Final Technical Report

Federal Agency and Organization: DOE EERE – Geothermal Technologies Program

Recipient Organization: West Virginia University Research Corporation
DUNS Number: 191510239
Recipient Address: PO Box 6002, Morgantown, WV 26506

Award Number: DE-EE0002745
Project Title: Recovery Act: Analysis of Low-Temperature Utilization of Geothermal Resources
Project Period: 1/29/2010 – 06/30/2014

Principal Investigator: Brian J. Anderson
Associate Professor
brian.anderson@mail.wvu.edu
304-293-9334

Date of Report Submission: June 30, 2015

Project Partners: Cornell University*, Iowa State University*, National Renewable Energy Laboratory (* indicates cost-share partner)

DOE Project Team: DOE Contracting Officer – Arlene Anderson
DOE Project Officer – Ava Norman
Project Monitor – Grant Logsdon

ACCOMPLISHMENTS

Project Summary: Over the project period we successfully completed all three Tasks and 27 Subtasks according to the Statement of Project Objectives. In summary, the three Tasks were:

- Task 1: To perform a techno-economic analysis of the integration and utilization potential of low-temperature geothermal sources. Innovative uses of low-enthalpy geothermal water will be designed and examined for their ability to offset fossil fuels and decrease CO_2 emissions.
- Task 2: To perform process optimizations and economic analyses of processes that can utilize low-temperature geothermal fluids.
- Task 3: To scale up and generalize the results of case study locations to develop a regionalized model of the utilization of low-temperature geothermal resources. A national-level, GIS-based, low-temperature geothermal resource supply model will be developed and used to develop a series of national supply curves.

The final products of this study include 17 publications, an updated version of the cost estimation software GEOPHIRES, and direct-use supply curves for low-temperature utilization of geothermal resources. The supply curves for direct use geothermal include utilization from known hydrothermal, undiscovered hydrothermal, and near-hydrothermal EGS resources and presented these results at the Stanford Geothermal Workshop. We also have incorporated our wellbore model into TOUGH2-EGS and began coding TOUGH2-EGS with the wellbore model into GEOPHIRES as a reservoir thermal drawdown option. Additionally, case studies for the WVU and Cornell campuses were performed to assess the potential for district heating and cooling at these two eastern U.S. sites.

1. Task 1 Analysis of integration/utilization potential of low-T geothermal sources

A primary objective of our research was to identify a strategy for energy- and cost-effective exploitation of EGS reservoirs for generation of electricity and district heat. For this purpose, we developed accurate models of subcritical and supercritical ORC using Aspen Plus V7.0 simulation software. A wide range of 25 working fluids was considered in this analysis. The cycle operating parameters were optimized for each configuration to maximize the utilization efficiency of geothermal resources, which is the ratio of net power output of the cycle to the exergy of the geothermal fluid entering the plant. The remaining performance indicators included thermal efficiency of the cycle, temperature of the reinjected geothermal brine, total heat transfer area of the heat exchangers, volumetric flow ratio of the turbine, its critical nozzle area, and the maximum pressure in the cycle. Apart from thermodynamic merits, working fluids were assessed based on safety and flammability, global warming potential, and ozone depletion potential. The dry working fluids, which are characterized by a retrograde shape of vapor saturation line, were shown to provide the best thermodynamic performance in both recuperative subcritical (ORC) and supercritical (SRC) organic Rankine cycles. By performing a comprehensive ambient temperature sensitivity study, we proved that these fluids perform well in the whole range of ambient temperatures typical for the Eastern U.S. and they are particularly suitable for the cogeneration applications.

Task 1 can be broken down into three major objectives: 1) Analyses of hybrid geothermal/biomass systems, 2) analyses of geothermal drilling costs, and 3) development of reservoir models to simulate low-temperature geothermal systems. In the subsequent sections we summarize the key results and finding for Task 1 as divided into these three objectives.

1.1. Hybrid Geothermal/Biomass Systems

We built a process model and conducted technoeconomic analysis for a biorefinery based on gasification platform. The biorefinery uses corn stover as the feedstock at 2,000 metric tons per day (tonnes/day), which is commercially and economically feasible as determined by a NREL study. The model is based on ASPEN and corresponding economic analysis tools. ASPEN Plus is used for technical analysis to obtain product distributions and related performance data. ASPEN Icarus is used for equipment sizing and costing. A modified NREL economic spreadsheet is used for economic analysis with consideration of DCFROR (discounted cash flow rate of return). The schematic of the overall model is shown in Figure 1.

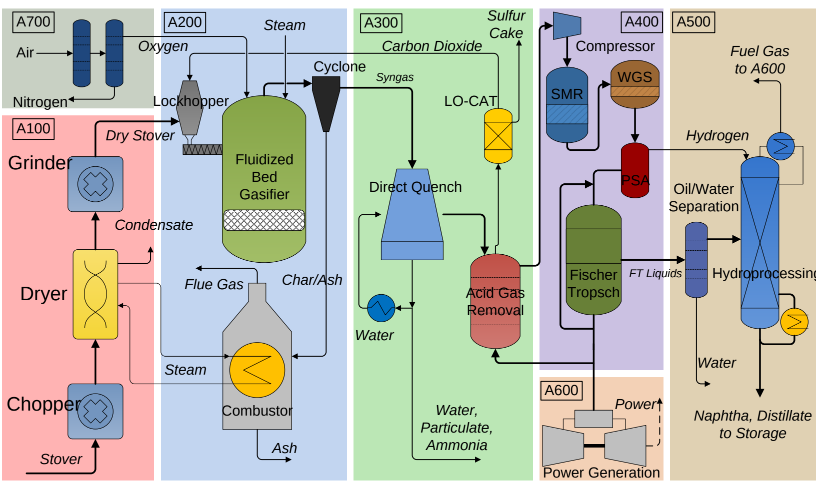


Figure 1: Schematic of ASPEN Plus model for the present biorefinery

Feedstock price is assumed $75 per tonne with moisture of 25%. The fluidized bed gasifier operates at 870°C and 400 psig. The expenses include capital cost and operation cost such as feedstock, utilities, catalyst, steam, water, waste disposal, etc. The internal rate of return is assumed to be 10%. The products of the biorefinery include gasoline, diesel fuel, and electricity. As a result of the technoeconomic analysis, the cost of gasoline-equivalent is $4.83 per gallon for the sustainable operation of the present biorefinery.

In order to utilize geothermal sources, we explored different ways of using geothermal steam at 150°C in this biorefinery. In the current analysis, geothermal steam is used to replace the original steam, which is purchased. There are three possible ways of utilizing geothermal steam in the present setup, including (1) for biomass drying, (2) as a gasifying agent, and (3) for steam reforming. First, in the current model, biomass feedstock is dried from 25% to 8% moisture level using 4,000 tonnes/day steam whose temperature is reduced from 200°C to 120°C. However, the waste steam is recycled and heated using the combustion heat of biochar. As a result, it is determined that geothermal steam will not be used for biomass drying in the present analysis. Second, the present gasifier uses 351 tonnes/day steam at 205°C for gasification. The steam consumption is continuous and thus it is feasible to use geothermal steam for this purpose. Third, steam for reforming is purchased and heated to 870°C before it is used in the reformer. Thus, in this study, geothermal steam is used to replace the purchased steam and heated to 870°C. In summary, it is determined that geothermal steam is used to replace the purchased steam and used in both the gasifier and reformer.

We have investigated possible uses of steam in the production of liquid fuels. We have assumed a target biochemical processing plant for conversion of bio-oil to gasoline and diesel fuel with an equivalent biomass utilization rate of 20,000 tons/day. We envision that this plant will fed by as many as ten smaller distributed pyrolysis plants which produce bio-oil based on a target feedrate of 2000 ton/day of biomass. We have identified two possible insertion points in this system, including the use of low-grade steam for biomass drying and for hydroprocessing. Assuming that a well can deliver 50 kg/s of steam at 150°C and the waste steam is 120°C, we find that such a well could serve the needs of a 200 ton/day pyrolysis plant, which is roughly 1/2 the size of the current largest biorefinery and 1/10 the size of the target plant of 2000 ton/day. If the waste steam temperature is reduced, then the capacity would increase, but in either case, such an application would require multiple wells. With regard to hydroprocessing, one such well could serve the needs of a 20,000 ton/day (biomass equivalent) biochemical processing plant for converting bio-oil to gasoline and diesel.

The technoeconomic analysis of a biorefinery based on biomass gasification was conducted. A number of methods are devised to utilize geothermal energy in the biorefinery. It is found that geothermal energy can potentially be used in a biorefinery for various purposes. In this study, geothermal heat is used to generate steam which in turn replaces the purchased steam for gasification and steam-methane reforming. The resulting fuel price utilizing geothermal energy is slightly higher but still comparable to that of the baseline conditions. Excess, unused geothermal energy can also be used in an organic Rankine cycle to generate electricity to add profits to the biorefinery. Overall, the cost of fuels produced by utilizing geothermal energy ranges from $5.17 to $5.48 per gallon gasoline equivalent compared to $5.14 of the baseline condition. The above costs are based on the 2012 cost year. The major motivation to integrate geothermal energy into a gasification-based biorefinery appears to be the reduction in greenhouse gas emissions resulting from steam production using fossil fuels. The advancement in the drilling technology together with appropriate government incentives can further enhance the feasibility of utilizing geothermal energy for biofuel production.

For more details see:

- Sudhanya Banerjee, Jordan A. Tiarks, Maciej Lukawski, Song-Charng Kong, and Robert C. Brown, "Technoeconomic Analysis of Biofuel Production and Biorefinery Operation Utilizing Geothermal Energy," Energy and Fuels, 27, 1381−1390, 2013.

Banerjee_EnergyFuels_2013.pdf

1.2. Drilling Cost Models

We evaluated the current and historical drilling costs of oil and gas wells and compared them with geothermal wells drilling costs. Based on API Joint Association Survey 1976-2009 data we developed a drilling cost index for U.S. onshore oil and gas wells. The Cornell Energy Institute (CEI) index describes year-to-year variations in drilling costs and allows us to express the historical drilling expenditures in current year dollars. The CEI trend consists of nine sub-indices for different well depth intervals and has been corrected for yearly changes in drilling activity. The CEI index shows 70% higher increase in drilling cost between 2003 and 2008 compared to commonly used Producer Price Index (PPI) for drilling oil and gas wells. Cost trends for various depths are proven to be significantly different. Behavior of the CEI index is explained based on oil and gas prices, cost, and availability of major well components and services.

Multiple methods were used to infer the cost-depth correlation for geothermal wells in current year dollars. In addition to analyzing reported costs of the most recently completed geothermal wells, we investigated the results of the predictive geothermal drilling cost model WellCost Lite. Moreover, a cost database of 129 historical geothermal wells has been assembled. The CEI index was used to normalize costs of these wells to current year dollars. A comparison of normalized costs of historical wells with recently drilled ones and WellCost Lite predictions shows that cost escalation rates of geothermal wells were considerably lower compared to hydrocarbon wells. Besides evaluating the average well costs, this work investigates economic improvements resulting from increased drilling experience. Learning curve effects related to drilling multiple similar wells within the same field were examined.

The drilling operators are pursuing deeper and more difficult to extract resources. Improved drilling technology has reduced the rate at which drilling cost increases with depth. The current average onshore drilling cost is described as a power function of a measured well depth. Drilling expenditures incurred in various years can be compared using a drilling cost index. The CEI cost index accounts for yearly changes in depth and type of U.S. onshore wells. The CEI trend offers superior accuracy and the longest lifespan (1976-2009) among available oil and gas well drilling cost indices. It shows that oil and gas well completion costs increased by over 250% between 2003 and 2008, followed by a modest 15% drop in 2009 (see Figure 2).

