

Technical Communication

Underground Mine Water for Heating and Cooling using Geothermal Heat Pump Systems

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Abstract. In many regions of the world, flooded mines are a potentially cost-effective option for heating and cooling using geothermal heat pump systems. For example, a single coal seam in Pennsylvania, West Virginia, and Ohio contains 5.1×10^{12} L of water. The growing volume of water discharging from this one coal seam totals 380,000 L/min, which could theoretically heat and cool 20,000 homes. Using the water stored in the mines would conservatively extend this option to an order of magnitude more sites. Based on current energy prices, geothermal heat pump systems using mine water could reduce annual costs for heating by 67% and cooling by 50% over conventional methods (natural gas or heating oil and standard air conditioning).

Key words: geothermal; heat pump; mine water; Pittsburgh coal seam

Introduction

Extensive areas of flooded mines underlie many populated regions of the United States and the world and provide an economic opportunity for extracting low-grade, geothermal energy. This opportunity is due to the fact that costs for conventional heating and cooling are rising globally, and in the U.S. are at the highest point in the past 50 years. For the past four years, natural gas, heating oil and propane prices have been increasing and are predicted to remain high for the foreseeable future. Furthermore, as the demand for coal continues to escalate worldwide, coal production and the contemporaneous development of flooded underground mines (i.e. new sources of low-grade geothermal energy) will increase at unprecedented rates. Data presented in this paper illustrate that flooded coal mines have been exploited more than any other type of mines for geothermal applications due to their broad-based accessibility. Low-grade geothermal energy from mine pools has been used on a global basis; however, due to relatively low conventional energy costs in the past, this exploitation has been limited, particularly in the U.S.

Another factor limiting the exploitation of geothermal energy from mine pools is the lack of knowledge about the location and condition of underground mine workings. Accurate mapping is needed to identify access locations and adjacent mine workings (both laterally and vertically) and to estimate void volume and degree of flooding. In the U.S., for reasons of miners' health and safety and environmental protection, many State and Federal agencies are now collaborating on compiling state-wide and

regional geographical information system (GIS) databases of modern mining operations, and to the best of their ability, historic mining operations. These publicly available large-scale databases, as they continue to be developed, can provide needed data for exploitation of geothermal energy from underground mine pools. In fact, this paper relies on a recent GIS database of mine pools in the significantly depleted Pittsburgh coal seam in the northern Appalachian coal basin of the United States to estimate potential geothermal energy that can be recovered in this region.

This paper also provides a description of geothermal heat pump technologies and an overview of typical applications. The authors recognize that many different configurations and operating parameters (e.g. mine water recycling in the mine) are possible for geothermal heat pump systems, but chose a simple, straight forward system for evaluating the efficacy of using mine water as a source of energy. The approach is recognized as being limited in terms of maximizing the efficiency of harvesting the low-grade energy source (mine water) using geothermal heat pumps. The authors, however, are hopeful that the reader, after reviewing this paper, will appreciate that mine pools represent a potentially attractive alternative and renewable energy source for heating and cooling.

Background

Heat Pump Technology

Heat pump technology has been around since 1852 when Lord Kelvin first developed the

concept (Lund et al. 2004). In the 1940s, Robert Webber modified the concept using the ground as the source of heat (Lund et al. 2004; IGSHA). These ground source or geothermal heat pumps systems gained popularity in the 1960s and 1970s. In the 1970s, due to oil shortages, many alternate types of energy systems became popular, including geothermal heat pumps (Bloomquist 1999). Today, 500,000 geothermal units are used for residential heating and cooling in the United States and Canada with an additional 400,000 units in Europe (Manitoba Budget Papers 2004). Lund et al. (2005) estimate the total number of 12KW equivalent geothermal heat pump units at 600,000 in the U.S. and 33,000 in Canada. Geothermal heat pumps are one of the fastest growing types of renewable energy in the world, with annual increases of 10% in approximately 30 countries in the last 10 years (Lund 2001). Current interest is very high due to the high prices of natural gas, heating oil and propane. The cost effectiveness of geothermal heat pumps is directly related to the cost of electricity (needed to drive the heat pump) relative to conventional heating fuels such as natural gas, heating oil, and propane. The history of these energy prices will be discussed in more detail later in this paper.

Heat pumps do just what their name implies – pump heat. Thus, in heat pump applications, the heat source is at a lower temperature than the space that is to be heated, and conversely, the heat sink is at a higher temperature than the space that is to be cooled. Because heat naturally flows from higher to lower temperatures, the term heat pump is used to indicate that it causes heat to flow in the opposite direction – similar to pumping water from a lower to higher place. There are many substances, called refrigerants, which undergo phase changes at a wide range of pressures and temperatures. The fact that these liquids absorb heat when they vaporize and give up heat when they condense allows heat to be transferred from one place (source) to another (sink). Heat pumps function using refrigerants that undergo a phase change at the temperatures and pressures used in the heat pump system. Heat pumps utilize a source of low grade heat (anything with a temperature above absolute zero (-273°C) contains heat), and pump this heat indoors using the thermodynamic principles of refrigerants with low-temperature boiling points. If the heat source is outside air, the system is referred to as air source or air coupled. If the heat source is the ground (either the soil or groundwater), it is called ground source, ground

coupled, earth coupled or simply a geothermal heat pump – using the heat from the earth.

Figure 1 shows a diagram of a heat pump system. In heating mode, the refrigerant in a cold liquid form gains heat from the outside source (air or ground) in a heat exchanger (evaporator), where it is converted into a cold vapor. In order for the heat pump to function properly, the liquid form of the refrigerant must be at a lower temperature than the outside heat source and the temperature of the heat source must be high enough to cause the refrigerant to evaporate (boil). After the liquid absorbs heat and is converted to a vapor, it is then compressed (requiring an input of electrical energy), converting it to a hot vapor. The hot vapor is sent to another heat exchanger (condenser). Here the hot vapor gives up the heat that was gained from the source in the evaporator and in the process is condensed to a hot liquid (The heat given up is what is used to heat the interior space). The hot liquid goes through an expansion valve where the drop in pressure converts it to a cold liquid and the process is repeated. In heating mode, the evaporator is placed in contact with the heat source.

The heat from the source is held and released in the refrigerant as it undergoes phase changes and is “pumped” from where it is evaporated to where it condensed. The majority of heat pumps operate on electricity, but some are gas driven. The amount of heat generated divided by the amount of energy needed to operate the heat pump is known as the coefficient of performance (COP). The smaller the difference in temperature between the heat source and the heat sink (required temperature of space to be heated), the greater the COP of the heat pump system. For this reason, geothermal heat pumps have a greater efficiency than air-source heat pumps; the source/sink temperature (the earth) is closer to the desired room conditions than outdoor air temperatures.

In cooling mode, the above process is reversed with the use of a reversing valve (not shown in Figure 1). Heat is removed from the interior space and transferred to the air or ground, which acts as a heat sink. Most residential air conditioning systems are air source heat pumps that take the heat from inside the house and deposit it outside to the air. Refrigerators work using a similar heat pump system – pumping heat from inside the box to outside the box. In cooling mode, the condenser would be in contact with the heat sink (the room atmosphere).

