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Geothermal energy recovery from underground mines

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ABSTRACT

Underground mines are extremely capital intensive, but despite this investment the traditional view has been that they have little useful value after closure. There are, however, potential positive uses of closed mines, in particular the generation of renewable geothermal energy. After closure, many mines flood and the relatively stable temperature of this water can be exploited by the use of geothermal recovery loops coupled to heat pumps. A review of the current situation, despite increasing pressures to identify sources of renewable energy, reveals that there are still only a limited number of existing and proposed installations. Nevertheless, a survey of those that do exist demonstrates the potential value of this approach. In particular, during the winter heat can be extracted from mine water and supplied for space heating, and in the summer the process can be reversed and the heat transferred back to the water to provide cooling.

Contents

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1. Introduction

For many countries, the mineral resource industry is a key employer and economic driver. The industry is also extremely energy intensive, with much of the energy provided by fossil fuels. In Canada for example, it is the largest industrial sector in terms of both energy consumption and greenhouse gas emissions [1]. Not surprisingly, therefore, the industry is placing significant focus on improving energy efficiency, as well as implementing cleaner production technologies [2,3]. This includes looking at life cycle modeling to define all environmental impacts [4], greenhouse gas emissions [5] and improved energy management [6] (Table 1).

Mines are often located in remote areas where harsh climates might discourage the development of large towns and cities. Settlements that do exist close to mines are often a direct result of the mine itself. They are, therefore, highly dependent on the continued operation of the mine for the employment and revenue it generates, as well as the importation of fuel. Such a strong dependence on a finite resource often results in decreased sustainability, particularly in developing countries [7]. For remote communities any renewable energy source to offset the consumption of imported fuels would, therefore, be highly desirable [8].

Established mineral resource operations very often own or occupy large tracts of marginal or non-productive land. Even junior companies can own a great deal of land due to their emphasis on prospecting [9]. This land plays a crucial role in the long-term sustainable development and expansion of mining. Legislation now ensures that reclamation of mine lands is planned and paid for before ground can be broken on any new mines [10]. The land must be reclaimed following closure of mining operations and in many cases must continue to be maintained.

A significant step towards sustainable mining would be non-traditional uses for the mine and its surrounding lands. In particular, uses that would allow them to continue to provide value and jobs to the community after mining operations cease. The alternate use of mine infrastructure following closure would contribute to the community in a practical sense and improve the morale of those who historically relied on the mine and its suppliers [11]. Worldwide the estimate for the number of abandoned mines is well over a million [12]. One option is to consider using these sites for energy recovery schemes that would both offset fossil fuel consumption, and reduce greenhouse gas emissions.

Disused underground mines have the potential to be used for the storage of energy [13], including compressed air energy systems (CAES) [14]. CAES use electricity from sources such as wind or off-peak output from utility power plants to compress air, which is then stored under pressure underground. When there is a peak demand for electricity, the compressed air is withdrawn from underground and used to power a turbine. CAES storage is commonly used where there are large voids, such as salt mines and limestone caverns [14]. There is also interest in use of warm mine water [15,16] and smelter off-gas [17] to support the growth of microalgae for on-site biodiesel production. Another study has looked at energy recovery from mine waste dumps [18,19]. A ground circuit heat pump system would collect energy from heat exchangers installed inside the dump and deliver it for space heating.

Another promising option and the focus of this review, is use of mines for geothermal energy recovery [20,21]. The approach is to use mine water as either a heat source or a heat sink. This has significant potential value as it can utilize otherwise unexploited resources that lie in an abandoned and flooded mine. An investigation in the US of about 1600 abandoned mines for prospects for on-going discharge of useful quantities of warm water resulted in a detailed look at 80 sites [22]. The most promising was found to be a mine in the Little Rockies, which discharged water at an average of 7.3 °C above the mean annual air temperature.