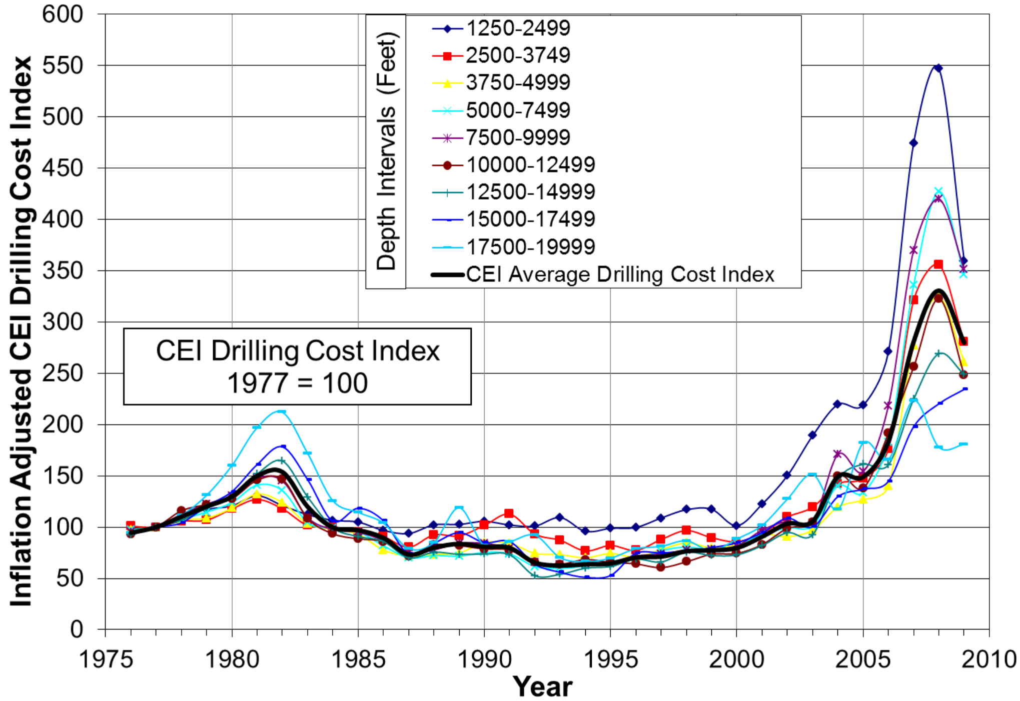


Figure 2 CEI and CEI Average drilling cost indices (1977 = 100). Both indices are adjusted for inflation using GDP deflator and changes in drilling activity.

The statistical analysis of learning potential in hydrocarbon drilling estimated the average onshore development wellbore to be 8% cheaper than the exploratory well of the same depth (see Figure 3). This number is likely to be higher if the diameter of a development well is higher or its casing program is more complex.

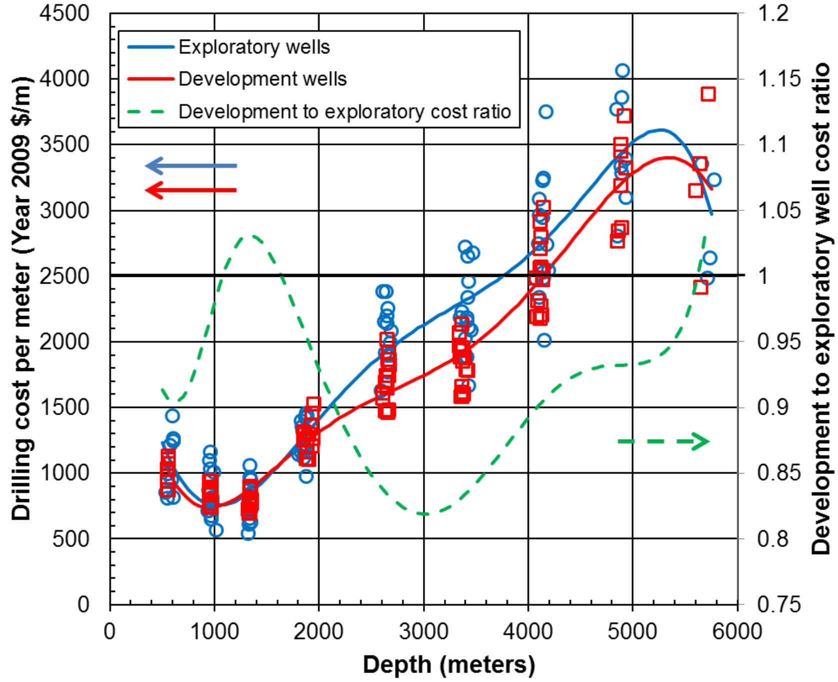
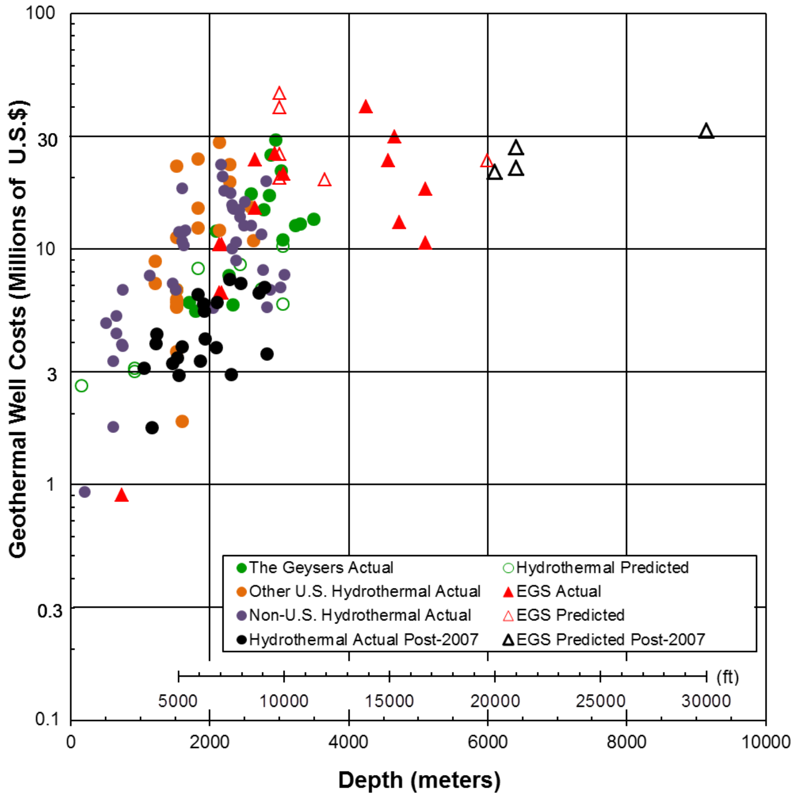


Figure 3 Average drilling costs per meter of exploratory and development wells. Correlation is based on 1989-2009 JAS data. Costs of onshore oil and gas wells were normalized to 2009 using the CEI drilling cost index.

Despite the increased complexity of geothermal wellbores compared to hydrocarbon wells, the costs of both are similar. The drilling cost index based on oil and gas wells proved unsuitable for geothermal wells. Significant progress in geothermal drilling technology resulted in much lower cost escalation rates over the last 35 years compared to hydrocarbon exploration.



1. Pre-2007 geothermal well costs were updated to US$ (yr. 2009) using CEI drilling cost index based on JAS (1976-2009) for onshore, completed US oil and gas wells.
2. Costs of post-2007 geothermal wells were not normalized to yr. 2009 and are presented in nominal US$ (2008-2012).

Figure 4 Geothermal well drilling costs as a function of measured well depth.

For more details see:

- Maciej Z. Lukawski, Brian J. Anderson, Bill Livesay, Chad Augustine, Louis E. Capuano Jr., and Jefferson W. Tester, "Drilling Cost Analysis of Oil, Gas, and Geothermal Wells,", Journal of Petroleum Science and Engineering, 118, pages 1-14 2014.

Lukawski, Drilling Costs.pdf

1.3. Reservoir Model Sensitivity Analyses

Low-temperature geothermal reservoirs using EGS technology to increase the permeability to geothermal fluids can be used for residential as well as commercial space heating, thus, reducing the carbon footprint of space heating compared to using natural gas or other fossil resources. The eastern United States generally has lower temperature gradients than the western United States; However, West Virginia, in particular, has higher temperature gradients compared to other eastern states. A recent study at Southern Methodist University by Blackwell et al. has shown the presence of a hot spot in the eastern part of West Virginia with temperatures reaching 150°C at a depth of between 4.5 and 5 km. This study examines a reservoir at a depth of around 5 km resembling the geology of West Virginia, USA. The temperature gradients used are in accordance with the SMU study.

In order to assess the effects of the reservoir conditions on the lifetime of a low-temperature geothermal system, we have performed a sensitivity analysis study on seven natural and human-controlled parameters within a geothermal reservoir: reservoir temperature, injection fluid temperature, injection flow rate, porosity, rock thermal conductivity, water loss (%) and well spacing. The sensitivity analyses used two different methods of parameter variation, ‘One Factor At a Time (OFAT) method’ and a Plackett-Burman design. For both the OFAT and Plackett-Burman designs, all seven of the parameters mentioned above were used. The OFAT method was performed by changing one parameter at a time, while keeping the rest at constant base case values. A 30-year timeframe of operation was used to run the reservoir simulations using TOUGH2 numerical simulation software developed at the Lawrence Berkeley National Laboratory using the EOS1 equation of state module for pure water. A porous medium approach was taken to design the reservoir. For the full-parameter sensitivity analysis, a two-level (L=2) Plackett-Burman experimental design was used, with the cumulative hot water production discounted to the current year as the measured variable for comparison. The discount rate chosen was 5% (to illustrate direct-use systems incorporated into public utilities), resulting in the contribution to the net present value of a reservoir. The effects of the parameters on the real and discounted production rates were assessed in this analysis.

The results of this study provide a preliminary assessment of the effects of various reservoir parameters on the economic viability of low-temperature geothermal utilization. They also provide a comparative approach between the parameters for the optimized exploitation of a reservoir. As expected, the initial reservoir temperature has the most significant effect on the reservoir productivity. A number of issues regarding the engineering, economical factors and the reservoir properties need to be addressed while setting up a geothermal plant. Among these, the reservoir properties form a pre-requisite. Thus, having an understanding of the parameters which can be beneficially exploited forms the basis of further research. The main objective of this paper, as stated before, is to achieve that understanding of the effects geothermal reservoir parameters on discounted heat production.

As it was expected, the reservoir temperature is the most important parameter to affect the production. It is a natural property of a reservoir, which cannot be altered, thus making it a decisive factor. This is proven from both the OFAT and PB design.

From the OFAT analysis, we can conclude that the variation in porosity and rock thermal conductivity does not affect the reservoir performance significantly. The Plackett-Burman analysis proves the same results. However, a reservoir with higher porosity provides ease of operation and does not require advanced engineering or EGS. The trade-off is between having a higher porosity and using the EGS technology. Higher costs of EGS can make a high porosity condition more favorable for the reservoir operation, because EGS technology is not yet economical in most cases. In fractured reservoirs, the rock thermal conductivity is not a highly sensitive parameter as the dominant force is again the fluid convection, but these reservoirs will offer ease of fluid flow and improved porosity.

The injection flow rate is a human-controlled parameter, while water loss can be controlled to some extent. The demand of hot water is the main factor, which affects these parameters. For a higher demand, higher injection flow rate with a minimum water loss is desired, but it will hasten the exhaustion of the reservoir. These two parameters are limited by the available reservoir. Thus, they can be manipulated once the reservoir analysis is complete.

Higher injection fluid temperatures decrease the amount of heat being extracted from a reservoir. It is a negative effect parameter of significant strength. Larger well spacing provides a larger reservoir volume for the extraction of heat. Thus, the productivity increases with the increase in the well spacing, but it is not as strong of a factor as reservoir temperature or injection flow rate.