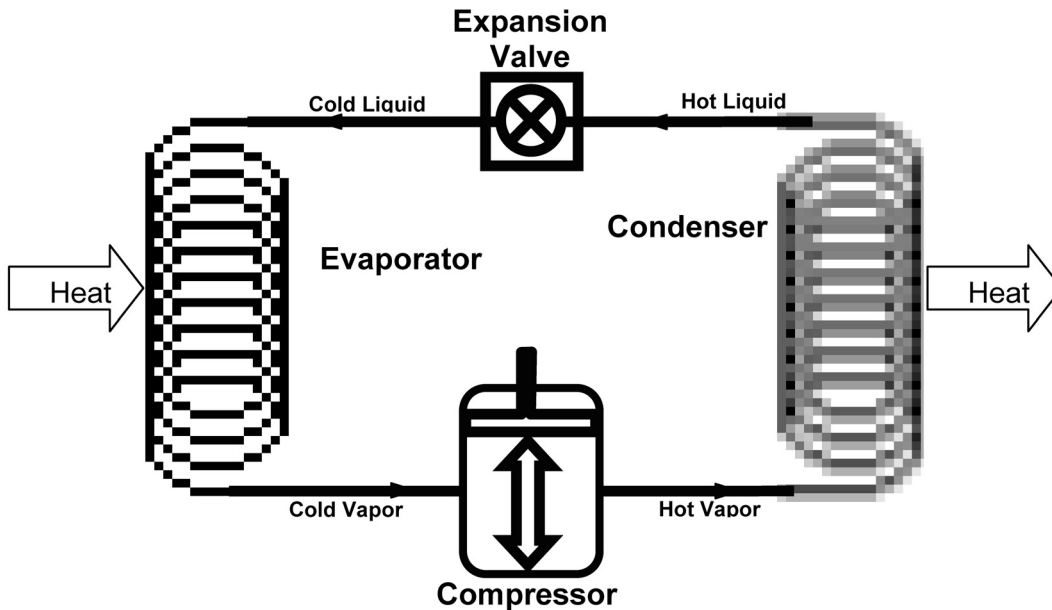


Figure 1. Schematic of heat pump system

Air Source Heat Pumps

An air source heat pump uses the outside air as a heat sink or heat source. In cooling mode, heat is extracted from the building and dispersed to outside air. The warmer it is outside, the more difficult it is to transfer heat. In heating mode, heat is absorbed from the outside air and distributed inside the building. The air source heat pump can usually provide all of the cooling requirements in summer months. During winter months, however, the air source heat pump requires supplemental heating if the outside air temperature drops below about 0°C. Homes with air source heat pumps typically use electrical resistance heating for supplemental heat. As stated earlier, the amount of heat generated divided by the amount of energy needed to operate the heat pump is known as the COP. Electrical resistance heating has a COP of 1.0 since it generates the same heat energy as it uses. The COP of air source heat pumps in cold climates is typically around 2 or less, depending on how often supplemental heat is required (Sound Geothermal Corp 2003). In addition, if the temperature is below 0°C, moisture in the air may freeze on the outside coils; they then need to be periodically defrosted, which is usually done with another set of electrical heating elements, further decreasing overall efficiency.

Ground Source Heat Pumps

Ground source heat pumps use the near-constant temperature of the earth (in soil/rock, ground water or deep surface waters). The earth is typically warmer than the outside air in the

winter (and acts as a heat source), and cooler than the outside air in the summer (and acts as a heat sink). Because of this, geothermal heat pumps systems are much more efficient than air source systems for both heating and cooling. They typically use about half of the energy needed for cooling with air source systems. For heating, the COP of geothermal heat pumps systems reported in the literature is typically between 3 – 4, and as high as 6 (Sound Geothermal Corporation 2003; O’Connell and Cassidy 2003). A ground source heat pump can be designed in a variety of styles based on the ground water access, land availability, and drilling costs. The two main categories of ground source heat pumps are closed and open loop systems (U.S. DOE 2001).

In a closed loop system, no fluid is extracted or discharged to the environment. There are two main types of closed loop systems, one that uses a secondary fluid (usually an antifreeze solution) in a length of thin-walled, high-density polyethylene pipe (HDPE) that is in contact with the earth and another that has the refrigerant in direct contact with the ground (DX). In the former type, the antifreeze solution gains and loses heat from the earth and transfers this heat via a heat exchanger to the refrigerant in the heat pump (Figure 2). The piping configuration containing the antifreeze can be oriented in the ground horizontally, vertically, or even in a spiral design, depending on the available land area and drilling costs. Typically, it can also be coiled within a surface body of water, at a depth of 2 to 3 m below the surface of the water. In the other type of system, the refrigerant is placed in direct

contact with the ground (or groundwater); this is called direct exchange or direct expansion (DX). This typically takes place in fairly small diameter copper tubing (0.64 – 1.9 cm ID) to save expense for both copper tubing and the required volume of refrigerant (PADEP 2001).

In the open loop system, ground water or surface water is extracted from the environment and subsequently discharged back into the environment. The water can be brought to the heat pump equipment and subsequently discharged. The typical flow rate for an open loop system is about 1 to 3 L/minute per kW of heating and cooling (PADEP 2001). There are three main designs of an open loop system: 1) single well open loop, 2) double well open loop, and 3) surface water open loop. The single well open loop system uses an extraction well as a means of obtaining the ground water. After the ground water is used in the heat pump system, it is discharged to a stream,

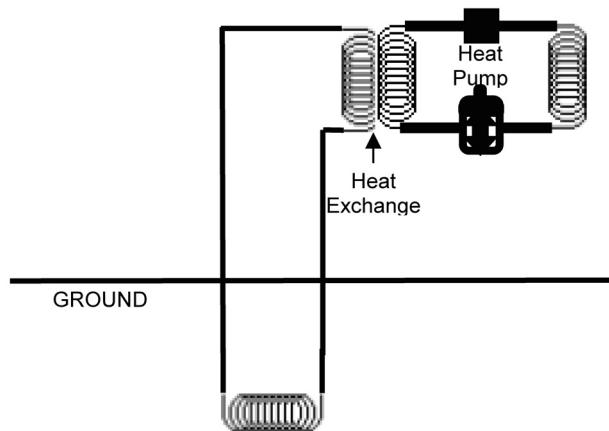


Figure 2. Closed-Loop geothermal heat pump system: the heat pump loop contains refrigerant and the ground loop contains an antifreeze solution.

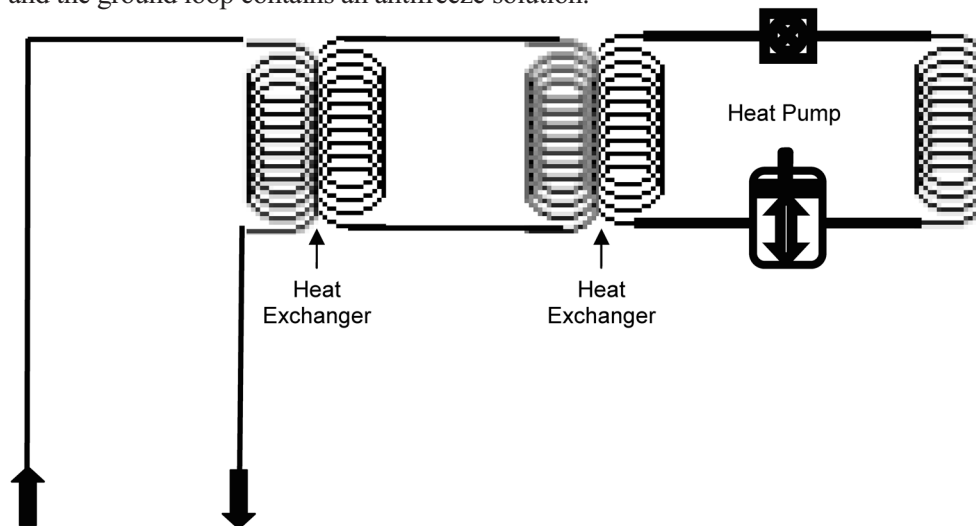


Figure 3. Open loop geothermal heat pump system using a secondary heat exchanger to avoid direct contact of the water with the heat pump; the heat pump loop would contain refrigerant and the open loop would use ground water (or mine water).

