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MODELING THE VIABILITY OF UNDERGROUND COAL FIRES AS A HEAT SOURCE FOR ELECTRICAL POWER GENERATION

Andrew D. Chiasson[1] and Cenk Yavuzturk[2]

1. Geo-Heat Center, Oregon Institute of Technology, Klamath Falls, OR, 97601 USA
chiassoa@oit.edu
2. Dept. Civil & Architectural Engineering, University of Wyoming, Laramie, WY, 82071 USA
cyturk@uwyo.edu

ABSTRACT

The objective of this study is to examine the viability of extracting thermal energy produced from underground coal mine fires for electrical power generation. Underground coal mine fires present a high temperature heat source available at relatively shallow depths as compared to conventional geothermal resources. Several hundreds of burning underground coal mines are believed to exist worldwide. They may extend in plan area up to tens of square kilometers and are estimated to burn for up to tens of decades.

The performance of a closed-loop thermal energy extraction system, consisting of an array of vertical boreholes, is modeled using computer simulation. At various underground temperatures, a two-variable optimization scheme is used to determine minimum borehole depth and mass flow rate required to yield a fluid temperature of 100°C entering a theoretical binary-cycle power plant. Geologic and thermal data for the model are taken from field studies of an actual underground coal mine fire in Wyoming, USA. Life-cycle cost analyses are conducted to assess the feasibility of production of 100 kW_e to 1000 kW_e. Simulation results show that, under certain conditions, the concept is economically comparable to other alternative power generation technologies.

1. INTRODUCTION

This paper presents a concept for potentially extracting thermal energy from underground coal mine fires for electrical power generation. The concept originated from observations made at an underground coal mine fire near Sheridan, WY, USA (Figure 1), where a 25-m to 30-m deep coal seam was mined using the room-and-pillar method from the early 1900s to 1943. Subsequent subsidence pits and cracks are believed to have triggered combustion of the un-mined coal (Dunrud and Osterwald, 1980). Exploratory drilling and surface temperature measurements revealed underground temperatures exceeding 500°C.

Underground coal fires in abandoned mines ignite primarily by spontaneous combustion when oxygen and water are introduced through subsidence cracks and unsealed shafts. Two of the more important factors causing heating and ignition appear to be coal rank and changes in moisture content (Dunrud and Osterwald, 1980). Most underground coal fires exhibit smoldering combustion and may only involve relatively small amounts of coal capable of burning in the presence of as little as 2% oxygen. Heat transfer to the surrounding rock occurs primarily by conduction and by convection within the collapsed zones.

Figure. 1. Surface effects (steam and smoke) of an underground coal mine fire near Sheridan, Wyoming (Dunrud and Osterwald, 1980). Note tire tracks for scale.

There are currently about 600 underground coal mine fires throughout the United States (Drakon Energy, 2002). With poor success in extinguishing them, most fires are left to burn themselves out with a predicted combustion time of up to 80 years for some locations. Fires at shallow depths (to <150 m) may have potential for thermal energy extraction for a variety of applications, particularly electricity production. A review of the literature yielded no publications reporting on electricity production from underground coal mine fires.

The objective of this research work has been to evaluate the concept of extracting thermal energy from underground coal mine fires for electrical power generation. This evaluation is made by means of a system simulation approach using TRNSYS (SEL, 2000). Life-cycle cost analyses are presented to assess the economic viability of electrical power production with a binary-cycle power plant.

2. METHODOLOGY

2.1. The Physical Model

A conceptual diagram of the physical system is shown in Figure 2. The physical parameters relevant to the modeling study were characterized as geologic, thermal, and system parameters.

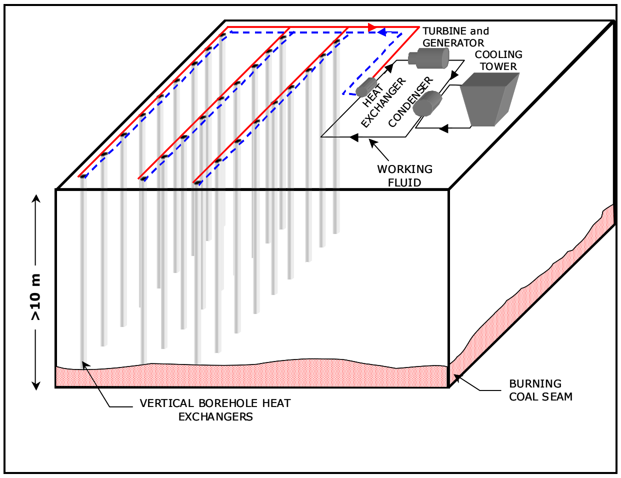

Figure 2. Conceptual diagram of the underground thermal energy extraction system and binary power plant.