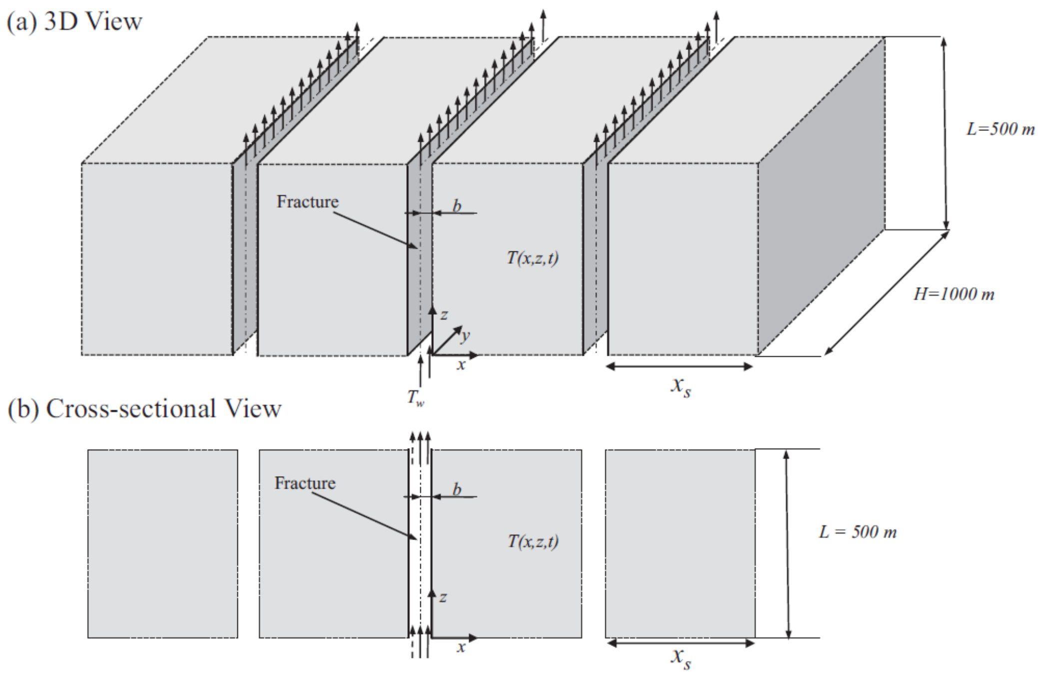


Figure 5 Conceptualized multifracture EGS reservoir. (a) Three-dimensional view of the multifracture EGS reservoir. x_s represents the spacing in between fractures. (b) Reduced two-dimensional view.

Although many natural hydrothermal geothermal systems have been shown to be productive over long periods of time, limited field testing of Enhanced or Engineered Geothermal Systems (EGS) has prevented adequate assessment of their sustainability. To estimate how renewable EGS reservoirs might be, an analytical approach employing Green's function was used to model transient thermal conduction in an idealized reservoir containing a single rectangular fracture to evaluate heat transfer effects during alternating periods of extraction and recovery. During recovery, the temperature along the fracture surface approaches the temperature of the bulk rock with the deviation from the surrounding bulk temperature decaying as $1/\sqrt{t}$ where t is the recovery time. Numerical simulations of a multiple parallel fracture reservoir using the TOUGH2 code agreed with the derived analytical solutions over a range of flow rates and interfracture spacings with only small deviation due to multidimensional effects.

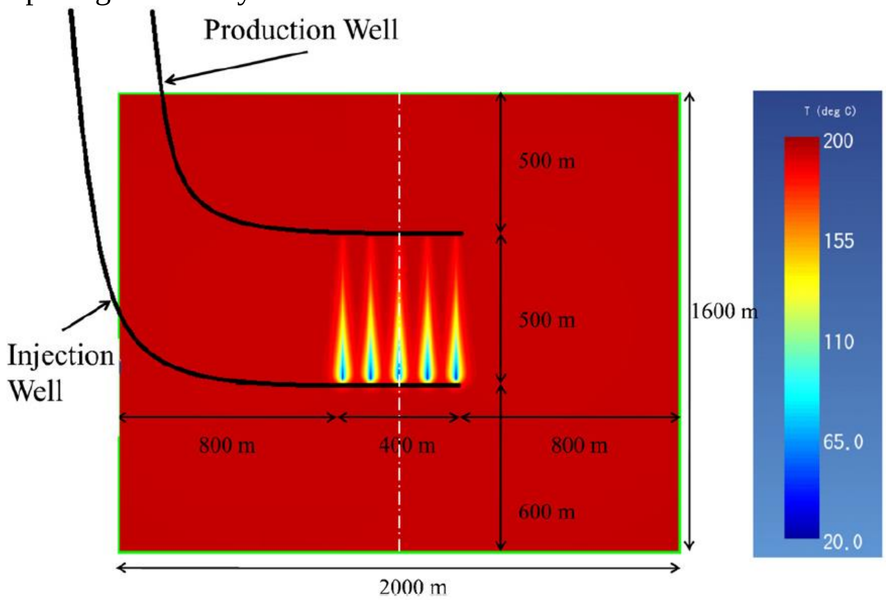


Figure 6 The simulation space used in TOUGH2. The dashed line down the middle indicates symmetry and thus only one side of the reservoir needs to be simulated. The presented reservoir has 5 fractures and has already undergone 10 years of extraction

Multidimensional effects are more pronounced near the inlet and outlet of the fracture and are reduced at higher flow rates. Thermal interactions between sufficiently spaced fractures are negligible for production periods of 10–30 years, suggesting that the single fracture analytical model can be applied to multifracture reservoirs provided that the mass flow used is on a per fracture basis. Simulation results show that multifracture EGS reservoirs have a greater capacity to sustain high outlet temperatures, suggesting that conductively dominated EGS systems can be regarded as renewable over time scales of societal utilization systems (three to five times the heat extraction time).

For more details see:

- Madhur Bedre and Brian Anderson, “Sensitivity Analysis of Low-Temperature Geothermal Reservoirs: Effect of Reservoir Parameters on the Direct Use of Geothermal Energy,” GRC Transactions, Vol. 36, 2012.

Bedre_GRC_2012.pdf

- Fox, Don B., Sutter, Daniel, Beckers, Koenraad F., Lukawski, Maciej Z., Koch, Donald L., Anderson, Brian J., Tester, Jefferson W., "Sustainable heat farming: Modeling extraction and recovery in discretely fractured geothermal reservoirs" Geothermics, 46, 42-54, 2013.

  Fox, et al, 2013 - Sustainable heat farn

- Nandanwar, M., and Anderson, B.J., "Coupled Reservoir, Wellbore, and Surface Plant Simulations for Enhanced Geothermal Systems", Proceedings of the Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202

  SGP-TR-202_Nandanwar.pdf

2. Task 2 Process optimization and economic analysis

Task 2 included two major objectives: 1) the development of a detailed geothermal cost model, GEOPHIRES, and 2) the analysis of three case study sites at the campuses of WVU, Cornell, and Iowa State University.

2.1. GEOPHIRES - GEOthermal energy for the Production of Heat and Electricity Economically Simulated

A new computer-based model has been developed to evaluate the levelized cost of electricity and/or direct-use heat from Enhanced Geothermal Systems (EGS). This software upgrades and expands the “MIT-EGS” model used in the 2006 “Future of Geothermal Energy” study. The upgrades include implementation of the latest geothermal well drilling and power plant cost submodels as well as incorporation of production wellbore heat losses. The main expansion consists of implementing different end-uses, i.e. electricity, direct-use, or combined heat & power (CHP). The new model “GEOthermal energy for the Production of Heat and Electricity Economically Simulated” (GEOPHIRES) can be used either as a stand-alone program or as a subroutine to be called from another program, e.g. MATLAB. GEOPHIRES has the option to either simulate an EGS reservoir and power plant for given parameters, or optimize their design, operating parameters and drilling depth to yield minimum levelized cost. Two case studies were analyzed. The first one provides an estimate of the levelized cost of electricity and direct-use heat with EGS, which is compared with predictions from the widely used GETEM (Geothermal Electricity Technology Evaluation Model). The second case study develops a supply curve for geothermal energy district heating using EGS for the states of New York and Pennsylvania – which are representative areas for low-enthalpy geothermal energy resources in the U.S.

In order to assess the economic feasibility of an Enhanced Geothermal System (EGS), a software tool was developed which combines reservoir and surface plant simulations with capital and operation & maintenance (O&M) cost predictions to estimate the levelized cost of electricity (LCOE) and/or heat (LCOH) with an EGS. This software tool is built upon the "MIT-HDR" model, developed at the MIT Energy Laboratory (Tester and Herzog, 1990 and 1991; Herzog et al., 1997); in 2000 upgraded into the "EGS Modeling for Windows" program (Kitsou et al., 2000) and in 2006 upgraded into the "MIT-EGS" model for the "Future of Geothermal Energy" study (Tester et al., 2006). The upgrades and expansions from the "MIT-EGS" model include (1) the evaluation of direct-use heat and combined heat & power (CHP) in addition to electricity; (2) inclusion of a standard discounted cash flow economic model besides a fixed annual charge rate model (FCR), and the BICYCLE model (Hardie, 1981); (3) the option to specify thermal drawdown with an annual percentage temperature decline besides the parallel fractures model, the 1-D linear heat sweep model and the $\dot{m}$/A thermal drawdown parameter model; (4) the simulation of production and injection wellbore heat transmission using Ramey's model (Ramey, 1962); (5) updated drilling and surface plant costs; and (6) the conversion of the GUI programming language from Visual Basic 6 into the .NET framework environment.

In order to reflect the major changes with respect to previous versions, the software tool has been renamed GEOPHIRES ("GEOthermal energy for the Production of Heat and Electricity Economically Simulated"). Our software tool differs from the widespread GETEM (Geothermal Electricity Technology Evaluation Model) program (Mines, 2008). It builds in system optimization capabilities, simulates direct-use heat or CHP utilization, and can be used either as stand-alone software or as subroutine in a larger user-developed program.

In GEOPHIRES, the EGS resource, reservoir, and surface plant are characterized by a set of 96 parameters (although not all are used simultane-ously). They are grouped into 7 different categories:

1. Resource parameters (geothermal gradient segments, rock thermal conductivity, rock density, …)
2. Engineering parameters (well depth, well diameter, end-use product, …)
3. Reservoir parameters (well separation, reservoir impedance, drawdown model, …)
4. Financial and operating parameters (project lifetime, capacity factor, interest rate, …)
5. Capital cost parameters (drilling costs, reservoir stimulation costs, …)
6. O&M cost parameters (wellfield O&M costs, make-up water costs, …)
7. Optimization parameters (initial guess and lower and upper limit for a total set of 9 parameters when GEOPHIRES is used in optimization mode)

Using these parameters, GEOPHIRES first simulates the production wellhead temperature over the lifetime of the plant, then calculates the annual generation of the end-use product and finally, combined with the capital and O&M costs, estimates the levelized cost of electricity and/or heat. The model is written primarily in FORTRAN 90, with some legacy parts of the code in FORTAN 77. The GUI is implemented in VB 9.0 under the .NET Framework 3.5. Currently, GEOPHIRES v1.0 is only available for the Microsoft Windows platform. Figure 7 shows a screenshot of GEOPHIRES with the input screen for the engineering parameters. The following subsections explain in detail how specific components of the model work.

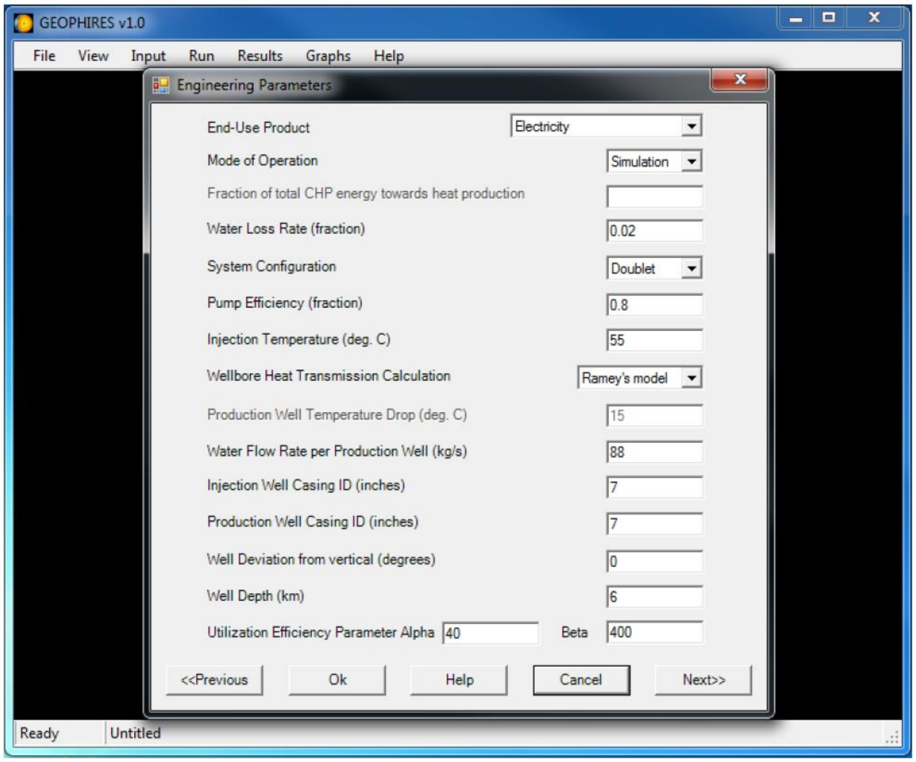


Figure 7 Screenshot of GEOPHIRES Graphical User Interface with engineering parameters input screen.