river, or lake. Depending on water quality, water treatment may be required. The double well open loop system is similar to the single well system, but a second well discharges the ground water back into the earth. The third design of an open loop system is a surface water system, which uses a large body of water to provide the water necessary for the heat pump system. Water is extracted from the body of water and utilized in the heat pump and discharged back to the body of water. In any of these open loop systems, if the quality of the water is such that it could cause scaling or corrosion within the heat pump, an additional heat exchanger may be used, as in the closed loop system (Figure 3). Since there is still a loop “open” to the environment, this would still be considered an open loop system.

Conventional Heating and Cooling Systems

A conventional heating and cooling system consists of a heating unit, such as a boiler or furnace, and a cooling unit, such as a chiller or air conditioner. Typical energy sources for the heating cycle are natural gas, heating oil or propane. In the United States, 56% of all homes use natural gas for heating, 29% use electricity, 8% use fuel oil (mainly in the Northeast), and 4% use propane (mainly in the Midwest) (U.S. DOE 2001b). The energy source for the cooling cycle is normally electricity. The basis for calculating heating energy costs is the heating load of the structure, the type and cost of operating fuel, and the efficiency of the furnace or boiler. The basis for calculating the cooling energy costs is the cooling load, the electrical costs, and the efficiency of the chiller or air conditioner. The distribution network through the structure for

heating can be via forced air ductwork or radiant heating units, such as radiators. Cooling is typically distributed using forced air ductwork.

Economics of Heating and Cooling Systems

The capital cost to install a geothermal heat pump system varies depending on loop type (open or closed), loop configuration (e.g. horizontal or vertical) and local factors (e.g. drilling/excavation costs), but can range between \$425 and \$850 per kW (U.S. DOE 2001b). Typical increases in capital costs of geothermal systems over conventional systems are on the order of 20 – 50%.

The other cost for heating and cooling systems is operating cost, which consists of maintenance costs and annual energy costs. Maintenance costs for geothermal heat pump systems depend on the type of system, but range from comparable to significantly less than standard heating and cooling systems (U.S. DOE 2001b). Bloomquist (1999) found that maintenance costs for ground source heat pumps are approximately 33% of the costs of conventional systems for a given capacity. The main operating cost for heating and cooling is for the energy required to operate the system. The costs of natural gas, heating oil, and propane have increased dramatically over the past six years. The historical costs of these fuels and how they impact the cost effectiveness of geothermal heat pump systems for heating are discussed below.

Cost Effectiveness of Geothermal Heat Pump Systems

The cost effectiveness of geothermal heat pump systems for heating is directly related to the cost of electricity (to operate the heat pump) compared to the cost of the other conventional fuels: natural gas, heating oil, and propane. Figure 4 shows the costs for electricity, natural gas, heating oil, and propane over the past 50 years. To make it easier to interpret these historical costs, Figure 5 normalizes these costs on a cost per GJ of heat basis. From this graph, it can be seen that natural gas has historically been the least expensive fuel on a cost/GJ basis, followed by heating oil, propane, and electricity, which has been significantly more expensive. However, to get a true representation of the actual cost to the consumer, the efficiencies of each system utilizing the fuel/energy source must be taken into account. Figure 6 displays these costs, using an assumed 84% efficiency for furnaces/boilers burning natural gas, heating oil, or propane (this is an average efficiency of existing systems) and a COP for a geothermal heat pump equal to a very conservative 3.1 (Sound Geothermal Corporation 2003).

Figure 6 can be used to compare the energy costs of conventional heating systems to the energy costs of a geothermal heat pump system. Comparing annual heating costs using heating oil to a geothermal heat pump system: from 1960 – 1973, heating oil was less expensive; 1974 – 1978,

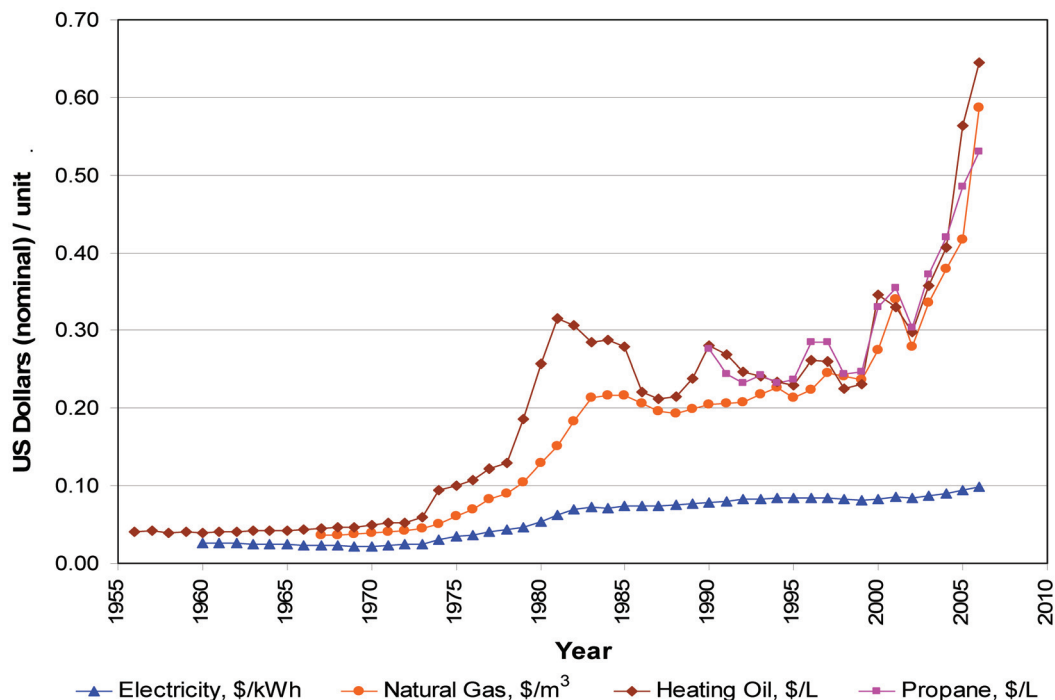


Figure 4. Residential costs for electricity, natural gas, heating oil, and propane over the past 50 years in the United States