2. Mine water from underground mines

Mines can essentially be classified as: (i) operating; (ii) not operating, but continue to be maintained; and (iii) closed. In an operating mine, dewatering to pump water from inside the mine to the surface is a common practice. Any failures or shortcomings in the dewatering system can manifest themselves as underground flooding of active mine workings. Water permeates into mines from a variety of sources, including surface accumulations, aquifers, bed separation cavities, solution cavities and old mine workings [23].

The design of a dewatering system involves a three-phase study prior to the development of the mine [24]. The first phase is a desk study based on a borehole census. The second phase looks at the impact of mining on the ground water and vice versa. The third phase looks to remove or reduce the hazard that the water poses to mining operations, including diversion and dewatering. This can be accomplished through trial dewatering, computer modeling and application of practical experience [24]. More advanced studies combine 1-D, 2-D, and 3-D models to provide high levels of accuracy [25,26].

Mines which only have low grade reserves left, may be maintained with the intent of reactivating them when ore prices become more favorable. These mines will continue to be dewatered to maintain stability and safety. In this state, the mine is said to be in maintenance mode. There are a number of tools that exist for calculating water inflow into mines which can be used for designing dewatering systems [27].

With fully closed mines, without ongoing dewatering water levels may continue to rise until the mine is flooded. Mines are often closely monitored during the re-flooding process to ensure that contaminated waters do not "leak" into the environment. For example, the Giant mine in the Yukon was monitored to ensure water levels remain below arsenic trioxide dumps stored in the mine 75 m below surface [28]. The Butte mine in Montana continued to have the water levels monitored for 25 years following stoppage of dewatering [29].

Nevertheless, mine water can leak out of mines in a relatively uncontrolled fashion. From 1976 until 2005, the Britannia mine in British Columbia was responsible for 14 million L/day of polluted water flowing into the ocean at Howe Sound [20]. The top of the mine is 1310 m above sea level [30]. The entrances to the mine, called glory holes, are, therefore, also located above sea level and from them acidic metal rich waters flowed down into Howe Sound.

Remediation of the mine included the plugging of one of the glory holes to cause all of the water to exit from one place, which was also accompanied by the successful installation and operation of a treatment plant in 2005. This water flowing from the mine may also present a great opportunity for energy recovery with heat pumps. No energy is needed for pumping the water, and also the capital costs associated with drilling can be avoided. However, the low pH (4.0–4.5) and high variability of flow rates will provide challenges in designing an energy recovery system.

The Wheal Jane tin mine in Cornwall, England was abandoned in March of 1991. By November 1991 the water levels in the mine were high enough that it started to flow from the mine adit [31]. The adit was subsequently plugged to keep the water from leaving the mine, and an emergency treatment system was put into place. This facility involved pumping water from the shaft and treating it with lime. Treatment was, however, suspended in January of 1992 due to turbidity issues. The adit plug failed soon after resulting in the uncontrolled release of 50,000 m^3 of mine water with a metal concentration of 3500 mg/L. Whereas, continued dewatering of the mine and treatment of the water as needed would have avoided this disaster, as well as potentially provide the opportunity to recover geothermal energy from the mine water.

Table 1
Energy use and greenhouse gas emissions by Canada's mining industry [1].

	1990	2004	2005	2006	2007
Total energy use (PJ)	2710.0	3,311.6	3244.3	3155.5	3471.6
Mining industry (PJ)	347.8	635.9	690.6	710.5	867.0
Mining % of total	12.8	19.2	21.0	22.5	25
Total GHG emissions (Mt of CO_2 emitted)	135.8	163.7	158.7	158.0	168.5
Mining industry (Mt)	18.7	33.7	35.3	36.4	44.4
Mining % of CO_2	13.8	20.6	22.3	23.1	26.3

Detailed site water balance and models, which incorporate potential consumers of geothermal energy will help to not only identify opportunities for energy recovery, but also uses of the energy on, or near, the site. Currently, modeling of water flows through, and out of a mine is, however, focused on those opportunities presented by flooded mines [32]. Models that have been developed to predict aqueous speciation, groundwater flow and reactive transport can be adapted and applied to abandoned mine systems [33]. This modeling is primarily aimed at assessing a heat map of geothermal reserves. It is, therefore, different from than that needed for an operating mine, which will require assessment of dynamic processes due to ore extraction activities.