2.1.1. Geothermal Energy End-Use Options

In GEOPHIRES, the user can choose from 3 end-use applications: electricity, direct-use heat and CHP. For the electricity option, all the geothermal heat is converted into electricity. The levelized cost of energy is calculated as the levelized cost of electricity (LCOE) in cents/kWh. For the direct-use heat option, no heat-to-power conversion takes place at the surface and the levelized cost of energy is expressed as levelized cost of heat (LCOH) in $/MMBTU. For the CHP option, the user can choose between three configurations: (1) topping cycle (high temperature electricity production in series with low temperature direct-use heat utilization), (2) bottoming cycle (high temperature direct-use heat utilization in series with low temperature electricity generation) or (3) parallel cycle (production fluid splits into two parts to meet direct-use heat and electricity cycle requirements at same temperature).

For the levelized cost of energy in CHP mode, GEOPHIRES has the option to either consider the produced heat as operating income and calculate the LCOE, or to consider the electricity as operating income and calculate the LCOH, or to calculate both the LCOH and LCOE with each end-use product attributed their fraction of the shared capital and O&M costs based on the energy consumption of the geothermal fluid.

Geothermal fluid pumping power is subtracted from the total produced electricity in the electricity and CHP mode, and it is considered an operating expense with a user-defined electricity price in direct-use heat mode.

2.1.2. Reservoir Thermal Simulation Models

Four models are available in GEOPHIRES to simulate the reservoir thermal drawdown: (1) The user defines the thermal drawdown in percentage temperature drop per year. This option is equivalent to the reservoir thermal simulation model in GETEM; (2) The reservoir is modeled using the 1-D linear heat sweep model (Hunsbedt et al., 1984) which assumes 1-D uniform flow through a fractured reservoir; (3) The reservoir is modeled as an infinite series of parallel, equidistant, and planar fractures with 1-D thermal conduction in the rock and 1-D uniform fluid flow in the fractures (Gringarten et al., 1975); (4) The user defines a thermal drawdown parameter as mass flow rate per unit area of an individual fracture. This model was utilized in early HDR reservoir modeling as reported by Armstead and Tester (1987).

2.1.3. Levelized Cost Economic Models

The user can choose between 3 economic models in GEOPHIRES to calculate the levelized cost of energy: (1) The fixed annual charge rate (FCR) model assumes a constant charge rate on the capital costs and no time-dependant value (discount) for invested capital. Different methods exist to estimate the FCR based on several economic parameters including rates of return on equity capital, debt interest rates, and depreciation (Edwards et al., 1982); (2) The standard levelized cost model is utilized, discounting future expenses and income back to the present and assumes a constant discount rate.

Two case studies were examined to test GEOPHIRES. In the first case study, we used GEOPHIRES as stand-alone program and calculated a currently unattractive LCOE but competitive LCOH for medium-grade EGS resources. These results highlight the potential of EGS for direct-use applications in the Eastern United States. In the second case study, we used GEOPHIRES as a subroutine to develop supply curves for geothermal district heating systems in New York State and Pennsylvania. We found that up to 20GWth of installed capacity of geothermal district heating systems can be provided in the mid-term with an LCOH around 15 $/MMBTU. As expected, model results are clearly dependent on assumptions directly related to assumed reservoir performance, resource quality, and a wide range of economic parameters, including drilling and plant capital costs and financial parameters.

For more details see:

- Beckers, K., Lukawski, M., Reber, T., Anderson, B., Moore, M., Tester, J., "Introducing GEOPHIRES V1.0: Software Package For Estimating Levelized Cost of Electricity and/or Heat from Enhanced Geothermal Systems", Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198

  SGP-TR-198_Beckers.pdf

- Koenraad F. Beckers, Maciej Z. Lukawski, Brian J. Anderson, Michal C. Moore and Jefferson W. Tester, "Levelized Costs of Electricity and Direct-Use Heat from Enhanced Geothermal Systems (EGS)" *The Journal of Renewable and Sustainable Energy*, 6 (1), 013141, 2014.

1.4865575.pdf

2.2. Campus Case Studies

Detailed case studies were performed to give extensive analyses for the two campus sites. The two campus sites provide significant differences in the types of heating systems, varying loads, and widely different cooling systems. The WVU system has a central steam generation system, but the WVU system is not owned by the University. Unlike the Cornell campus site, WVU uses a significant number of absorption chiller systems allowing for more year-round utilization of geothermal heat. The Cornell campus site employs a university-owned central steam system that may allow for simultaneous usage of geothermal and biomass and a lake-source cooling system.

2.2.1. West Virginia University case study

In 2010, Frone, Richards, and Blackwell at Southern Methodist University (SMU) Geothermal Lab identified elevated geothermal temperatures in West Virginia. With the updated data from oil and gas field, the new temperature profile is significantly higher than the previously estimated in the MIT report – *The Future of Geothermal Energy* (Tester, et al., 2006). The high temperature geothermal region extends from the north central WV i.e. from Monongalia County where WVU is located, to Greenbrier County in the southeastern WV. This part of the study evaluates the potential to develop the EGS based GDHC systems in the state of West Virginia, beginning with a case study on West Virginia University campus.

The geologic cross section *D-D'* (Ryder, et al., 2009) from the U.S. Geologic Survey is the nearest geologic cross section to illustrate the geologic framework at WVU, as shown in Figure 8, which suggests no massive aquifer layer beneath WVU. WVU is located about 20 km north of the well (API 47-049-00244) owned by the Phillips Petroleum Company, as shown in Figure 8. The 100-meter-thick Tuscarora Sandstone at depth 3.3 km (10000 feet) is of interest, as the successful EGS project at Gross Schoenebeck in Germany also has very similar geologic conditions with that of West Virginia, as shown in Table 1. The wells at Gross Schoenebeck were successfully stimulated by massive water fracture treatment which is a common reservoir fracturing method in oil industry, and an economical productivity was reached for a 70 kW geothermal power plant. The 30-meter-thick Oswego Sandstone at depth 3.6 km (12000 feet) is also of interest. The Oswego formation extends along the Appalachian basin to the central New York state where horizontal wells have been drilled, making it the fourth largest natural gas production formation in the state of New York (NYSDEC, 2011), suggesting that sufficient permeability may also be reached with proper stimulation at WVU.

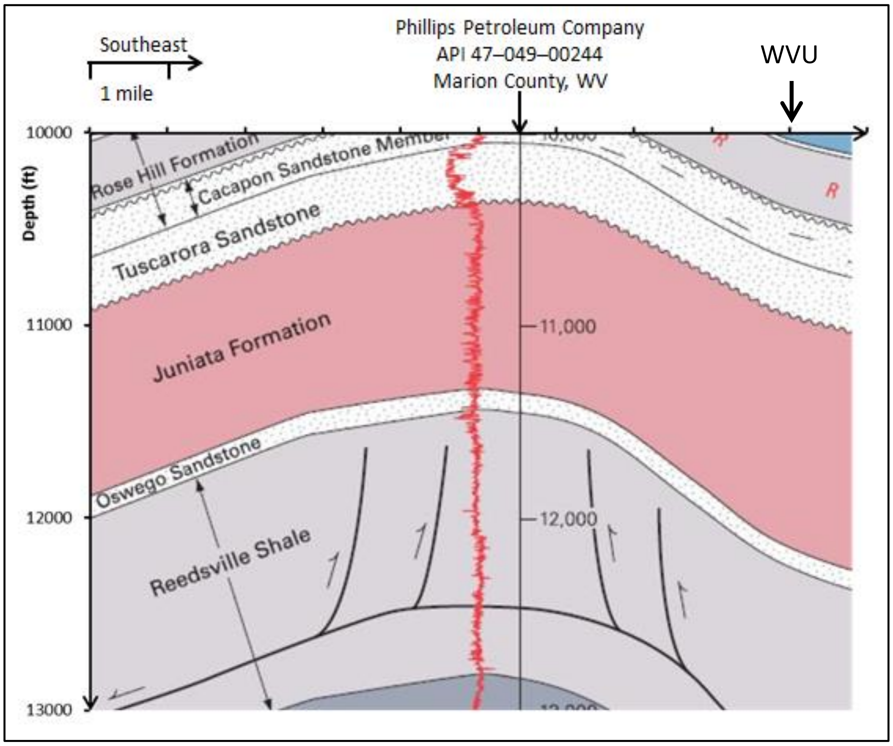


Figure 8 Geologic formations near Morgantown, WV at depth of 3 to 4 km, the Tuscarora and Oswego Sandstone are of interest for GDHC development.

Table 1: Comparison of the geologic conditions between Gross Schoenebeck and Morgantown, WV, data from Hurter, et al. (Hurter, et al., 2002) and Castle and Byrnes (Castle and Byrnes, 2005).

	Rock Type	Depth, m	Average Permeability, mD	Average Porosity, %
Gross Schoenebeck	Conglomerates	4200 to 4230	0.003	4.8
	Volcanics	4230 to 4294	0.005	4.3
WVU	Tuscarora Sandstone	3200 to 3350	0.0048	6.8

To ensure comprehensiveness and accuracy, three other sub-cases were also solved for different economic environments. Case I estimated the LCOH for a general EGS based GDHC system. Case II considered certain tax preferential regulations and incentives for a renewable energy project. On the basis of Case II, Case III solved the LCOH exclude the surface facility operation and maintenance costs. It is because currently the university is purchasing steam from the steam company at $ 12/MMBtu, which also does not account for the surface operation and maintenance costs. Thus, the LCOH calculated in Case III was used to compare with this steam cost.

Geothermal temperature maps were generated by collaborating with the SMU Geothermal Lab. Figure 9 shows the geothermal temperature map of WV at 4.5 km. To interpolate geothermal temperatures at other locations, the inverse distance weighted method was used and achieved by ArcGIS, which assumed the temperatures for the locations that are close to one another are more alike than those that are farther apart. Such an algorithm gives a more accurate estimation if the sample data is densely located. At 4.5 km, geothermal temperature in Morgantown is in the range of 130 to 150°C. The geothermal gradient at WVU was calculated to be 26.5°C/km.

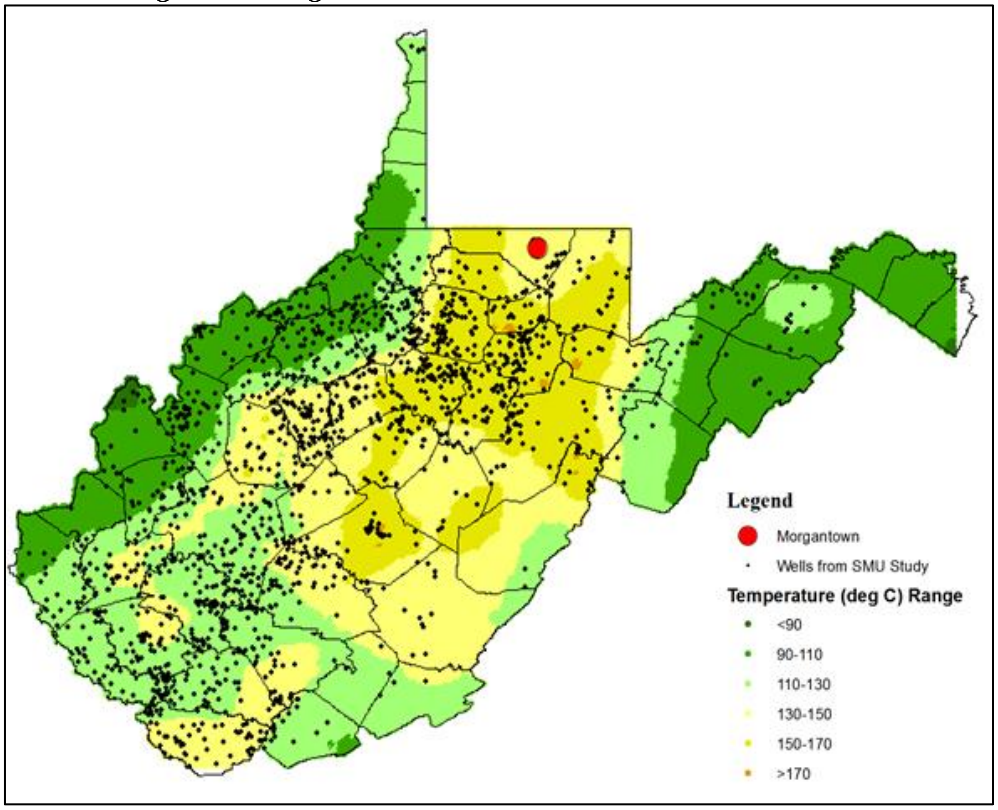


Figure 9 Geothermal temperature map of West Virginia at 4.5 km, black dots show the locations of oil and gas wells from which SMU updated their temperature profiles.