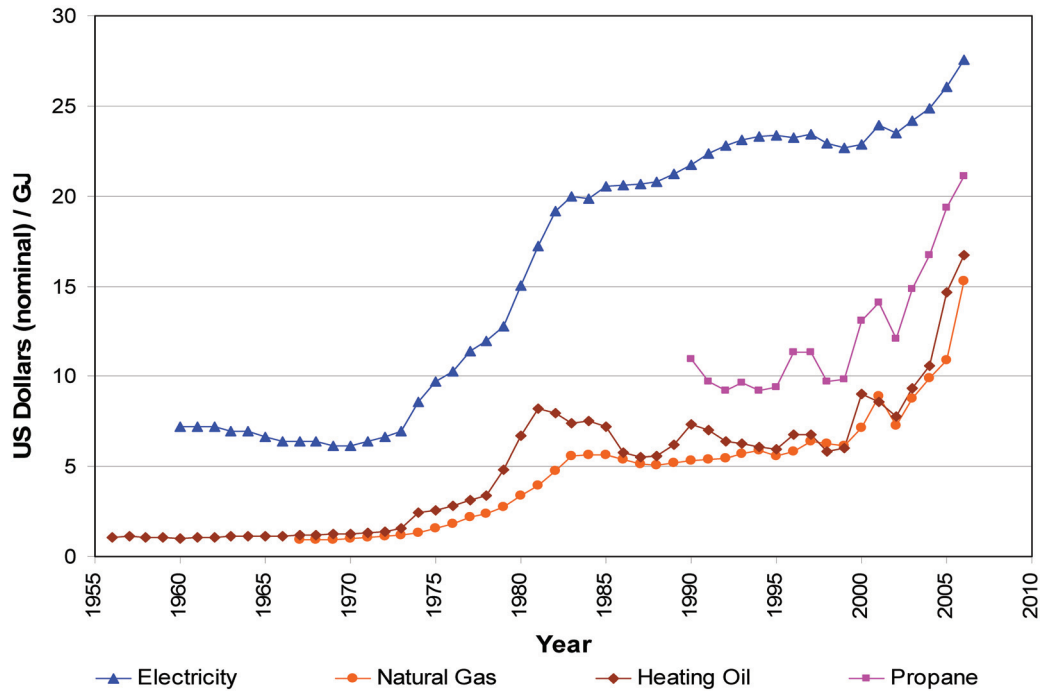


Figure 5. Residential costs for electricity, natural gas, heating oil, and propane on a \$ (U.S.) per GJ basis

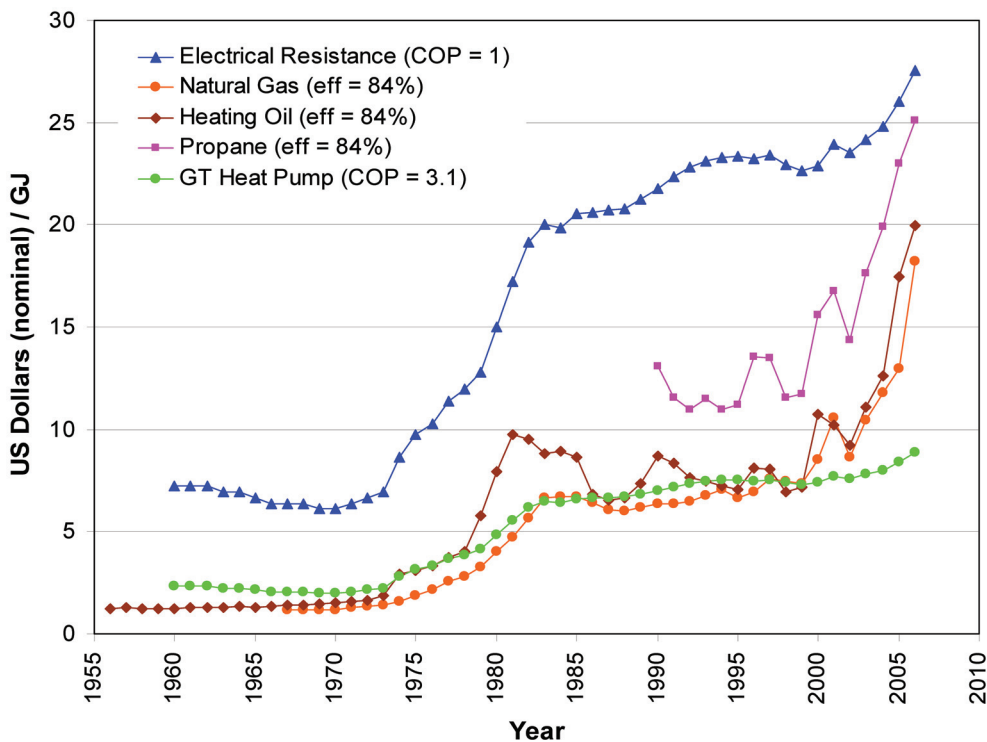


Figure 6. Residential costs for electricity, natural gas, heating oil, and propane on a \$ (U.S.) per GJ basis, assuming all furnaces are 84% efficient and a COP of 3.1 for the geothermal heat pump.

they were about the same cost; 1979 – 1985, heating oil was more expensive; 1986 – 1999, they were about the same cost; and from 2000 to the present, heating oil was more expensive. The latest costs from early 2006 indicate that use of heating oil would cost \$19.94 per million GJ compared to \$8.88 per million GJ for electricity to operate a geothermal heat pump system. Comparing annual heating costs using natural gas to a geothermal heat pump system: prior to

1982, natural gas was less expensive; 1983 – 1999, they were about the same cost; and from 2000 to the present, the cost of natural gas was higher. The latest costs from early 2006 indicate that using natural gas would cost \$18.21 per million GJ compared to \$8.88 per million GJ for a geothermal heat pump system. Figure 6 only lists propane costs back to 1990; for that period, heating costs using propane was always more expensive. The latest costs from early 2006

indicate that using propane would cost \$25.11 per million GJ compared to \$8.88 per GJ for a geothermal heat pump system.

Mine Water Use in Geothermal Systems

Typically, an open loop system would be used for mine water in geothermal heat pump systems. If the mine water is deemed corrosive or scale-forming, an additional loop could be used to isolate the mine water from the heat pump. This would include a heat exchanger (commonly a frame and plate heat exchanger) to transfer the heat between the mine water and heat pump (see Figure 3). In terms of nomenclature, it is important to note that the scheme described above is defined as an open loop system regardless of whether or not the mine water is discharged to a surface stream or back into the mine pool after heat transfer. In the case of a surface discharge, design considerations must focus on the heat transfer of the conventional heat exchanger. However, if the mine water is to be returned to the mine voids (pool), design considerations could potentially also include the heat transfer in the mine pool and adjacent rock strata. The heat transfer consideration becomes more likely in situations when very large volumes or high percentages of the mine pool are being extracted (e.g. district heating). Mine pools typically are so enormous (volumetrically) and represent such a large heat source/sink that recycling large volumes of water can likely be done without impacting the heating and cooling capacity of the overall mine pool. However, it is recognized that there is a finite amount of low-grade geothermal energy stored in any mine pool and a finite heat transfer rate at which the host rock surrounding the mine pool can return the thermally altered water to ambient mine pool temperatures. We estimate that about 30% of the mine water could be annually extracted from and returned to the mines in the Pittsburgh seam without worrying about the long term heat transfer effects; this would increase the potential use of mine water heat pump technology by an order of magnitude over simply using discharging mine water.