Ideally, energy recovery systems should be designed and developed as the mine itself is being planned. This would allow forward planning of the incorporation of geothermal energy recovery, either during ore extraction or post-closure. However, this is not the current practice, with the nearest being the analysis of mine galleries prior to flooding [34]. This analysis was carried out in order that heat exchanger design could be optimized and a unit installed prior to flooding.

3. Geothermal energy recovery systems

The usual method to exploit geothermal energy contained within mine water is heat pumps in conjunction with either open or closed loops [20,35]. Heat pumps can be used to provide both space heating and cooling. In the winter, energy is taken from the water and in the summer, energy transferred into the water [36]. If the mine water is used only for heating, it may cause the temperature of the water to slowly decrease, resulting in a diminished heating capacity. Additionally the level of the water in the mine must be considered, not only to optimize the geothermal system, but to also minimize oxidization of the ore body [12].

The amount of energy recovered will depend primarily on the size and number of heat pumps that are installed. These in turn will be based on the temperature and flow of water from, or back into, the mine. If the water is to be discharged into the environment following the removal of energy, then water regulations must also be consulted to ensure that it meets requirements. For instance in Ontario, Canada, regulations state: "*The natural thermal regime of any body of water shall not be altered so as to impair the quality of the natural environment. In particular, the diversity, distribution and abundance of plant and animal life shall not be significantly changed.*" [37]. The guidelines also limit hot water to a maximum of 10 °C above the local ambient temperature, although they lack a guideline for cool water discharges.

If the water is to be returned underground following energy recovery, then it is imperative that the geothermal capacity of the mine be determined. If the system is oversized for the geothermal resource then the temperature of the water will steadily decline until the recovery of energy from the mine is no longer sustainable. If the heat pump system is reversible and provides both space heating and cooling, then the size of the system can increase compared to a system used solely for heating [36]. That is, the addition of energy to the water during the cooling season supplements the energy removed during the heating season. This can greatly reduce or even eliminate the temperature degradation of the mine water.

There are two basic types of geothermal loop systems coupled to a heat pump that can be employed with mine water.

3.1. Closed loop

Most residential geothermal setups utilize closed loops [38], with the loops placed in the ground in a variety of ways, or even in a pond or lake if there is one in close proximity. For mines closed loop systems will be utilized if the source of water is contaminated. This is likely to be the case with operating mines, or with flooded mines with poor water quality. For a mine an in-shaft system is the most likely, as illustrated in Fig. 1. The simple closed loop system features an in-shaft heat exchanger coupled to a heat pump to provide space heating/cooling for buildings using in-floor loops [39].

3.2. Open loop

Open loop systems are appropriate when there is a large volume of water of reasonable quality. This type of geothermal installation is found, therefore, in closed flooded mines when the water does not have any problematic characteristics, such as extreme pH, suspended solids or hardness. As shown in Fig. 2, open loops can be installed in a single shaft, with the pipes at different elevations, or in separate parts of the mine. During the winter the water is taken from the deeper part of the loop, where it is warmer, and injected back at higher elevation. In the summer this is reversed, with cool water taken from higher up and it is discharged back into the deeper well.