With geothermal gradient at 26.5°C/km and surface temperature at 10°C, drilling depths for case 1, 2, 3, 4, and 5 were calculated to be 5.67 km, 5.25 km, 4.16 km, 3.23 km, and 2.65 km, respectively. With the maximum flow rate of one production well at 50 kg/s, the number of wells including injection and production were calculated to be 2, 2, 3, 3, and 4 for each case. Overall drilling costs were calculated to be $39.92, 36.67, 45.21, 39.48, and 48.35 million, respectively. The O&M cost of the reservoir field was estimated at $1.79 million per year for all the five cases.

The levelized cost of heating is estimated as $14.33/MMBtu, which is higher than cost of the current steam based heating and cooling system at $12/MMBtu. To further decease the LCOH, cascading applications to decrease the return temperature should be considered, such as geothermal based green house, or using geothermal heating for snow melting under pathways and for the tracks of the university personal rapid transition (PRT) system. In addition, increasing maximum flow rate of the production well is also recommended with improved well field technology in the near future. If a lower return temperature can be achieved at 30°C, and the maximum flow rate can be achieved at 65 kg/s, LCOH for the WVU GDHC system can be as low as $13.61/MMBtu.

For more details see:

- He, Xiaoning, Anderson, Brian J., "Low-Temperature Geothermal Resources for District Heating: An Energy-Economic Model of West Virginia University Case Study," Proceedings of the Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28-30, 2012, SGP-TR-194

  He_SGW_2012.pdf

- Xiaoning He, "Feasibility and Supply Analysis of U.S. Geothermal District Heating and Cooling Systems", PhD Thesis, West Virginia University

  He Thesis.pdf

- Xiaoning He and Brian Anderson, "Techno-Economic Assessment of a Geothermal District Heating and Cooling System: A Case Study of West Virginia University," Report, 2013

  WVU case study.pdf

2.2.2. *Cornell University Geothermal Case Study*

An extensive analysis of geothermal energy integration at Cornell University was performed to evaluate the potential of supplementing Cornell's energy system with heat extracted from the earth using Enhanced Geothermal Systems (EGS) technology. EGS are deep subsurface reservoirs that have been created to extract economical amounts of heat from low permeability and porosity rock formations. High availability of medium- and low-grade geothermal energy in the form of EGS and ongoing improvement of heat mining technologies are main reasons substantiating the present study.

This study evaluated a hybrid energy production system as a step towards a sustainable future. We examined the benefits of the synergy between renewable and conventional energy resources. To do this, we designed and analyzed a case study of a hybrid energy system at the Ithaca campus of Cornell University. Cornell University's buildings and facilities provide a representative model of a distributed energy system for mid–sized communities of about 30,000 people. Cornell's location in a relatively high grade EGS region for the Northeastern U.S.

provides a further opportunity to evaluate the potential of using low enthalpy geothermal for district heating. To evaluate the feasibility of geothermal energy at Cornell, we analyzed the implementation of EGS in the existing Cornell infrastructure. The proposed hybrid cogeneration plant combines the existing infrastructure of the natural gas combined heat and power (CHP) plant with EGS and torrefied biomass boiler supplementing a fraction of the peak heat demand. Key steps of our analysis are to:

1. Identify and characterize existing heat and electricity generation systems.
2. Examine energetic characteristics of introducing geothermal energy into the existing campus energy supply system.
3. Evaluate the performance and economic aspects of heat and electricity provided by the proposed CHP-EGS-biomass hybrid systems at Cornell.
4. Estimate environmental effects of transitioning to an EGS energy supply system.

We have considered several cases in how EGS could be implemented. Apart from providing a buffer from fuel and electricity costs, it also leads to better energy utilization through heat cascading applications. In addition, the designed system opens multiple pathways for transitioning to a net zero carbon emissions plant. We developed metrics to assess the economic performance of EGS, and calculated expected reduction in greenhouse gases (GHG) emissions.

The use of EGS can substantially reduce both fossil energy consumption and carbon emissions of the Cornell University campus. Although implementation of EGS yields 10 to 23% increase in the LCoE in today's low gas price market, it leads to a pathway of becoming independent from natural gas prices, amongst other external factors. Our results show that the use of EGS can lower natural gas consumption by 20 to 31%, which results in a net CO_2 emissions reduction ranging from 13 to 31%.

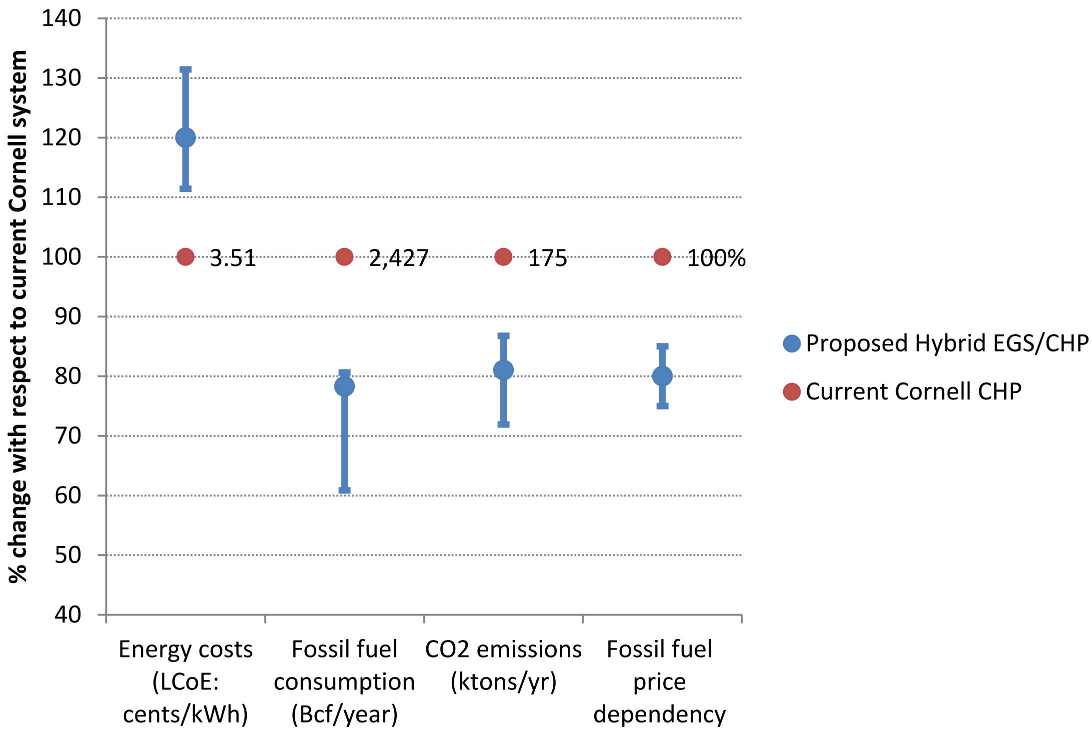


Figure 10 Summarized results of the proposed hybrid EGS/CHP system at Cornell University. Values are normalized to the current Cornell CHP plant.

Implementing EGS adds complexity but also flexibility to the Cornell energy generation system. Similarly to any complex system, interfaces become increasingly important, as addition of geothermal system affects the CHP operation. However, strengthening synergies and awareness of the limitations can result in greater gains.

Major recommendations

The main recommendation of this report is that Cornell should take action sooner rather than later in order to achieve the goal of transforming the campus into a less environmentally intrusive entity. Geothermal energy utilization using EGS technology provides a viable option but it will take several years to be implemented. Action should be taken now to provide time required for thorough geologic and geophysical surveys, environmental risk assessment and regulatory approvals required to create a successful EGS plant.

Most importantly, such an investment would place Cornell University at the forefront of sustainable energy development providing a model to emulate other academic institutions and communities. Clean energy generation is proven to be feasible, but requires case specific analysis to effectively result in mitigation of climate effects while also being an economically viable investment.

Transitioning to a cleaner future requires a multidisciplinary team approach with conventional power production coupled to renewable energy supply from geothermal, biomass, solar and other renewable resources. In addition, it is very beneficial to investigate the production side in tandem with the distribution and demand side. Efficient district heating network, low-temperature space heating systems, micro grids and building control systems can reduce the primary energy consumption. It is very important for the energy systems to be viewed holistically, making sure transitions interface and support each other in the most efficient manner, possibly under the guidance and planning of an umbrella organization.

For more details see:

- Maciej Z. Lukawski, Konstantinos Vilaetis, Lizeta Gkogka, and Jefferson W. Tester, "Hybrid Geothermal Energy Utilization - a Case Study of Combined Heat and Power (CHP) and Enhanced Geothermal System (EGS) at Cornell University," Report, 2013.

  Cornell Case Study.pdf

- Lukawski, M., Vilaetis, K., Gkogka, L., Beckers, K., Anderson, B., Tester, J., "a proposed hybrid geothermal - natural gas - biomass energy system for Cornell University. Technical and economic assessment of retrofitting a low - temperature geothermal district heating system and heat cascading solutions", Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198

  SGP-TR-198_Lukawski.pdf

2.2.3. Analyze organic binary Rankine cycles configuration performance

The cumulative work produced using ORC and SRC with initial wellhead temperature ranging from 120°C to 200°C was calculated for each of the considered working fluids. We proved that the choice of working fluid in EGS geothermal power plants will most likely be different than for the units utilizing high-grade hydrothermal resources. The selection of fluid will often be determined by the lower bound for heat source temperature set by the exhaust vapor quality requirements.

Extremely detailed optimizations of low-temperature electricity generation using various binary fluids have been completed. A presentation on this task was presented at the 2012 GRC. For a gasification case, simulations were carried out for conditions of 21%, 30%, 40% and 50% oxygen levels in the gasifying agent on wet basis. Different types of biomass feedstock are used for the study, including various woody biomass and corn stover. Due to the differences in feedstock composition and operating conditions, the syngas composition varies and the model is able to predict these variations. The simulation results agree well with experimental data that show increases in hydrogen and carbon monoxide as the oxygen level increases in the gasifying agent.

3. Task 3 Regionalization/generalization and scale-up of results

We developed a regional and national-level GIS tools for the assessment of low-temperature geothermal resources. This effort was concentrated on the assessment of hydrothermal resources, both known and undiscovered, and EGS resources. These resource estimates were coupled with determined demand-side centers to calculate a supply curve for direct-use geothermal energy utilization using low-temperature geothermal resources. A Monte Carlo method was applied to estimate and propagate the uncertainty in the resource availability, resource quality, and demand-side characteristics.

3.1. State and Regional Utilization

Recently published geothermal maps in New York, Pennsylvania, and West Virginia have shown the availability of temperatures for direct thermal use applications at economical drilling depths shallower than 6 km (Shope et al., 2012; Stutz et al., 2012). However, uncertainties in resource assessment coupled with expected high drilling costs for deeper wells often restrict the feasibility of low grade geothermal resources. Our study focuses on utilizing new methodology developed in collaboration with Southern Methodist University (SMU) to quantify the uncertainties associated with the assessment of geothermal heat flow in New York, Pennsylvania, and West Virginia, with the possibility of applying these techniques to thermal gradient and temperature-at-depth maps.

A thorough statistical and spatial analysis of the variability and the uncertainty associated with the produced maps was undertaken to provide a robust and quantifiable estimate of the availability of geothermal heat flow in New York, Pennsylvania, and West Virginia. Areas of higher resource potential and lower uncertainties were found to be along the eastern border of the Appalachian Basin in Pennsylvania. In New York, promising areas included various counties of central New York, as well as the southernmost border of the western and central portion of New York with the neighboring state of Pennsylvania. The methods and techniques applied to this case study are potentially useful for quantifying the uncertainty associated with selecting future exploration sites based on resource maps.

The objective of this work is to evaluate opportunities for the use of low-temperature geothermal resources in district-heating applications in New York and Pennsylvania, and to develop a supply curve for those applications. By exploring options for these two states we hope to provide a representative sample of what could be possible for many other states located in the northern tier of the U.S. where heating demands are high.