The geologic parameters include soil and rock types and depth to the coal seam. The thermal parameters consist of thermal conductivity, volumetric heat capacity, and average temperature of the geologic materials. The system parameters consider the number, spacing, and depth of boreholes; heat transfer fluid properties and flow rate; and the borehole heat exchanger geometry (Figure 3). The system parameters must also account for the overall efficiency of the binary power plant in order to determine the electric power output.

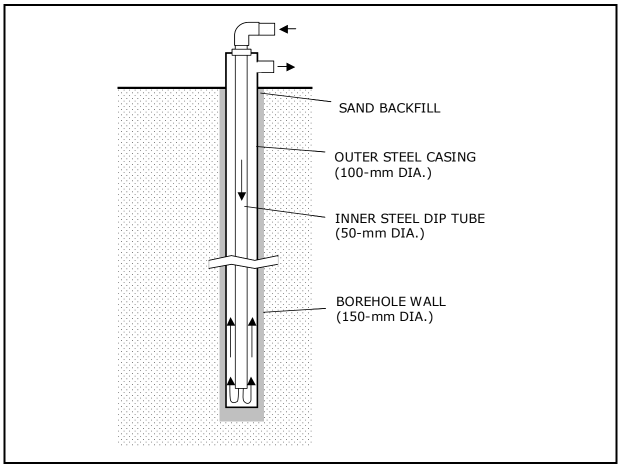

Figure 3. Conceptual diagram of a concentric-type borehole heat exchanger.

2.2. The Mathematical Model

The basis of the mathematical model for this study was the work of Yavuzturk and Spitler (1999), which is an extension of Eskilson (1987). A series of dimensionless, time-dependent temperature response factors known as g-functions have been developed from a transient finite difference model that approximates the time-dependent solution to the heat diffusion equation in and around the heat extraction borehole. The g-functions are fixed for prescribed borehole field geometry and borehole spacing/depth ratio. The g-function allows the calculation of the temperature change at the borehole wall in response to a step heat extraction pulse, which can be determined by summing the responses of the previous step functions:

$$T_{borehole} = T_{\infty} + \sum_{i=1}^{n} \frac{(q_i - q_{i-1})}{2\pi k} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}\right) \quad (1)$$

where t is the time (s), t_s is a time scale (s) ($H^2/9\alpha$, where α is the thermal diffusivity of the rock (m^2/s)), r_b is the borehole radius (m), H is the borehole depth (m), k is the thermal conductivity (W/m-K), $T_{borehole}$ is the temperature at the borehole wall (^{o}C), T_{∞} is the average underground temperature, q is the step heat extraction pulse per length of bore (W/m), i denotes the time step, and g is the temperature response factor (g-function). The temperature of the heat transfer fluid exiting the borehole is calculated iteratively by an overall energy balance.

2.3. The Computer Model

The mathematical model has been implemented for use in TRNSYS (SEL, 2000), a component-based, transient system simulation environment. The purpose was to allow the underground heat extraction model the versatility to be coupled to other component models such that larger system simulations could be conducted, such as a complex power plant with associated equipment.

The thermal performance of each TRNSYS component model is described by a FORTRAN subroutine. By a script language, components are linked together in a manner similar to piping and wiring in a physical system. Each component model is formulated on the concept of inputs, parameters, and outputs. Inputs are received by the model and may change with time. Parameters are fixed in the model and do not change with time. Outputs are calculated by the model and also change with time. The configuration of the underground heat extraction model is shown graphically in Figure 4.