However, to determine the heating and cooling capacity (number of homes and/or businesses that can benefit from low grade geothermal energy) of mine pools, assuming that mine water is recycled between the surface and underground pool, many factors beyond the scope of this paper would need to be considered (e.g. the rate of natural recharge, in situ heat exchange). Another complexity associated with attempting to better understand and determine the maximum energy

capacity of a mine pool is the interconnectivity of adjacent mine pools, both laterally and vertically. Multiple seam coal mining is common; for example, the Pittsburgh coal seam has five other major coal seams above it that have been mined and are likely to be interconnected by natural and induced (subsidence) fracture systems. Prior to investigating the thermodynamic and hydrologic settings of underground mine pools, broad-based public acceptance and support of this concept of mine water as a renewable energy source is needed. This is likely to occur as energy costs continue to increase. Finally, industrial support is needed to evaluate how mine design and access could be planned for to help facilitate post-closure use of the mine pool.

The water quality characteristics of coal mine water may include high dissolved solids loading and low pH. For this reason, mine water that is pumped to the surface is commonly treated to raise pH and precipitate metals. In order to determine the scaling and corrosion potential of this water in heat pump systems, the Langelier Saturation Index (LSI) and the Ryznar Stability Index (RSI) calculations can be used (Rafferty 2000). A review of influent mine water quality data (from the Pittsburgh coal seam) at two mine water treatment plants indicates the scaling potential to be minimal and the corrosion potential to be high, based on these calculated indices. However, both formulas predict scaling more accurately than corrosion (Rafferty 2000). It is important to note that if a system is installed and maintained to be air tight, scaling and corrosion can be minimized. In the event that oxygen cannot be eliminated, the mine water can be passed through an isolation plate heat exchanger, thereby reducing the water contact to only the ground loop piping and the heat exchanger. Mine water would not be in direct contact with the refrigerant. Also, corrosion resistant materials can be incorporated into the piping system and the plate heat exchanger to further reduce the corrosion potential.

There have been a few examples of the successful use of mine water in geothermal heat pumps systems in the past. Systems have been installed in Canada, the United States, and the United Kingdom using water from abandoned coal and lead mines.

Springhill, Nova Scotia, Canada

In Springhill, Nova Scotia, flooded abandoned underground coal mines are used to heat and air condition approximately 14,000 m² of interior space. The space is used to manufacture plastic

products (Ropak Can-Am Ltd) and consists of manufacturing, material storage, office areas. The supply well is 140 m deep and pumps mine water at a rate of 240 L/min to the heat pump system, which consists of 11 heat pumps. Inlet mine water temperature is a consistent 18°C with outlet temperatures of about 13°C in winter and 25°C in summer. The water is returned to the mine 30 m below the surface. The capital cost for the heat pump system, including two wells drilled to the mine was about 20% higher than the estimate for conventional oil furnace system. Maintenance costs were thought to be considerable lower than what would be expected for the oil furnace system. The estimated COP for the system was 3.6. The company estimated that the geothermal system saves \$160,000 per year in energy costs over a conventional oil furnace system. The payback period for the additional capital cost was estimated to be less than one year using energy costs from 1989 (Jessop et al. 1995).

Park Hills, Missouri, United States

A municipal building in Park Hills, Missouri uses water in abandoned lead mines to heat and cool a 750 m², two-story building. The supply well is 120 m deep and pumps 14°C mine water at a rate of 280 L/min to the heat pump system, which consists of 9 heat pumps with a 113 kW capacity. A secondary plate-and-frame heat exchanger is used to isolate the mine water from the heat pump system. The water is returned to the mine via a return well. The geothermal heat pump system cost an estimated 20% more than a conventional system composed of rooftop air conditioners and natural gas heating system (\$132,400 compared to \$110,200). In 1996, it was determined that the system saved \$4800 over the estimated energy cost for a conventional system (about 30% savings). The pay back period was calculated to be about 4.6 years using energy costs from 1996. No information concerning maintenance costs could be found (GHPC 1997).

Shettleston, Scotland, United Kingdom

Sixteen houses in Shettleston were rehabilitated to make them more energy efficient and to implement a geothermal heat pump system using water from an abandoned coal mine. The supply well pumps 12°C water from an abandoned coal mine 100 m below the surface. Two heat pumps use the heat in the mine water to heat water to about 55°C. This water is stored in a large thermal storage tank before being circulated to the houses. After flowing through the heat

pumps, the mine water is discharged below the water table (John Gilbert Architects 2006a).

Lumphinnans, Scotland, United Kingdom

Eighteen houses in Ochilview, Lumphinnans were rehabilitated to make them more energy efficient and to implement a geothermal heat pump system that uses water from an abandoned coal mine. The supply well pumps 14.5°C water from the mine, which is 170 m underground. The heat pump system uses the heat in the mine water to heat water to 45 - 53°C, which is stored in a large thermal storage tank before being circulated to the houses. The storage tank is necessary since the heat pumps work from an economy tariff and is only available for 18 hours per day. After flowing through the heat pumps, the mine water, now at 3°C, is discharged to a permeable strata layer above the mine pool. Annual heating costs were reduced by 80% (John Gilbert Architects 2002, 2006a).

Other Potential Locations

In Timmins, Ontario, Canada, a 3-year study was conducted to determine the potential of using the water in an underground coal mine below the city to heat and cool public buildings throughout Timmins. The cost of retrofitting and long distance pumping of the water was too high for use in many buildings. However, the Shania Twain Center is considered a candidate for this technology. The mine water is 200 - 250 m below the surface at a temperature of 12 - 13°C (Louiseize 2005). A project partially funded by the EU is investigating the use of mine water for heating and cooling of large-scale developments in the Netherlands and Scotland. Representatives from other former coal mining countries (Germany and Poland) are also involved. The project looks to rebuild the economy of past coal mining town by locating developments over abandoned mines (Energy Vortex 2005). The Dept of Civil Engineering at Newcastle-upon-Tyne University is investigating the use of mine water for heating and cooling in the UK. They envision housing and industrial sites being developed around old mine shafts to take advantage of low heating and cooling costs by using the mine water as a source and sink for heat. Water temperatures of above 15°C are characteristic of mine water below 150 m (Sutton, ARC Today 2002).

Exploitation of mine water in geothermal heat pump systems is also being planned in Poland and Slovakia (Bajtos 2001; Malolipsy 2003). Malolipsy (2003) modeled heat exchange in the

mine voids to determine the renewability of the resource. There have also been uses of mine water for direct heating of ventilation air at a molybdenum mine in Empire, Colorado in the United States. The mining company uses the 29°C mine water to directly heat the air used for ventilation to prevent ice buildup in the intake air shafts, water line freezing, mine employee discomfort and equipment related problems. Water is pumped at 4300 L/min and used to heat 45.3×10^6 L/min of air (Jensen 1983).

Additional Potential Use of Underground Mine Water in the U.S.

Abandoned underground mines (coal, lead, zinc, and limestone) can be found throughout most of the states, with many of these mines already flooded. Coal mines are considered the most likely candidates for exploiting geothermal energy because of their typical broad-based accessibility. Figure 7 shows the coal bearing areas of the U.S. and illustrates the aerial extent of coal deposits. Coal production will continue to increase as long as the demand for coal continues to grow. The most recent update on demonstrated U.S. coal reserves shows that 67% (310,000 million t) of the total reserves will require the use

of underground, rather than surface, mining methods (U.S. DOE 1999). Also noteworthy is that coal can be mined approximately five times faster using longwall mining than with a continuous miner. The approximate 5,000 km² of the Pittsburgh coal seam (described below) mined during the past two centuries using various methodologies (pick and shovel, drilling and blasting, continuous miner) could now be mined in about 40 years using longwall mining.