The U.S. Department of Energy and other organizations have been using supply curve analysis to evaluate renewable energy technologies for decades. Recently, the National Renewable Energy Lab (NREL) published a supply curve for geothermal electricity production in the United States (Augustine et al., 2010; Augustine,2011). However, that study evaluated geothermal electricity production exclusively while neglecting geothermal direct-use and district heating possibilities. This leaves an opportunity for development of a supply curve for district heating applications, of which there have been very few, if any, attempts. Supply curves are generally used to visualize the cost of supplying a given quantity of a certain good (in this case heat). For energy resources the price of supplying the good (i.e. energy) typically increases as more total energy is required. This is because the highest quality and most affordable resources will generally be developed first, followed by successively poorer grade and more expensive resources. The supply curve developed in this study plots the total cumulative heating capacity in the study region against the projected levelized cost of supplying that heat.

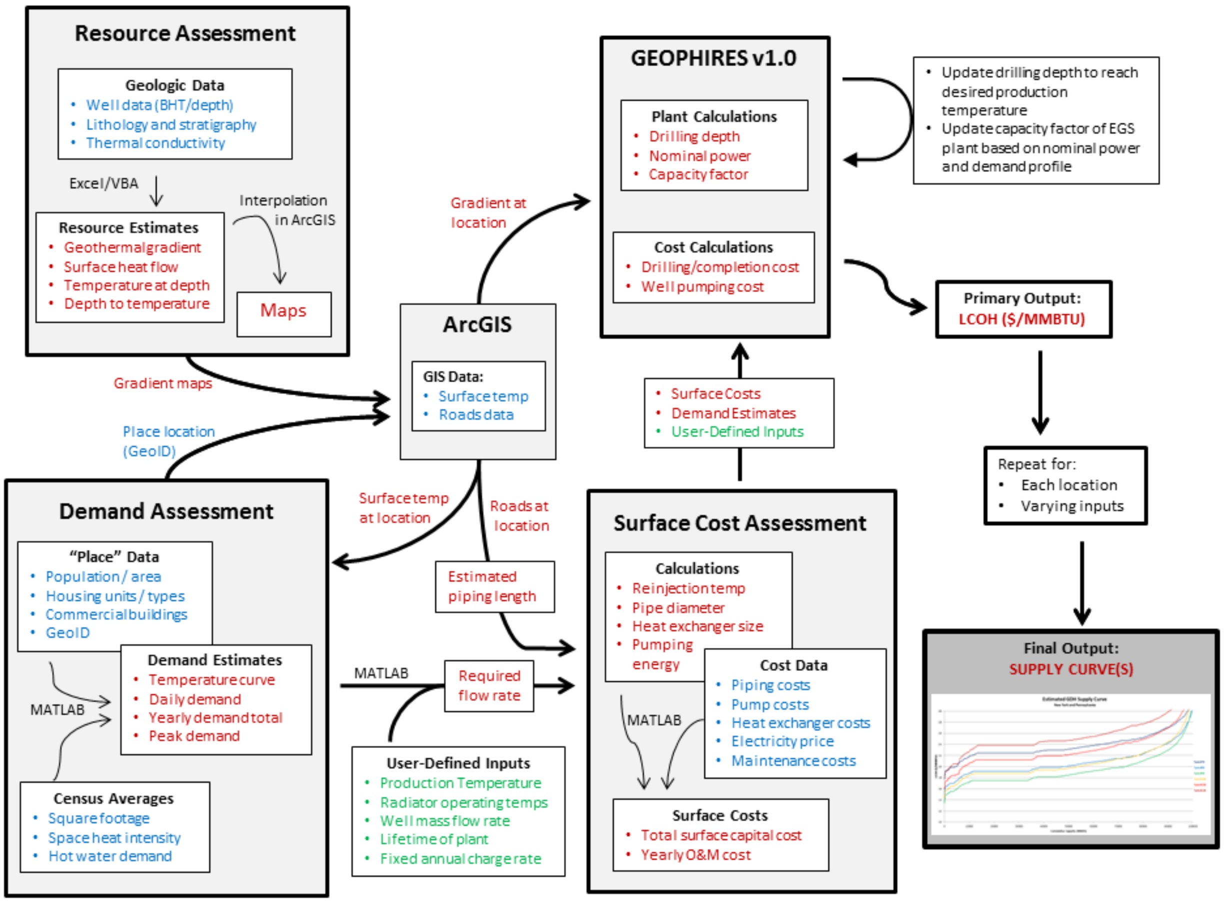


Figure 11 Overall work flow diagram for the model and data processing structure developed to evaluate geothermal district heating options.

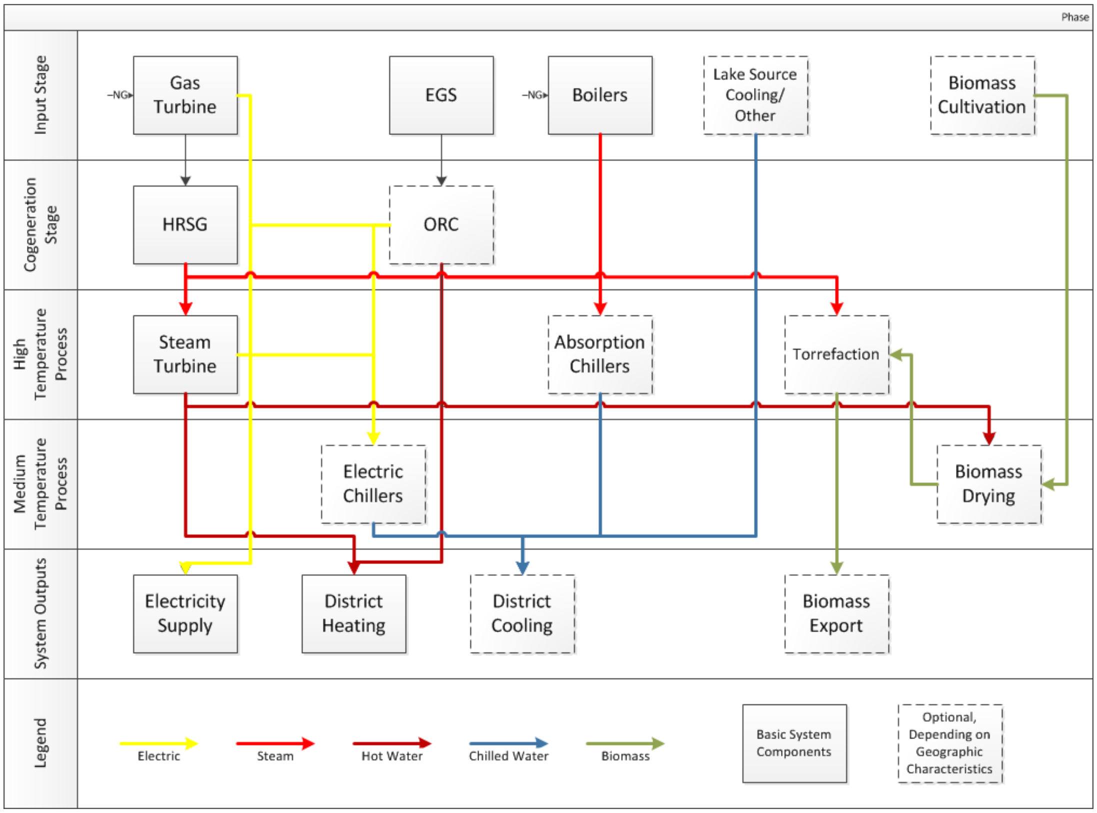


Figure 12 Model process for full optimization of low-temperature geothermal utilization.

Figure 13 shows the locations of the thirty communities with the lowest LCOHs for the initial learning phase. These communities represent those with the most potential initially and thus comprise the best communities in which to focus initial targeted efforts—e.g. more detailed analyses, feasibility studies, and eventual pilot projects. With commercially-mature EGS technology, the lowest projected LCOHs drop to less than $11.00/MMBTU.

Table 2: Base case conditions, assumptions and other user-defined inputs for three deployment scenarios.

Parameter	Initial learning (years 0–5)	Midterm development (years 6–20)	Commercially mature (years 20+)
Maximum flow rate (kg/s)	30	50	80
Lifetime (years)	30	30	30
Drilling/comp costs (vs. today) (%)	100	90	85
Plant/network costs (vs. today) (%)	100	95	90
O&M costs (vs. today) (%)	100	95	90
Secondary temperature regime (°C)	70/40	60/35	50/30
Minimum pinch temperature (°C)	3.0	2.5	1.5
Production temperature range (°C)	75–125	75–125	75–125
Maximum system-wide ΔT (°C)	65	65	65
HX heat transfer coefficient (W/(m^2 K))	5000	5500	6000

Parameter	Initial learning (years 0–5)	Midterm development (years 6–20)	Commercially mature (years 20+)
Discount rate (CBO rate) (%)	4.0	4.0	4.0
Portion of roads w/DH network (%)	75	75	75
Branch distance (service lines) (m)	35	35	35
Network pump efficiency (%)	80	85	85
Peak boiler efficiency (%)	85	90	90
Network maintenance costs ($/m/year)	7.65	7.65	7.65
Natural gas retail price ($/MMBTU)	7.51	8.26	10.51
Electricity retail price (¢/kWh)	7	7	7
Well separation (m)	500	500	500

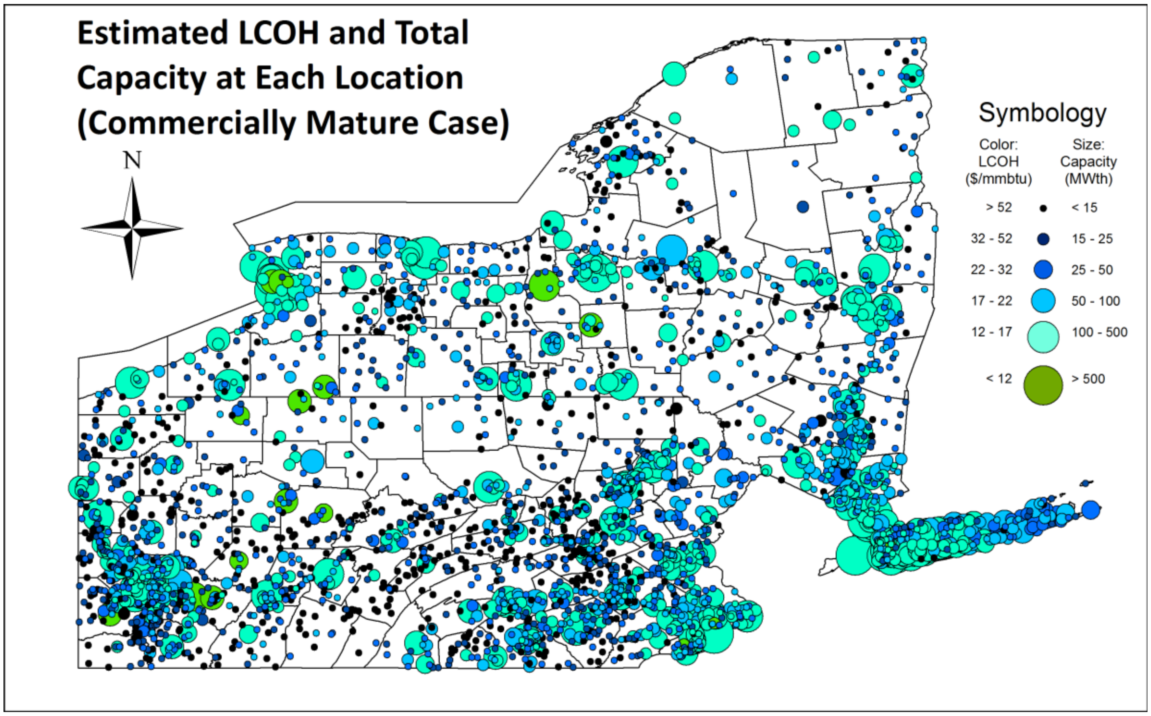


Figure 13 Estimated LCOH and total heating capacity for every community in the dataset given the commercially-mature phase assumptions.

For more details see:

- Gloria Andrea Aguirre, Jery R. Stedinger, and Jefferson W. Tester, " Geothermal Resource Assessment: A Case Study of Spatial Variability and Uncertainty Analysis for the State of New York and Pennsylvania ", Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198.