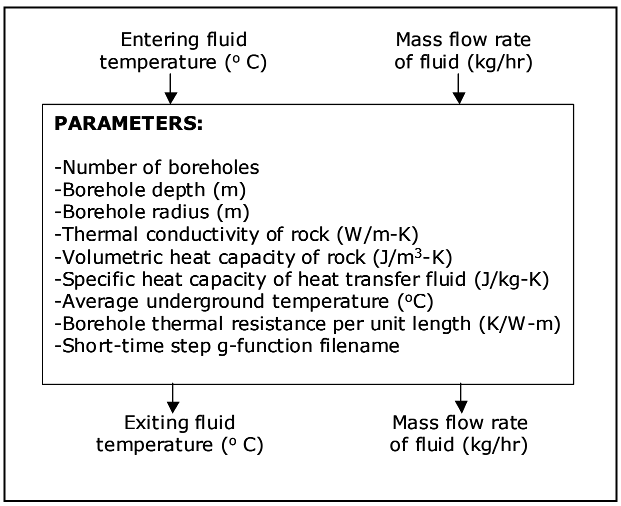

Figure 4. Underground heat extraction component model configuration for TRNSYS.

2.4. The Overall Modeling Approach

In a closed-loop system, many factors are inter-dependent, and it was therefore necessary to make some simplifying assumptions. The overall modeling approach consisted of optimizing borehole depth and mass flow rate through the borehole heat exchanger network to meet a fixed acceptable minimum entering fluid temperature to the power plant. This approach assumed a constant thermal extraction rate from the borehole network. One major simplifying assumption was that the average underground temperature remains constant throughout the simulated life.

GenOpt (LBNL, 2004), a generic optimization software package was coupled to TRNSYS to optimize the borehole depth and mass flow rate. The optimization scheme used was the simplex method of Nelder and Mead (1965) with updates by O'Neill (1971). The minimization function was defined as:

$$\left|T_{\min} - T_{desried}\right| \times H^2 \times \dot{m} \qquad (2)$$

where T_{min} is the minimum temperature of the fluid exiting the boreholes (°C), $T_{desired}$ is the desired minimum temperature exiting the boreholes (°C), H is the borehole depth (m), and $\dot{m}$ is the total mass flow rate (kg/hr). Squaring the borehole depth gives a heavier weighting to this parameter. The desired minimum acceptable fluid temperature exiting the borehole network (i.e. the fluid temperature entering the power plant) was fixed at 100°C.

System simulations were conducted for various heat extraction rates ranging from 100 kW_t to 1000 kW_t. The simulated life cycle was 20 years. Based on field observations at the underground coal mine fire near Sheridan, WY, model parameters were as follows:

- borehole radius: 76 mm
- rock thermal conductivity: 2.1 W/(m-K)
- rock volumetric heat capacity: 2000 kJ/(K-m^3)
- heat transfer fluid: water
- average underground temperature range: 160°C to 360°C

To estimate the actual electrical power output, it was necessary to estimate the net plant thermal conversion efficiency. The ideal theoretical efficiency (η_{ideal}) is given by:

$$\eta_{ideal} = 1 - T_L / T_H \qquad (3)$$

where T_L is the absolute temperature of the condenser (K), T_H is the temperature of the fluid exiting the underground borehole heat exchanger network (K). The net efficiency of the binary power plant was taken as 50% of the ideal efficiency based on the work of Nichols (1986) and Entingh et al. (1994). The condenser temperature was assumed to be 30°C.

The foregoing system simulations assumed no borehole-to-borehole thermal interference. In order to investigate thermal interference between boreholes, the heat extraction model was used to simulate a 10 x 10 borehole matrix. The boreholes were assumed to be equally spaced in a square pattern. Model parameters were those described above with an average underground temperature of 260°C. The borehole spacing was successively increased, and an optimum borehole spacing was assumed to be approached when the incremental heat extraction rate became negligible.

2.5. Economic Analysis

A simple economic analysis was conducted by determining the levelized cost of electricity production for various plant capacities and underground temperatures. To examine the sensitivity to drilling costs, levelized costs were computed at drilling rates of \$50/m and \$75/m. Factors included in the simple economic model were capital costs, operating and maintenance costs, and plant capacity factor.

