 days of heating with 90 days of cooling is calculated separately to give a range of the levelized cost (Table 5).

Table 5: Levelized Cost of Energy in Six Cases and Two Scenarios

Case	Heating (MW_{th})	Cooling (kW_{th})	Levelized 180d/180d ($/$kWh_{th}$)	Levelized 90d/90d ($/$kWh_{th}$)
1	16.24	9935	0.037	0.074
2	16.24	9935	0.036	0.072
3	16.08	9935	0.036	0.072
4	16.24	9935	0.035	0.070
5	16.26	9935	0.034	0.069
6	16.24	9935	0.034	0.068

The levelized cost is between $0.034~0.074/$kWh_{th}$, or $9.96~21.68/MMBtu. One should note that some parts of the capital costs are not taken into consideration in this case study, including the water cost, waste treatment, the pumping cost of water, the auxiliary equipment for drilling, etc. However, there is no need for a new pipeline distribution system and stream splits. The actual value of the levelized cost is expected to be slightly higher.

From Case 1 to Case 6, the total direct cost on plant-side increases because of the increase of heat exchangers' size for higher flow rate. As a result, the annual manufacture cost increases. While the trends of the levelized cost goes down, this tells that the drilling cost accounts for the most of the capital cost of the whole project. The cost of the steam is currently about $12/1000 lbs. Based on the Evansdale campus master plan, it is assumed that every 1000 lbs of steam provide 1 MMBtu of energy [WVU, 2011]. So the current cost of energy is $12/MMBtu. Comparing to the result of the case study, which is between $9.96–21.68/MMBtu, it may be possible to use geothermal energy cheaper than the steam if it is properly treated. The methods would include proper maintenance of the equipment to extend the project's lifetime, to provide heating or cooling to more buildings, such as students' dormitory or new residential buildings around the campus.

CONCLUSION

This paper describes Aspen models of a hot water distribution system for heating and absorption chiller systems for cooling to present a year-round energy consuming scenario of the Evansdale Campus at West

Virginia University. An economic evaluation of the project that includes the drilling cost of the geothermal system and the total direct cost and the manufacturing cost of the heating and cooling systems on plant-size is performed. Six cases were considered to compare the influence to levelized cost of different temperatures and flow rates of geothermal hot water. The result of this case study shows that WVU has the opportunity to use the geothermal energy at a cost comparable to steam, which is the current energy source.

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APPENDIX

1. Geothermal Water Calculation Sheet

No.	BLDG	Msteam lb/hr	λ kJ/mol	Cpsteam KJ/mol/k	dTsteam K	dTwater K	Cpwater kJ/kg/K	Mwater lb/hr
1	Annex	1858	36.7	0.047	74	60	4.219	16396.38
2	Allen Hall	6388	36.7	0.047	74	60	4.219	56372.49
3	Greenhouse	950	36.7	0.047	74	60	4.219	8383.511
4	New AG	12500	36.7	0.047	74	60	4.219	110309.4
5	S. AG	2045	36.7	0.047	74	60	4.219	18046.61
6	Phase2	6000	36.7	0.047	74	60	4.219	52948.49
7	New CEMR	6150	36.7	0.047	74	60	4.219	54272.2
8	ERB	3019	36.7	0.047	74	60	4.219	26641.92
9	ESB	11504	36.7	0.047	74	60	4.219	101519.9
10	MRB	4726	36.7	0.047	74	60	4.219	41705.76
11	CAC	6089	36.7	0.047	74	60	4.219	53733.89
12	NRCCE	3468	36.7	0.047	74	60	4.219	30604.23
13	Library	1345	36.7	0.047	74	60	4.219	11869.29
	SUM	66042						582804

2. Heat Transfer Coefficient and Mass Flow Calculation Sheet

PipeName	Mwater	Din	Di in	Re	Pr	hi	Do in	w in	Dl in	U
Annex	16397	3	3.068	169495.1	1.2415	584	3.5	0.216	0.273272	2.99
main2	566422	10	10.02	1792823	1.2415	1180	10.75	0.365	0.86506	2.82
pipe 0	64757	6	6.065	338626.1	1.2415	514	6.625	0.28	0.528407	2.86
Allen Hall	56372	4	4.026	444076.7	1.2415	962	4.5	0.237	0.354884	2.94
Greenhouse	8384	3	3.068	86663.28	1.2415	341	3.5	0.216	0.273272	2.98
main3	501666	10	10.02	1587856	1.2415	1071	10.75	0.365	0.86506	2.81
New AG	110309	6	6.065	576827.7	1.2415	787	6.625	0.28	0.528407	2.86
main4	391356	10	10.02	1238706	1.2415	878	10.75	0.365	0.86506	2.81
S. AG	18047	6	6.065	94369.01	1.2415	185	6.625	0.28	0.528407	2.83
Phase2	52948	4	4.026	417104	1.2415	915	4.5	0.237	0.354884	2.93
main5	320360	8	7.981	1273049	1.2415	1126	8.625	0.322	0.69157	2.84
New CEMR	54272	4	4.026	427531.6	1.2415	933	4.5	0.237	0.354884	2.94
main6	266087	8	7.981	1057378	1.2415	971	8.625	0.322	0.69157	2.84
Library	11869	4	4.026	93500.81	1.2415	276	4.5	0.237	0.354884	2.91
NRCCE	30604	6	6.065	160035.1	1.2415	282	6.625	0.28	0.528407	2.85
main7	223612	8	7.981	888590.4	1.2415	845	8.625	0.322	0.69157	2.83
ERB	26642	6	6.065	139315.4	1.2415	252	6.625	0.28	0.528407	2.84
main8	196970	8	7.981	782720.1	1.2415	763	8.625	0.322	0.69157	2.83

CAC	53734	6	6.065	280984.3	1.2415	443	6.625	0.28	0.528407	2.86
MRB	41706	6	6.065	218087	1.2415	361	6.625	0.28	0.528407	2.85
ESB	101520	6	6.065	530866	1.2415	736	6.625	0.28	0.528407	2.86

3. Aspen Plus Model of Heating System in Engineering Campus