  Aguirre_SGW_2013.pdf

- He, X., and Anderson, B.J., "Supply Characterization of Hydro-Geothermal Resources in the Western U.S.", Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198.

  SGP-TR-198_He.pdf

- Timothy J. Reber, Koenraad F. Beckers, Jefferson W. Tester, The transformative potential of geothermal heating in the U.S. energy market: A regional study of New York and Pennsylvania, *Energy Policy*, 70, pages 30-44, 2014.

Reber
1-s2.0-S0301421514

3.2. National-level Low-Temperature Utilization Supply Curves

Previous work on supply analysis of geothermal energy have only been focused on geothermal power generation, e.g. Petty, et al., 1992 and 2007, and Augustine, et al., 2010. As time goes on, more geothermal exploration activities, as well as more advanced energy utilization technology have been developed. Thus, the latter report has covered more categories of geothermal resources than the former ones with lower estimated cost. This study focuses on the approach to characterize the supply curve of geothermal district heating and cooling systems in the United States. In this project, geothermal resources were categorized; resources characteristics were identified; resources' thermal potential and corresponding cost of energy were estimated; finally, the supply curve was generated. Though focusing on different types of utilization, the supply analysis of geothermal power generation gives reasonable assumptions on the market settings and provides inspiring methods for reservoir characterization. Some of them were adopted in this study for the supply analysis of geothermal district heating and cooling. The innovation of this study is to expand the supply analysis into the GDHC application, and for the first time to include energy market in the geothermal research.

Figure 14 shows the flow diagram to develop the supply curve in this study. The primary steps include the resources characterization and cost estimation. The following discusses how geothermal energy is categorized, how the reservoir is characterized and how the potential is estimated for each category of the resources.

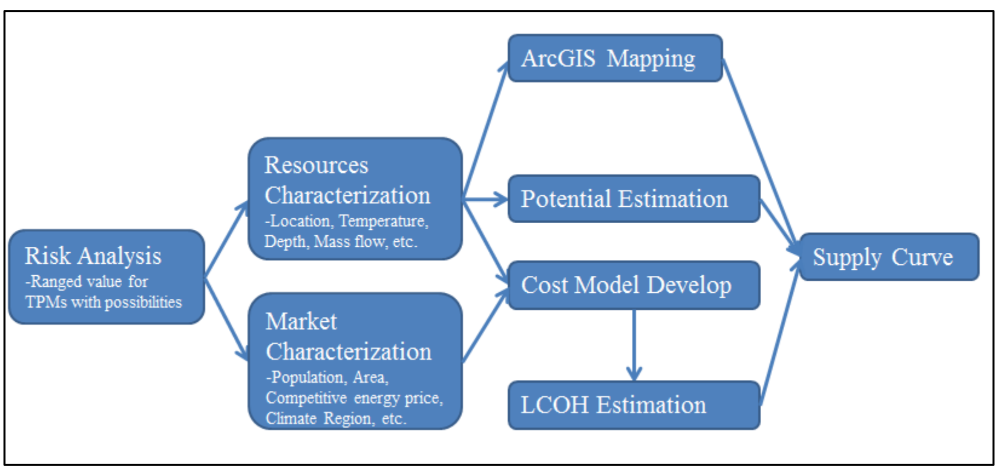


Figure 14 Flow diagram to develop the supply curve for GDHC applications.

Based on the preliminary research, market demand impact on the economics of a GDHC project is much stronger than that on the economics of a geothermal power generation project. It is because the GDHC system is very location sensitive: geothermal heating and cooling must be consumed at the same location where it is produced, or the severe energy loss during the long hot water distribution will very much corrode the advantage of the low energy cost. However, the geothermal power plant can operate at a remote area, while the electricity is still able to be transferred thousands of miles away efficiently. This is why the previous geothermal power supply analysis is "*not constrained by the potential market*" (Petty, et al., 1992). But in this study, the size of the energy market is a crucial factor. Since the supply analysis is based on a site-by-site thermal potential and cost estimation, the energy market demand was also estimated site-by-site.

Figure 15 shows the supply curve of three categories of geothermal resources, Figure 16 combines them together, and Figure 17 partially enlarges the part with reasonable cost. The near hydrothermal EGS resource is always coupled with its corresponding hydrothermal one with a slightly higher cost. Since most of the low cost hydrothermal resources have already been developed into power generation, their corresponding EGS resources may be good choices for expanding the existing system. There are also a large amount of hydrothermal resources undiscovered with a very low LCOH, which deserve more attentions in the future geothermal exploration.

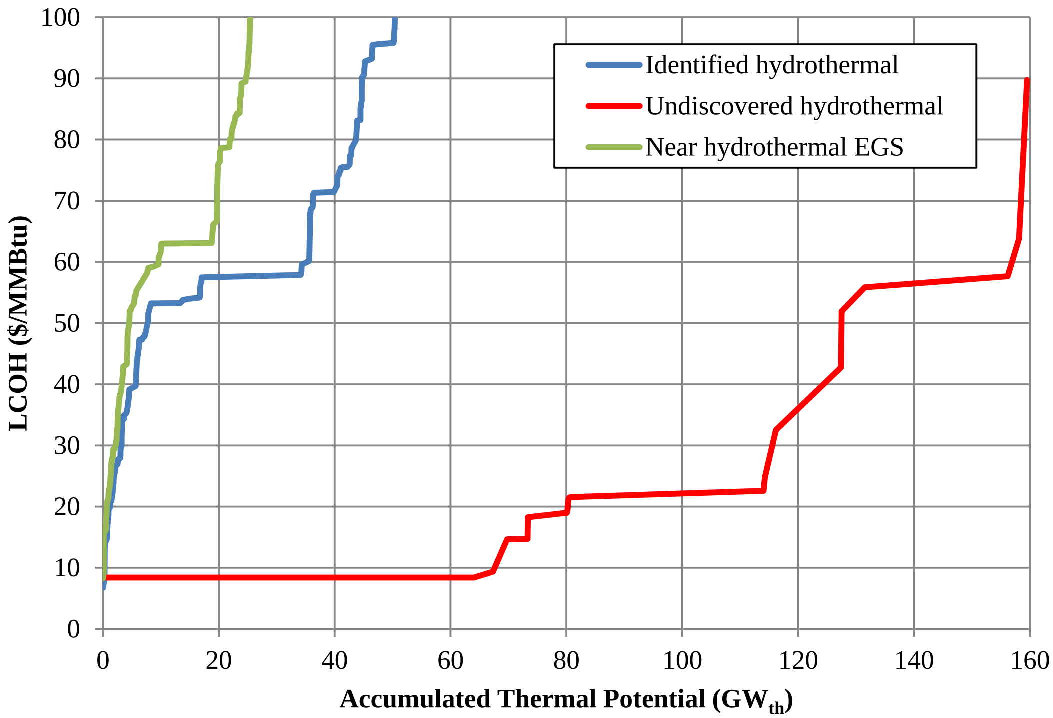


Figure 15 Supply curve for U.S. GDHC applications with different categories of geothermal resources.

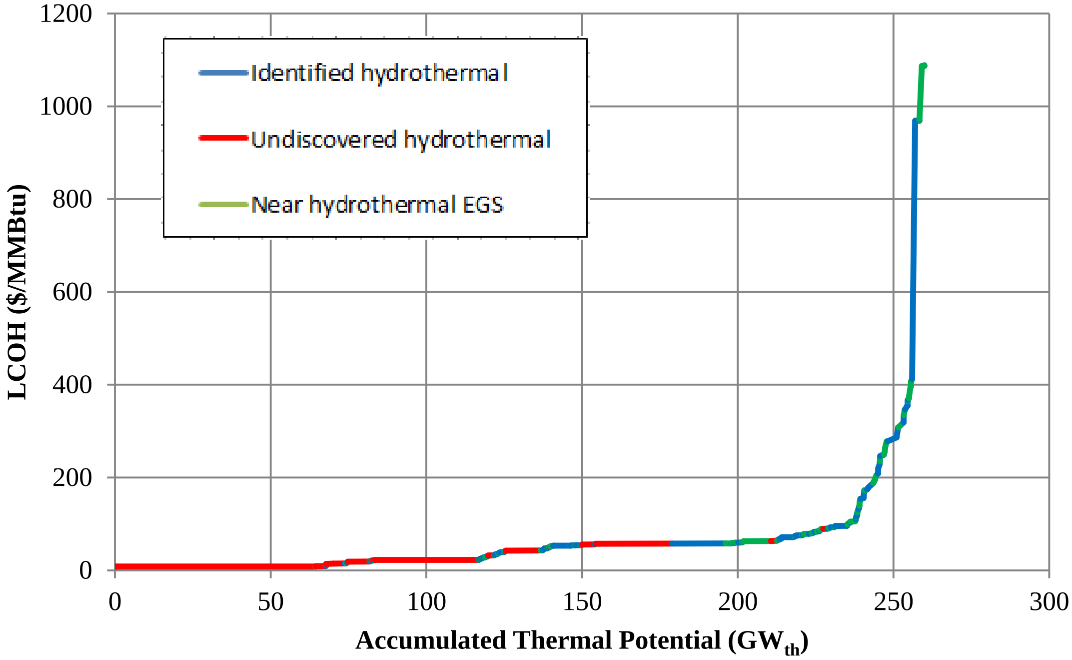


Figure 16 Combined supply curve for U.S. GDHC applications with different categories of geothermal resources.

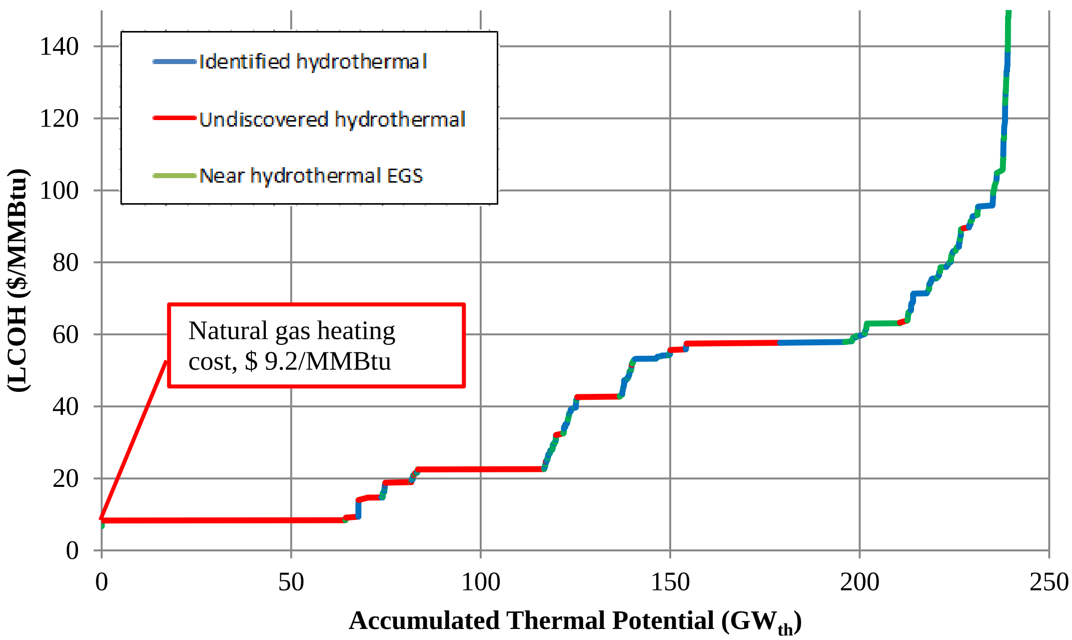


Figure 17 Partial enlargement of the supply curve, in comparison with the current natural gas retail heating cost, $9.2/MMBtu.

Geothermal resources were categorized into identified hydrothermal resources, undiscovered hydrothermal resources, near hydrothermal EGS resources and the deep EGS resources. Owing to the high cost of the deep EGS resources, only the first three categories have been discussed in this part of the study. 253 hydrothermal resources were identified from literature review, and 253 near hydrothermal EGS resources were assumed. Due to the uncertainties of the undiscovered resources, this category of hydrothermal resources was estimated by calculating their occurrence possibility in each state. As a summary, estimated thermal potential from each category of the resources is presented in Table 3. Following the fact that nearly half of the identified hydrothermal resources have already been developed into other applications such as power generation, the remaining potential from this category is about 47,566 MW_{th}, which is concentrated in the states of California, Nevada, Alaska, and Oregon. Estimated thermal potential from the undiscovered hydrothermal resources is about 159,566 MW_{th}, which is concentrated in the states of California, Nevada, Hawaii, Alaska, and Oregon. Estimated thermal potential from the near hydrothermal EGS resources is about 40,958 MW_{th}.