Capital and operating and maintenance (O&M) cost models were determined from curve-fits to data presented in DiPippo (1998). Capital cost (in U.S. dollars) of binary plants up to 1000 kW_e capacity is given by:

$$CapitalCost = 0.44x^2 + 2390x \qquad (4)$$

and annual O&M costs are given by:

$$Annual\ O\&M\ Cost = 26.3x + 17717 \qquad (5)$$

where x refers to the binary plant capacity in kW_e. The plant capacity factor is taken as 0.8 and an annual discount rate of 6% is assumed over the 20-year life cycle. The drilling costs are expressed in \$ per meter of vertical bore and include all materials and labor to install all vertical and horizontal transfer piping.

3. RESULTS AND DISCUSSION

3.1 System Simulations

The optimized borehole depths and mass flow rates at various average underground Earth temperatures are shown in Figure 5 that produced a minimum exiting fluid temperature of 100°C over a 20-year life-cycle. The borehole length is expressed in m per kW of thermal energy extracted. An example temperature profile versus time is shown in Figure 6 for an average underground temperature of 260°C. An example of the optimization results from GenOpt are shown for this same case in Figure 7. Note that for these results, borehole-to-borehole thermal interference was not considered.

A review of the data presented in Figure 6 reveals that the borehole length begins to increase exponentially below average underground temperatures of about 300°C. A review of Figures 6 and 7 shows that the optimization scheme proved to be quite reliable. The underground exiting fluid temperature does not approach the target of 100°C until about year 17, typical of a conduction heat transfer profile. At that temperature, the approximate net binary plant efficiency is 10%, which is in agreement of values reported by Nichols (1986) and Entingh et al. (1994).

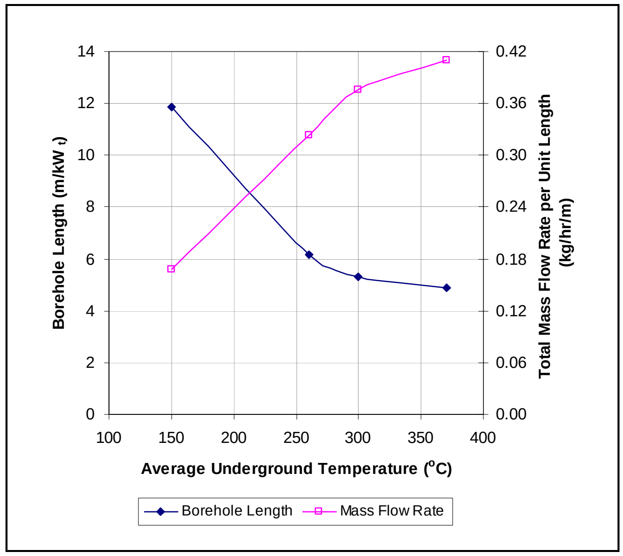

Figure 5. Optimized borehole lengths (per kW heat extracted) and mass flow rates at various average underground temperatures.

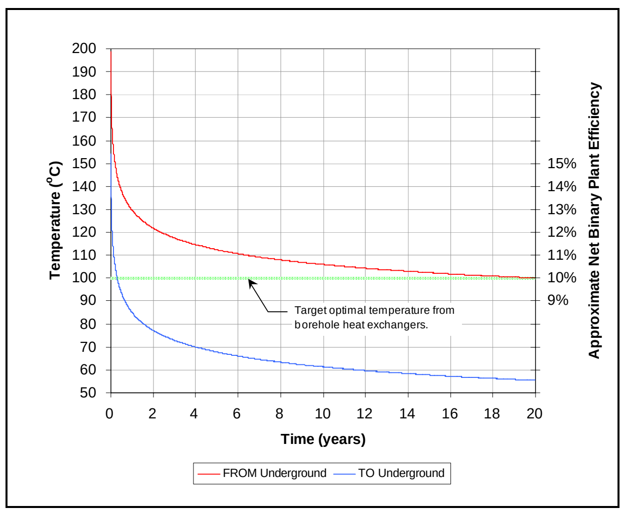

Figure 6. Example temperature profile of fluid exiting the underground thermal energy extraction system with an average underground temperature of 260°C.

Considering the net conversion efficiency of the binary plant, the number of boreholes of arbitrary depth can be determined to provide a desired electrical power output. Figure 8 shows the number of 100 m deep boreholes required to provide various quantities of electrical power at various underground temperatures.