The broad and varied access of mine water allows for assorted approaches or applications of heat pump technologies. In general, a low-grade heat source will be available either from surface discharges (pumping or gravity/artesian flows) or from an underground reservoir or lake-like situation. Due to the large volumes of mine pool waters and underground void space, the heating and cooling capacity of mine water can be much greater than most conventional natural groundwater settings. The accessibility of abandoned mine water for beneficial use varies. Generally, in abandoned, pre-law mining situations, mine water drains out of the hillsides or flows out the typically shallow underground workings by artesian discharge. These abandoned mine water discharges can range between tens to thousands of

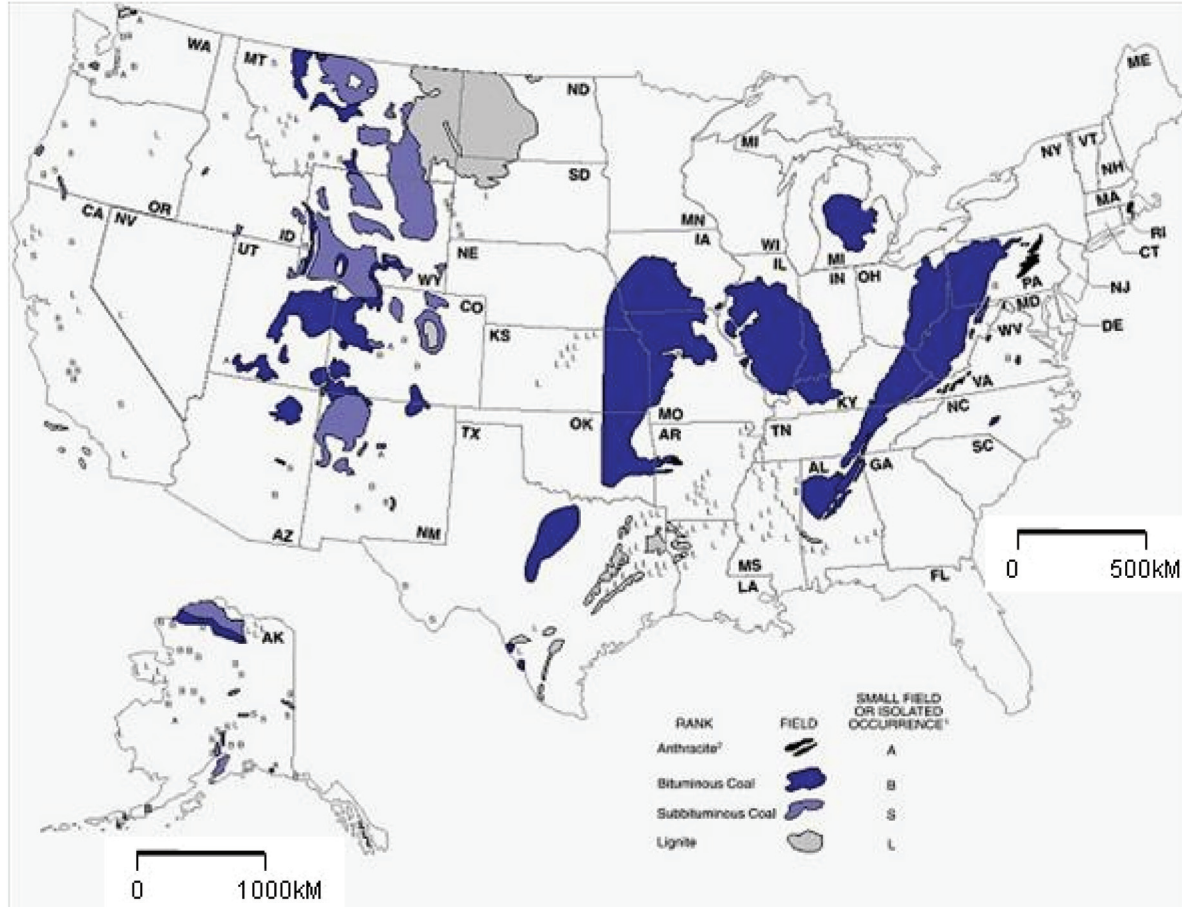


Figure 7. Coal bearing areas of the United States

liters per minute. These numerous discharges are commonly the result of natural, site-specific settings (e.g. sink holes, fracture zones, geologic anomalies) and their locations are sometimes unknown due to poor or unavailable maps. These shallow underground sources provide the easiest access; however, their discharges were generally not engineered. In the modern mining scenario, mine pools are generally at a depth between 50 and 250 m; contemporary mapping allows mine pools to be located and volumes to be determined more accurately. Modern mine water handling and treatment operations, mandated by current environmental and mining regulations, are well engineered and have discharges that are clearly identified and characterized. Also, because they are engineered, these discharges are typically large and discharged through pumping operations at pre-determined locations. Utilization of underground mine water in geothermal heat pumps should be extremely cost effective, particularly at water treatment sites where the mine water is already being pumped and treated, since such sites would be excellent opportunities for single well open loop systems.

The Potential Use of the Pittsburgh Coal Seam

This paper discusses the potential use of mine water in the Pittsburgh coal seam in Pennsylvania, West Virginia, and Ohio for heating and cooling. This historic coal seam is currently flooding and will completely fill and begin discharging water in the relatively near future. As shown in Figures 8 and 9, the availability of underground mine water in the Appalachian coal region is very widespread. The heating and cooling capacity of this underground mine water is a valuable resource that is not being used. Treated water is simply discharged to a receiving stream. The amount of water that is currently being surface discharged (from treatment plants and uncontrolled, abandoned discharges) from underground coal mines in just the Pittsburgh coal seam totals about 2.0×10^{11} L/yr (Donovan et al. 2004). This water could potentially be used to heat and cool up to 3.74 million m² of interior space, roughly equivalent to 20,000 homes (185 m² each). This annual volume (and calculated heating and cooling capacity) represents only 3.9% of the total stored volume in the Pittsburgh coal seam. Consequently, the ground water in abandoned underground coal mine workings represents an enormous resource in the form of a stored low-grade heat source. Throughout the Pittsburgh coal basin region (Figure 8), the water is easily accessible and maintains a constant temperature of 10 to 13°C (U.S. DOE 2001a).

Only 12 out of over a total of 1,200 underground coal mines are currently active in the Pittsburgh coal seam, which is just one of several coal seams that have been mined in the Appalachian coal region. The rest of the underground coal mines have been closed, and are flooded, flooding, or free draining. Approximately 13,000 km² have been mined in the northern portion of Appalachia and nearly 5,000 km² are currently flooded (Donovan et al. 2004). Many of the largest underground mines have closed during the last 20 years and are either flooded or flooding. The flooded underground volume in the Pittsburgh coal seam is estimated to be 5.15×10^{12} L (Donovan et al. 2004). Throughout the basin, 2.0×10^{11} L/yr (equivalent to 380,000 L/min) are discharged (Donovan et al. 2004). This discharged volume will increase as the flooding mines fill and begin to discharge at the surface. Approximately 77% of this discharged water does not pass through a treatment plant; however, a large portion of the remaining percentage is pumped and treated.