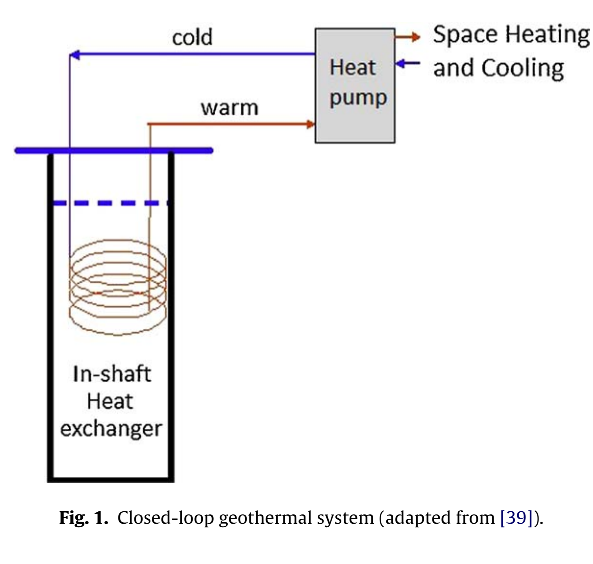

Fig. 1. Closed-loop geothermal system (adapted from [39]).

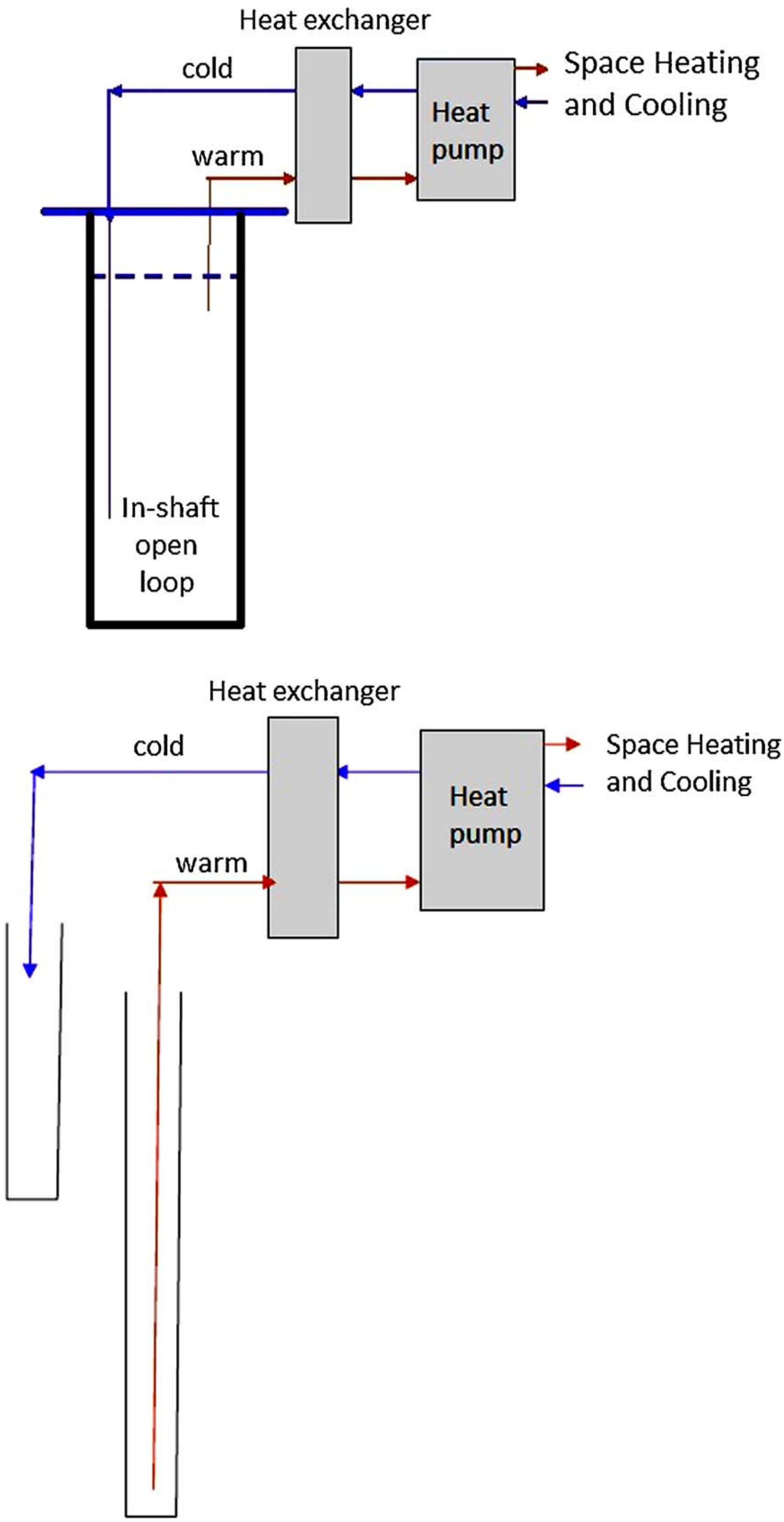

Fig. 2. Open-loop geothermal system (adapted from [39]).

4. Space heating and other applications for geothermal energy recovered from mines

There are a number of applications for the geothermal energy recovered from mine waters. The vast majority of existing projects and feasibility studies, however, use systems that upgrade the energy with heat pumps and provide space heating to buildings. In-floor heating is preferred over forced air, as it provides better efficiency. Space cooling can be also provided by reversing the heat pumps. The use of space cool-

Table 2
Geothermal mine water use in Germany (adapted from [59]).

Mine name	Mine type	Location	Installation date	Capacity	End user
Heinrich mine	Hard coal	Essen–Heisingen	1984	~350 kW	Space heating retirement home
Zollverein mine	Hard coal	Essen–Katernberg	2000	N/A	Space heating school
Shaft 302	N/A	Marienberg/Sachsen	2007	N/A	Adventure-bath
N/A	Tin	Ehrenfreidersdorf, Sachsen	1994	N/A	Space heating school
N/A	Tin	Ehrenfreidersdorf, Sachsen	1997	82 kW	Museum building, visitor mine

ing can help to improve the sustainability of large systems [36].

Geothermal district heating systems provide the same service as space heating, but to a larger number of buildings. For this reason it is preferable to design and install district heating and/or cooling systems early in the development of a community [21]. With district heating systems, a larger number of heat pumps will typically be also utilized. This typically requires multiple wells to be drilled, as is the case with the geothermal district heating system in Heerlen, Netherlands [40]. The five wells at Heerlen are located around the town which allows them make use of several mine shafts (see Section 5.3), thereby reducing the cost of the surface distribution network District heating