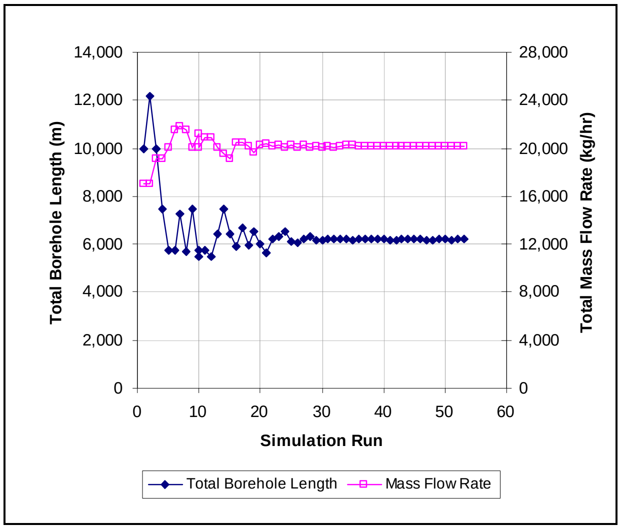

Figure 7. Optimization results for the case with a heat extraction rate of 1000 kW at an average underground temperature of 260°C.

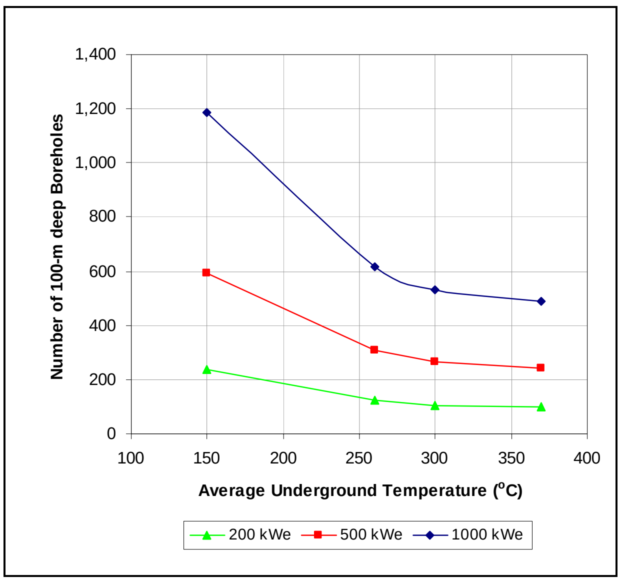

Figure 8. Number of 100-m deep boreholes required to produce various electrical power outputs at various average underground temperatures.

Results of the borehole interference simulations are shown in Figure 9. A review of Figure 9 shows that optimum borehole spacing is approached at about 50 m. These results indicate that a borehole spacing of progressively less than 50 m would result in increasing thermal interaction between boreholes, and therefore a progressively less than optimum quantity of thermal energy extraction. On the contrary, borehole spacings larger than 75 m would result in less than optimum use of land.

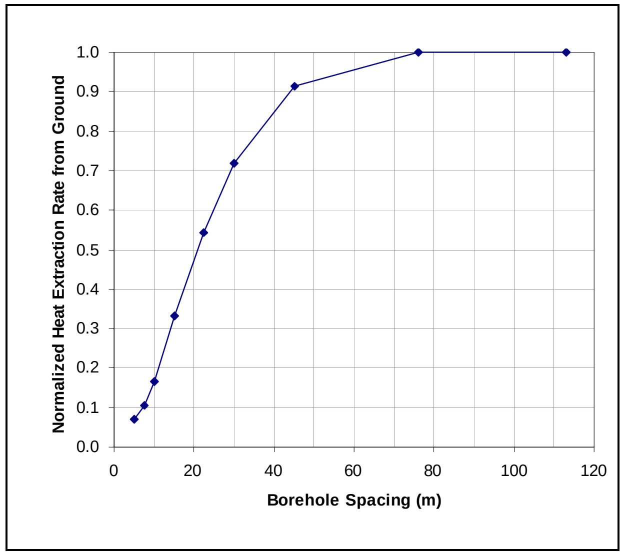

Figure 9. Normalized heat extraction rate versus borehole spacing.

Combining the results presented in Figures 8 and 9, the required land area for an underground thermal energy extraction system can be determined. Assuming a borehole spacing of 50 m, required land areas are shown in Figure 10. A review of this figure reveals that quite large expanses of land would be required to produce 1 MW of electrical power, particularly at average underground temperatures less than 300°C.