Table 3: Estimated thermal potential and the corresponding lowest LCOH from the western U.S. geothermal resources.

	5 Percentile, MW_{th}	50 Percentile, MW_{th}	95 Percentile, MW_{th}	Lowest LCOH, $/MMBtu
Identified hydrothermal resources	33,250	72,577	113,535	6.74
Undiscovered hydrothermal resources	70,953	159,566	253,071	8.39
Near hydrothermal EGS	40,958			7.87

This study also developed a cost model for the GDHC system, which enables a matrix of 20 user-defined inputs to characterize the geothermal resources as well as the target energy demand. The cost model was used for every resource to simulate the lifetime heating/cooling process, capital investment, and operation and maintenance activities. As a result, the lowest LCOH of identified hydrothermal resources to develop a GDHC system is at Weiser in Idaho, with a

LCOH at $ 6.74/MMBtu. That of the undiscovered hydrothermal resources is estimated at $ 8.39/MMBtu in the state of California, and that of the near hydrothermal EGS resources is $ 7.87/MMBtu, also at Weiser in Idaho. For similar geologic settings, LCOH for the identified hydrothermal resource is the lowest, while that for the undiscovered hydrothermal resource is the highest because of the high exploration cost. All the resources with competitive levelized cost can be characterized as with a median or high reservoir temperature, a median or low drilling depth, and with a large population size. Analysis of the results revealed that population has significantly greater effect on LCOH than geothermal gradient. The energy demand has the most significant negative effect, while drilling cost has the most significant positive effect on LCOH. Increasing the energy demand is the most effective way to decrease LCOH.

Finally, the supply curve of GDHC application was developed. It shows the order in which resource should be developed based on the LCOH results. There are about 50% of the thermal potential with a levelized cost lower than $ 40/MMBtu. With the exception of the lowest cost of the identified hydrothermal resource (Weiser area, ID) and its corresponding EGS resource, over 60 GW_{th} of the potential is still undiscovered, with a cost lower than the natural gas heating. Moreover, there is another 35 GW_{th} of the undiscovered hydrothermal resources with LCOH between less than $ 25/MMBtu. The near hydrothermal EGS is the least expensive type of EGS resource. The levelized cost of the near hydrothermal EGS is a little higher than its corresponding identified hydrothermal resource. Thus in the supply curve, the near hydrothermal EGS and the identified hydrothermal resource are usually coupled. In fact, there is not much thermal potential available from identified hydrothermal resources, since most of the low cost resources have already been developed with other applications such as power generation. So the near hydrothermal EGS corresponding to the most competitive identified hydrothermal resources may be a good choice for expanding the existing system.

For more details see:

- He, X., and Anderson, B.J., "Supply Characterization of Geothermal District Heating and Cooling Applications in United States", Proceedings of the Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202

  SGP-TR-202_He.pdf

- Xiaoning He, “Feasibility and Supply Analysis of U.S. Geothermal District Heating and Cooling Systems”, PhD Thesis, West Virginia University

  He Thesis.pdf

CONCLUSION/SUMMARY

Geothermal district heating and cooling has the potential to offset a considerable amount of fossil fuels consumption in the U.S. The GDHC system produces a more stable base-load energy while produces much less greenhouse gas and particulates emissions than conventional heating and cooling systems. However, the literatures on studies analyzing the economic impacts of installing or retrofitting existing systems are few in number. This study is unique in that its purpose was to utilize supply analyses for the GDHC systems and determine an appropriate economic assessment of the viability and sustainability of the systems. The significance of this study is to present a cost model for the GDHC system which for the first time takes the energy market demand into consideration for a geothermal project. By showing the technical feasibility and economic benefits of the GDHC systems, this study bridges the gap between theoretic design of the system and popularizing it among the public. Developing GDHC systems will help the national energy industry restructure to a more renewable and sustainable oriented system, and protect the national energy security. By evaluating the opportunities to develop GDHC systems in the United States, the following conclusions were made by this study:

- The western U.S. is much more geothermally active than the eastern part. The overall geothermal potential is estimated with a mean of 273,100 MW_{th}, with levelized cost of heat (LCOH) as low as $6.74/MMBtu, at Weiser in Idaho. Usually, the LCOH of the identified hydrothermal resource is the cheapest. The reservoir stimulation cost causes the near hydrothermal EGS has a higher LCOH. The most expensive one is the undiscovered hydrothermal resource due to the high exploration cost.
- A GDHC system based on West Virginia University campus is simulated as a preliminary case study which helps for detailed EGS based GDHC system research in the future. Results show that a doublet geothermal well system (one injection and one production), which is drilled to 5.25 km to ensure a geothermal temperature of 148.9°C can provide sufficient energy for the Evansdale campus heating and cooling demand. Maximum flow rate of 50 kg/s should be maintained at peak energy demand. The LCOH is calculated as $14.33/MMBtu, which is higher than the current steam based system ($12/MMBtu).
- Energy production costs of the proposed hybrid systems quantified by the Levelized Cost of Electricity are higher, yet still competitive compared to the existing Cornell CHP plant. The LCoE is higher by 0.4-1.1¢/kWh, while providing significant environmental gains. As portrayed in our study, EGS provides a buffer to the volatility of electric and natural gas prices. Therefore, an EGS/CHP hybrid system can be beneficial even at low gas prices.
- While only a small fraction of the population of New York and Pennsylvania can achieve LCOHs of less than $12/MMBTU, more than half of the population of both states could be served with GDH costing $15/MMBTU or less.
- GEOPHIRES LCOE estimates are comparable with values found in literature for similar EGS conditions, as, for example, in some of the cases studied by Mines and Nathwani using GETEM. When comparing EGS with other renewable (including hydrothermal) and non-renewable energy technologies for electricity generation, EGS is currently not expected to be cost-competitive except with photovoltaic and concentrated solar energy.

However, with moderate technological improvements that would emulate the production characteristics of commercial hydrothermal systems in operation today, EGS utilizing medium- and high-grade geothermal resources is predicted to become cost-competitive with all renewables, including hydrothermal, and most non-renewable energy technologies.

- Because of the low natural gas prices that exist in the U.S. today (around $5/MMBTU as delivered to industrial consumers), electricity generated using high efficiency natural gas fired combined cycles is the exception that no alternative can compete with. In addition, even for industrial direct-use heat, EGS using today's technology is not economically competitive with natural gas boilers with today's wholesale industrial gas prices. Also in comparison with natural gas boilers for space and water heating using residential gas prices ($11/MMBTU), EGS district heating systems are currently not cost-competitive. For commercially mature technology though, it is predicted that even for low- grade geothermal resources, EGS for industrial direct-use heat would be cost-competitive with projected 2030 industrial natural gas prices ($7/MMBTU). Further, EGS district heating systems for medium-grade resources are expected to become cost-competitive with natural gas boilers at projected 2030 residential natural gas prices ($14/MMBTU).

PRODUCTS / DELIVERABLES

4. Publications, Conference Papers, and Presentations:

- Xiaoning He, "Feasibility and Supply Analysis of U.S. Geothermal District Heating and Cooling Systems", PhD Thesis, West Virginia University

  He Thesis.pdf

- Timothy J. Reber, Koenraad F. Beckers, Jefferson W. Tester, The transformative potential of geothermal heating in the U.S. energy market: A regional study of New York and Pennsylvania, *Energy Policy*, 70, pages 30-44, 2014.

  Reber
  1-s2.0-S03014215140

- Maciej Z. Lukawski, Brian J. Anderson, Bill Livesay, Chad Augustine, Louis E. Capuano Jr., and Jefferson W. Tester, "Drilling Cost Analysis of Oil, Gas, and Geothermal Wells,", *Journal of Petroleum Science and Engineering*, 118, pages 1-14 2014.

  Lukawski, Drilling
  Costs.pdf

- Koenraad F. Beckers, Maciej Z. Lukawski, Brian J. Anderson, Michal C. Moore and Jefferson W. Tester, "Levelized Costs of Electricity and Direct-Use Heat from Enhanced

Geothermal Systems (EGS)” *The Journal of Renewable and Sustainable Energy*, 6 (1), 013141, 2014.

1.4865575.pdf

- He, X., and Anderson, B.J., "Supply Characterization of Geothermal District Heating and Cooling Applications in United States", Proceedings of the Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202

SGP-TR-202_He.pdf

- Nandanwar, M., and Anderson, B.J., "Coupled Reservoir, Wellbore, and Surface Plant Simulations for Enhanced Geothermal Systems", Proceedings of the Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202

SGP-TR-202_Nandan
war.pdf

- Sudhanya Banerjee, Jordan A. Tiarks, Maciej Lukawski, Song-Charng Kong, and Robert C. Brown, “Technoeconomic Analysis of Biofuel Production and Biorefinery Operation Utilizing Geothermal Energy,” *Energy and Fuels*, 27, 1381−1390, 2013.

Banerjee_EnergyFue
ls_2013.pdf

- Fox, Don B., Sutter, Daniel, Beckers, Koenraad F., Lukawski, Maciej Z., Koch, Donald L., Anderson, Brian J., Tester, Jefferson W., "Sustainable heat farming: Modeling extraction and recovery in discretely fractured geothermal reservoirs" Geothermics, 46, 42-54, 2013.

Fox, et al, 2013 -
Sustainable heat farn

- Gloria Andrea Aguirre, Jery R. Stedinger, and Jefferson W. Tester, " Geothermal Resource Assessment: A Case Study of Spatial Variability and Uncertainty Analysis for the State of New York and Pennsylvania ", Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198.

Aguirre_SGW_2013.pdf

- He, X., and Anderson, B.J., "Supply Characterization of Hydro-Geothermal Resources in the Western U.S.", Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198.

  SGP-TR-198_He.pdf

- Peluchette, J., Anderson, B.J., "Optimization of Integrated Reservoir, Wellbore, and Power Plant Models for Enhanced Geothermal Systems" Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198

  SGP-TR-198_Peluchette.pdf

- Lukawski, M., Vilaetis, K., Gkogka, L., Beckers, K., Anderson, B., Tester, J., "a proposed hybrid geothermal - natural gas - biomass energy system for Cornell University. Technical and economic assessment of retrofitting a low - temperature geothermal district heating system and heat cascading solutions", Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198

  SGP-TR-198_Lukawski.pdf

- Beckers, K., Lukawski, M., Reber, T., Anderson, B., Moore, M., Tester, J., "Introducing GEOPHIRES V1.0: Software Package For Estimating Levelized Cost of Electricity and/or Heat from Enhanced Geothermal Systems", Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198

  SGP-TR-198_Beckers.pdf

- Sudhanya Banerjee, Jordan Tiarks, Song-Charng Kong, Terry Meyer, Robert C. Brown and Brian Anderson, “Application of a Kinetics Model to Simulate Biomass Gasification Using Oxygen and Steam” American Institute of Chemical Engineers Annual Conference, Pittsburgh, PA, October 28-November 2, 2012.

- Jordan Tiarks, Sudhanya Banerjee, Yanan Zhang, Terry Meyer, Song-Charng Kong, Robert C. Brown and Brian Anderson, “Techno-Economic Analysis of a Biorefinery Utilizing Geothermal Energy for Biomass Drying and Auxilliary Power Generation” American Institute of Chemical Engineers Annual Conference, Pittsburgh, PA, October 28-November 2, 2012.
- Madhur Bedre and Brian Anderson, “Sensitivity Analysis of Low-Temperature Geothermal Reservoirs: Effect of Reservoir Parameters on the Direct Use of Geothermal Energy,” GRC Transactions, Vol. 36, 2012.

  Bedre_GRC_2012.pdf

- He, Xiaoning, Anderson, Brian J., "Low-Temperature Geothermal Resources for District Heating: An Energy-Economic Model of West Virginia University Case Study," Proceedings of the Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28-30, 2012, SGP-TR-194

  He_SGW_2012.pdf

- Banerjee, Sudhanya, Tiarks, Jordan, Zhang, Yanan, Kong, Song-Charng, Meyer, Terrence, Brown, Robert C., Anderson, Brian. “Techno-Economic Analysis of Biorefinery Utilizing Geothermal Energy for Processing," Proceedings of the Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28-30, 2012, SGP-TR-194

  Banerjee_SGW_2012.pdf