using geothermal resources from mines can be also extended to include development of commercial or industrial parks [41]. These parks in turn will generate jobs through the businesses that are opened and supported. This will be only an option, however, for mine sites with large enough populations in close proximity [26].

A study that examined the relationship between district heating utilities and industry [42], looked at industry providing waste heat for district heating and the district heating providing energy for industrial operations. They concluded that substantial savings can be made through a partnership between district heating operations and industry, but the potential downside is the "*uncertainty concerning the future of the industry providing the waste heat*". When a mine is providing waste heat to district heating operations, no such uncertainty exists, as mines can remain an independent sustainable source of energy long after the closure of mining activities.

A potential barrier to successfully developing a geothermal district heating system is competition with "*relatively affordable gas and oil supplies and separate, well-developed electricity and fuel delivery infrastructures*" [43]. This is not the situation in cases such as the Con mine study in Yellowknife (see Section 6.1), where alternate energy sources such as natural gas are not available [39]. Furthermore, with rising fuel costs and demands to reduce greenhouse gas emissions, such a barrier is likely to become less relevant.

Following the installation of a district heating system, analyses have been utilized to determine what aspects are contributing to system inefficiencies [44]. In systems that were studied, it was found that the most significant wastages of energy were due to hot water losses in the distribution system. Not only can such studies help to improve existing systems, but can also provide guidance for the design of new systems.