The easiest access to this geothermal heat source would be at: surface (gravity or artesian) discharges within and adjacent to coal seam outcrops, which are found throughout the region (from early, unregulated mining operations), and modern treatment facilities that are operated based on legal obligations. U.S. regulations require coal companies to treat mine water to specific effluent limits (pH between 6 – 9, Fe less than 3.0 mg/L and Mn less than 2.0 mg/L) prior to discharge. Typically, water is pumped from the mine pool to the surface for treatment, and subsequently discharged to a nearby stream. In this conventional scenario of pump and treat, the extra cost of installing a mine water pumping system for the purpose of heating and cooling with heat pump technology is eliminated.

If this technology were applied to the entire flooded Pittsburgh coal basin, using just the water currently being discharged (380,000 L/min), to heat and cool $\approx 20,000$ homes, approximately 437,000 MWh would be saved annually, compared to standard electrical heating and cooling. Along with these energy savings, annual emissions of SO_x and NO_x would be reduced by 2100 and 920 t, respectively. Compared to air source heat pumps, 238,000 MWh of electricity would be saved annually, with a resultant reduction of 100 and 500 t of SO_x and NO_x, respectively. Pumping ground water from mine pools for use in large installation heat pump systems could increase these annual savings by up to an order of magnitude.

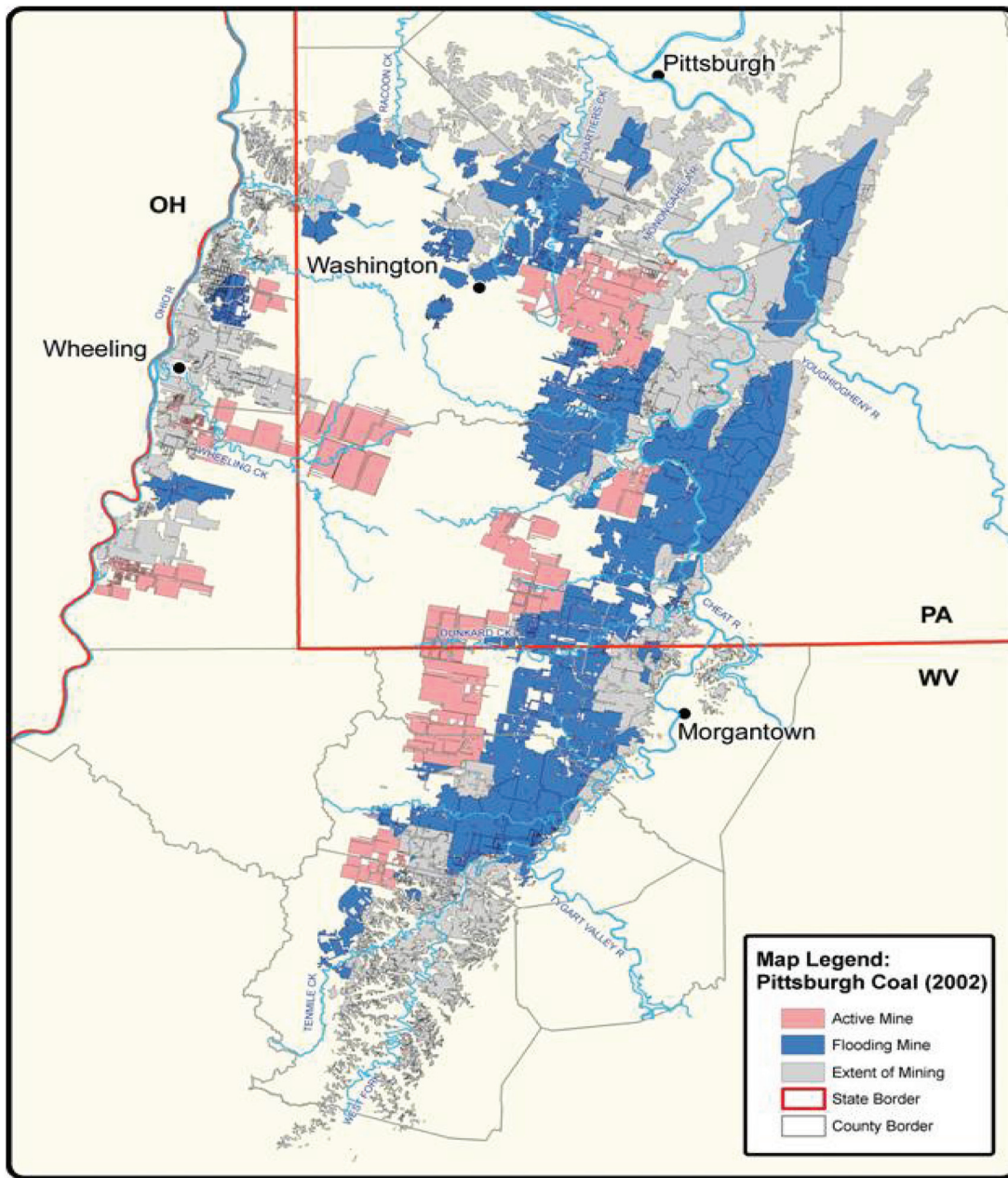


Figure 8. Status of mining in the Pittsburgh coal seam

Table 1 shows the cost for one GJ of heat for geothermal heat pump technology compared to conventional heat technology using actual energy cost in the Pittsburgh area. Electricity and natural gas costs were calculated using the author's utility bills (December 2005 for electricity and January 2006 for natural gas); the total cost (including taxes and other incidental charges) was divided by the amount of the commodity received (KWh for electricity or m^3 for natural gas). Heating oil and propane prices were based on actual delivered cost to a consumer in the Pittsburgh area, again dividing the total cost divided by the volume received.

In addition to the cost of the electricity to operate the geothermal heat pump, there would be a cost to pump the water to the system. Pumping the

water from a discharge to the system (less than 1 m lift) would add about \$0.14 per GJ. The costs to pump from depths of 30, 75, 150, and 300 m would add \$0.44, \$0.87, \$1.60 and \$3.06 per GJ, respectively.

An illustrative example of potential annual cost savings using data from one author's house is given below. The house is 45 years old with 263 m^2 of above-ground living space. The house has average to below average insulation and uses a new 97% efficient, forced air natural gas furnace for heating. For this example, the amount of natural gas used from October 2004 through April 2005 to heat the house in Pittsburgh, PA was used. Each month, 34 m^3 was subtracted, representing the amount of natural gas used for hot water heating, which was the only other use of