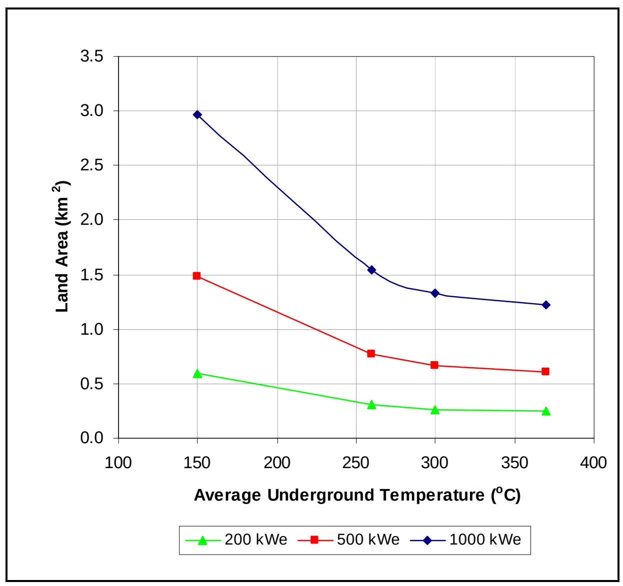

Figure 10. Land area (with 100-m deep boreholes) required to produce various electrical power outputs at various average underground temperatures.

3.2. Economic Analysis

The levelized cost of electricity production for various plant capacities and underground temperatures is shown in Figure 11. For comparison purposes, levelized costs of electricity production with other technologies are shown in Figure 12.

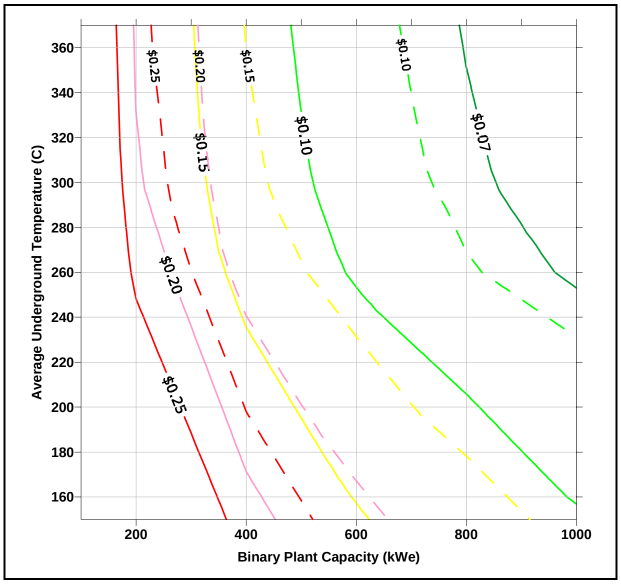

Figure 11. Levelized costs of electricity production at various binary plant capacities and average underground temperatures. Solid lines represent \$50/m and dashed lines represent \$75/m drilling cost.

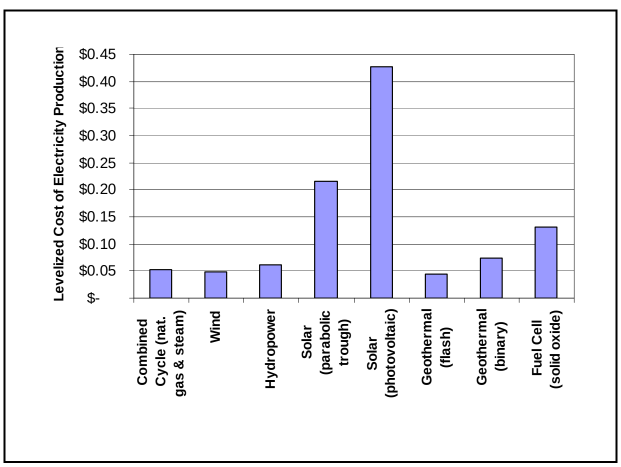

Figure 12. Levelized costs of electricity production for various alternative technologies (California Energy Commission, 2003).