There are, however, other possible uses for geothermal energy recovered from mine waters. Considering the regions that many mines are located in, these include snow melting. Traditional use of salt on roads can greatly increase concentrations of contaminants in the environment, as well as deteriorating road surfaces and corroding vehicles [45]. Underground thermal energy storage has been utilized in Japan for over 20 years, particularly on steep sections of road or sharp curves [46]. The snow melting systems in Japan utilize geothermal energy from underground heat exchangers. Mines could provide a similar opportunity, with energy being needed only to pump the warm water. If the mine water has a heavy sediment load, then removal systems may be needed to avoid reducing the life of the pumping equipment [47]. Closed loops could be also used if the water quality is too poor.

The heat in mine water could be provided for fish farms [48] and greenhouses [49]. Similarly, the energy from mine water could be used to regulate the temperature of microalgae raceway ponds, allowing a lengthened growing season for cultivation [15,16]. Key products that can be obtained from the microalgae are nutraceuticals and biofuels [50]. Other products, which might be obtained, include proteins, carbohydrates, vitamins, pigments and enzymes [51].

Nutraceuticals such as omega 3 and 6 fatty acids can be produced by microalgae and used instead of those sourced from fish oils [52]. Biodiesel can be produced via transesterification from lipids contained within the microalgae. These fuels are biodegradable and produce less CO_2 and NO_2 than gasoline or diesel [53]. Even a 20% biodiesel blend can result in a substantial reduction in emissions, particularly if paired with a diesel particle filter [54]. This 20% biodiesel blend is approved by several engine manufactures, provided the biodiesels meets standard ASTM fuel quality specifications [55]. There is growing interest to reduce diesel emissions in underground mines for health reasons, with biodiesel seen as a possible approach to achieving this [56].

Further environmental benefits could be obtained if CO_2, a key growth nutrient of microalgae, can be sequestrated from air vented from operated mines or from the off-gas of mineral processing plants [51,17]. If this fuel is used underground in place of diesel equipment the ventilation requirements for the mine should be reduced, adding further energy savings [15].

5. Existing geothermal energy recovery from flooded closed mines

There have been a number of successful installations worldwide to recover energy from mines. These installations all have a similar profile in that they utilize water from closed flooded mines, upgrade the heat with heat pumps and use it for space heating of buildings. The space heating is typically achieved with in-floor heating loops, although a heat exchanger can be used following the heat pumps to provide forced air heat for retrofits in buildings [41]. Some of the installations have been designed so that in the summer the direction of flow can be reversed and cooling provided as well. The installations vary in size from single buildings up to district heating and cooling systems.

5.1. Canada

An energy recovery system has been implemented at the closed Ropak Can Am coal mine in Springhill, Nova Scotia, Canada [57]. This was one of the first installations in Canada, leading to Ropak being awarded an Energy Efficiency Award by the Canadian Electrical Association in 1990 [58]. A heat pump system provides space heating, but also allows the system to be reversed to provide space cooling in the summer. The system utilizes an open loop design, taking water from one part of the closed mine at a depth of 140 m, and dumping it into another part of the mine at the water surface. As a result 16,700 m^2 of buildings are conditioned by 11 heat pumps, while the mine continues to be dewatered. The dewatering has been continued in order to keep the uppermost workings dry as they have been turned into an attraction for a mining museum located on the surface.

5.2. Germany

Table 2 is adapted from [59] and summarizes successful cases of geothermal mine water use in Germany.

The paper does not elaborate on these installations in any detail, other than to say that heat exchangers and heat pumps are typically used. The authors also endorse the fact that abandoned flooded mines have great potential for energy recovery, listing the following characteristics as important for determining feasibility:

- distance of mine/adit to potential user
- discharge of mine water
- temperature of mine water
- hydrochemical composition of water
- mineralization of mine water
- stability of the tunnels and adits
- infrastructure of the workings
- extent of the mine field
- depth of the shafts and workings.