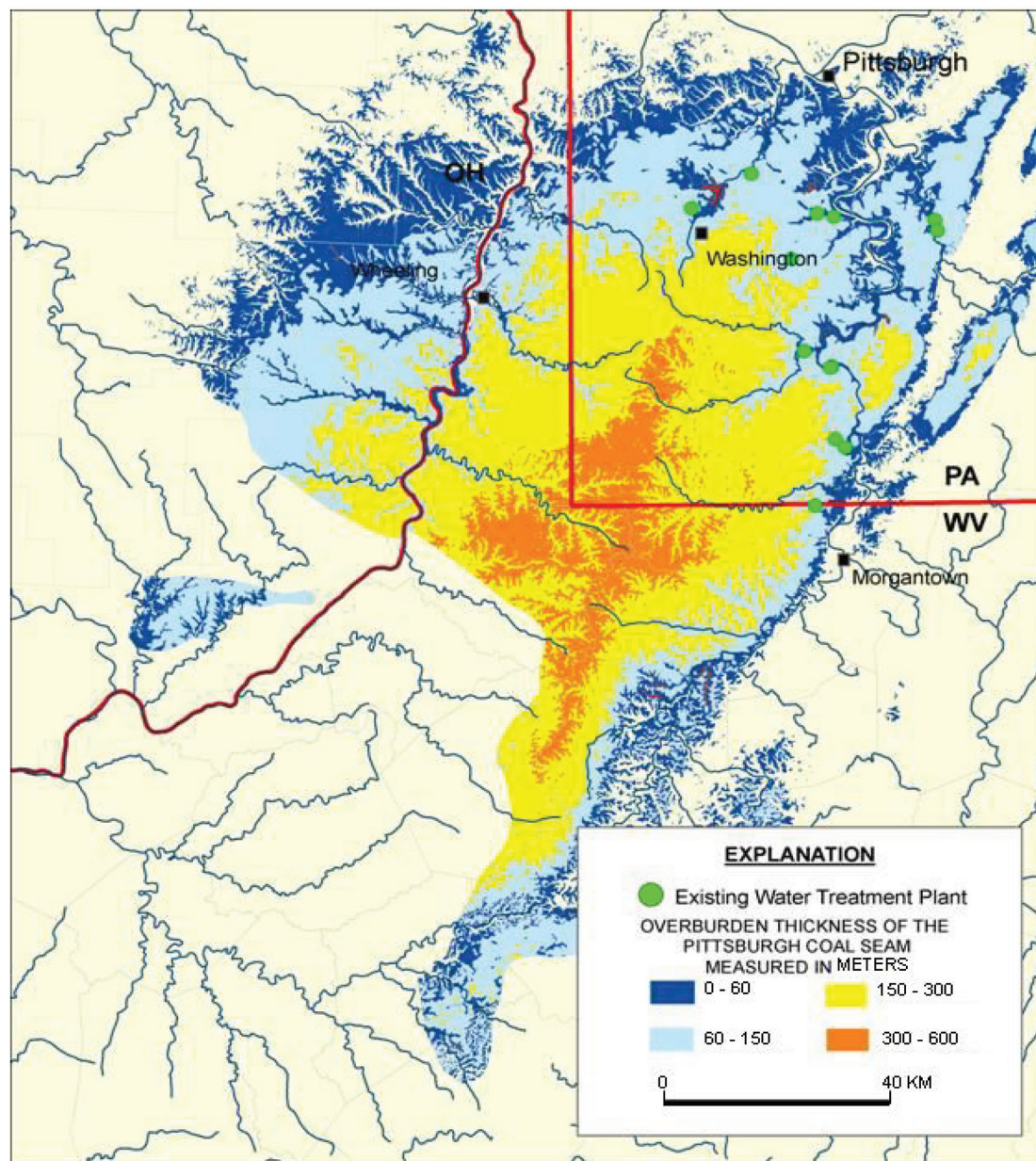


Figure 9. Overburden depths above the Pittsburgh coal seam in Pennsylvania, West Virginia and Ohio and location of existing water treatment facilities in Pennsylvania.

Table 1. Costs per gigajoule of heat using typical heating systems

Energy source	Formula for cost per GJ	US\$/GJ*
Propane	$(39.8 \times \text{cost/liter}) / \text{efficiency}$	30.37
Electrical Resistance	$(278 \times \text{cost/kWh})$	19.74
Fuel Oil	$(26.0 \times \text{cost/liter}) / \text{efficiency}$	19.22
Natural Gas	$(26.0 \times \text{cost/m}^3) / \text{efficiency}$	18.54
Geothermal Heat Pump	$(278 \times \text{cost/kWh}) / \text{COP}$	6.37

*Assumed cost of propane = \$0.641/liter, electricity = \$0.071/kWh, fuel oil = \$0.621/liter, and natural gas = \$0.599/m³ (all energy costs based on actual fuel costs and utility bills in the Pittsburgh area). Furnaces were assumed to be moderately efficient (84%). A COP value of 3.1 was used for the geothermal heat pump using mine water that was gravity discharged.

natural gas in the house. This volume was based on the summer use of natural gas when its only use would be for heating water. A total of approximately 3280 m³ of natural gas was used for heating during the winter of 2004-2005. This

equates to the use of about 130 GJ of heat. Table 2 shows the costs for conventional heating and a geothermal heat pump system that would be incurred to produce this amount of heat.

In 2004, a new furnace, with air conditioning, electrostatic air cleaner, and humidifier cost about \$8000, including installation. Assuming a geothermal heat pump system would, on average, cost an additional 20%, this would amount to an extra \$1600. The payback period based on the annual heating costs in Table 2 would be 1.2 years. This does not include savings for cooling, which would be about 50% of the estimated annual cooling costs of about \$210, equal to about \$105 per year savings. Total annual heating and cooling costs would be reduced from \$2300 for the existing system to \$875 for a geothermal heat pump system using mine water. This represents a 62% reduction in heating and cooling costs for an annual savings of \$1425.

Legal Issues

Mining companies are required to treat mine water, and so mine water has always been considered a liability. Though no legal conflicts associated with mine water use have arisen, to the knowledge of the authors, if this technology proceeds, the legal rights for mine water would need to be clarified. Given the geothermal potential of mine water, non-mining entities may be enticed to use mine pool water for heating and cooling capabilities. If mine water is brought to the surface at a non-treatment plant location, the water would be either returned directly back into the mine pool or a treatment plant would have to be installed. In the U.S., in order to directly discharge back into the mine pool, a Class V Injection Well Permit might be required. In this situation, it would appear that the need for water treatment cost compensation would need to be addressed to allow a non-mining entity to use the water.

Summary and Conclusions

Use of underground mine water in geothermal heat pumps could be extremely cost effective, particularly at existing mine water treatment sites where the mine water is already being pumped and treated. Operational costs are much lower than that of conventional heating and cooling options. Costs per unit of heat for geothermal heat pumps using underground mine water are only 33%, 34%, and 21% of the costs incurred using fuel oil, natural gas, or propane, respectively. Cooling costs using mine water and geothermal heat pumps should be less than 50% of the costs associated with conventional air conditioning systems.

The availability of mine water in the Appalachian coal region is very widespread. The

Table 2. Costs for 130 GJ of heat using typical heating systems compared to a geothermal system using mine water

Energy source	Cost, U.S. \$
Propane	3420
Electrical Resistance	2570
Fuel Oil	2160
Natural Gas	2090
Geothermal Heat Pump	770

*Assumed cost of propane = \$0.641/L, electricity = \$0.071/kWh, fuel oil = \$0.621/L, and natural gas = \$0.599/m³ (all energy costs based on actual fuel costs and utility bills in the Pittsburgh area). All furnaces were assumed to be 97% efficient. A COP value of 1.8 was used for the air source heat pump. A COP value of 3.6 (which is the energy star criteria for open loop systems) was used for the geothermal heat pump using mine water that was being pumped from a depth of 75 m (approximate depth to the Pittsburgh coal seam under author's house).

heat in the mine water is a valuable resource that is currently being wasted when treated (or untreated) mine water is discharged to a receiving stream. The amount of water currently being discharged from underground coal mines in just the Pittsburgh coal seam totals about 2.0×10^{11} L/yr. This volume of water could potentially be used to heat and cool up to 3.74 million m² of interior space, roughly equivalent to 20,000 homes. Using the water stored in the mines would conservatively extend this option to an order of magnitude more sites. Because some mines are currently filling, these volumes will increase in the future. Research is needed to demonstrate and develop this valuable resource.

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