A review of Figures 11 and 12 shows that the concept of extracting thermal energy from underground coal fires for electricity generation is comparable to other alternative power generation technologies only under certain conditions. As with other geothermal technologies, the levelized cost of electricity generation is strongly dependent on the average underground temperature, drilling cost, and plant capacity. Economies of scale for larger capacity binary plants can be seen in Figure 11.

At relatively low underground temperatures (i.e. 160°C), larger-capacity plants appear more favorable, assuming adequate availability of land area for the underground extraction system. Drilling costs would need to be kept below \$50/m for this technology to be economically competitive at low underground temperatures. With increasing underground temperature, slightly smaller capacity plants appear favorable depending on the drilling rate.

4. CONCLUSIONS

This paper has presented a concept for potentially extracting thermal energy from underground coal mine fires for electrical power generation. The system consists of a closed-loop array of vertical boreholes with electricity being produced by a binary power plant. A system simulation approach was used to evaluate the viability of the concept.

Simulation results showed that in order to produce a minimum entering fluid temperature of 100°C to a binary power plant over a 20-year life cycle, required borehole depths per kW of electrical power output would need to range from 50 m/kW_e (at 360°C underground temperature) to 120 m/kW_e (at 150°C underground temperature). At 100°C entering water temperature, the binary plants considered in this study are about 10% net efficient. For minimum thermal interference between boreholes, the required spacing was found to exceed 50 m.

An economic analysis revealed the levelized cost of electricity to be strongly dependent on the average underground temperature, drilling cost, and plant capacity. Currently, the concept can be competitive to other alternative electric power generation technologies if drilling rates are kept below \$50/m and/or the average underground temperature is relatively high.

This study represents a first step in evaluating the concept of electricity generation from underground coal fires, and further work is necessary to fully evaluate its viability. In particular, assumptions were made regarding the spatial and temporal uniformity of the underground temperature. In reality, this would not be the case, and little work has been done to date to estimate the life-cycle of a coal fire and its evolution with time. Further, it would be desirable to develop remote-sensing and other field techniques to explore and track these fires.

ACKNOWLEDGEMENTS

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REFERENCES

California Energy Commission (2003). “*Comparative Cost of California Central Station Electricity Generation Technologies*”, Publication # 100-03-001.

DiPippo, R. (1998). “Geothermal Power Systems”, In *Standard Handbook of Power Plant Engineering*, 2nd Ed., pp. 8.27-8.60, McGraw-Hill, Inc., New York.

Drakon Energy (2002). Personal communication.

Dunrud, C.R. and Osterwald, F.W. (1980). *Effects of Coal Mine Subsidence in the Sheridan, Wyoming, Area*. Geological Survey Professional Paper 1164, United States Department of the Interior, U.S. Government Printing Office, Washington, D.C.

Entingh, D.J., Easwaran, E., and McLarty, L. (1994). “Small Geothermal Electric Systems for Remote Power”, *Geothermal Resources Council Bulletin*, Vol. 23, No. 10. pp. 331-338.

Eskilson, P. (1987). *Thermal Analysis of Heat Extraction Boreholes*. Doctoral Thesis, University of Lund, Department of Mathematical Physics, Lund, Sweden.

Lawrence Berkeley National Laboratory (LBNL) (2004). *GenOpt 2.0, Generic Optimization Program, Version 2.0*. Simulation Research Group, Building Technologies Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory.

Nelder, J.A. and Mead, R. (1965). “A Simplex Method for Function Minimization”, *Computer Journal*, Vol. 7, No. 4, pp. 308-313.

Nichols, K.E. (1986). “Wellhead Power Plants an Operating Experience at Wendel Hot Springs”, *Geothermal Resources Council Transactions*, Vol. 10, pp. 341-346.

O,Neill, R. (1971). “Function Minimization Using a Simplex Algorithm”, *Journal of Applied Statistics*, Vol. 20, No. 3, pp. 338-345.

SEL, (2000). *TRNSYS Reference Manual, a Transient Simulation Program*, Version 15, Solar Engineering Laboratory, University of Wisconsin-Madison.

Yavuzturk, C. and Spitler, J.D. (1999). “A Short-Time Step Response Factor Model for Vertical Ground Loop Heat Exchangers”, *ASHRAE Transactions*, Vol. 105(2), pp. 475-485.