The Wismut Shaft 302 in Marienberg [60] is part of a mine that produced uranium and did not receive adequate remediation procedures prior to closure. The shaft is 144 m deep and was secured by two platforms at different levels, as well as a fence on the surface. The shaft underwent remediation in 2005, as well as a geothermal study, which concluded that the bottom landing was suitable for a geothermal plant. The water quality was high with a temperature of 12 °C, and a capacity of over 120 m^3/h. A geothermal plant was subsequently installed that features a secondary closed loop heated by the mine water. The system supplies a heat capacity of 690 kW, and is tied into public heat generation plants in order to provide for consumer peak demand.

In Freiberg, a castle that is roughly 500 years old now has a system underway to use the geothermal energy in mine water to provide both space heating and cooling [61]. A 200 m section of an abandoned mine gallery located 60 m below the castle provides water at a temperature of 10.2 °C. Two boreholes have been sunk into the gallery (190 mm diameter for feed and 330 mm diameter for return) and are designed to provide water at 3 L/s to a heat pump. The heat pump has a coefficient of performance (COP) of 3.5 and is linked to in-floor loops to provide both heating and cooling.

5.3. Netherlands

This Heerlen energy recovery installation [40] is on a much larger scale than those previously discussed. The project utilizes wells drilled into flooded coal mine workings. The intention is to provide space heating and cooling for 350 dwellings, 3800 m^2 of commercial floor space and 16,200 m^2 of community buildings. In-floor heating is utilized in all buildings, as opposed to radiators or forced air, as it has the greatest efficiency. The community buildings include a school, library, community center and a residential care home. This district heating and cooling system is a part of the regeneration of the core of Heerlen. This was regarded as necessary due to poor city planning aggravated by the local economic hardships faced following closure of the coal mines.

Following a study of the underground geothermal resources, five 700 m deep wells were drilled. The quality of the mine water dictated that plastic pipes and titanium heat exchangers be used to resist corrosion. Using an open loop design, warm water is pumped from this depth in the winter and re-injected into the shaft at 450 m. In the summer the water is taken from a depth of 250 m where it is cooler. Four heat pumps with a capacity of 700 kW and a COP of 5.6 are able to provide 80% of the annual heat requirements. The additional heat is provided as needed by 2 MW of conventional gas boilers. The high COP of the heat pumps is due to the minimal amount of energy upgrading that is required, as the mine water is extracted at 30–35 °C from 700 m. In the summer, mine water is taken from the separate 250 m deep wells that collect water at 16–19 °C.

5.4. Norway

The Folidal mine in Norway was in operation to produce copper, zinc and sulfur from 1748 until 1941 [41]. Over this time a community became established around the mine. Following mine closure, the underground Wormshall cavern continued to be used by the community for concerts and banquets. A heat pump system was commissioned in October 1998 to upgrade heat from mine water and use it to heat the cavern. A 600 m long 50 mm diameter closed-loop was installed in a deep shaft. A single heat pump was then used to generate air at 22 °C to provide space heating. Together the energy recovery system and the cavern continue to provide value to the community, despite the fact that the mine has long been closed.

5.5. Scotland

An installation in Shettleston has been created to demonstrate that energy recovery from flooded coal mines can be feasible on a small scale. Water is being taken from a depth of 100 m to supply heat pumps [62]. Two heat pumps are used to heat the water to 55 °C, which is then stored in a tank before distribution to end users for space heating. The end users are 16 houses which were also upgraded to be more energy efficient as part of the project. The buffering tank located between the heat pumps and the houses reflects electricity economy tariffs, which limit operation of the heat pumps to 18 h a day. The buffering capacity with a reserve of hot water is required, therefore, for the other 6 h a day.

Another installation in Scotland at Lumphinnans is very similar to the one at Shettleston [63]. It also heats a small group of houses that were rehabilitated in order to make them more energy efficient. A flooded coal mine is again used, but it is slightly deeper at 170 m. Both of the Scottish systems are designed only for providing space heating, not cooling. The combined effort of house rehabilitation and the energy recovery system was able to reduce the heating costs of 18 houses by 80%.

5.6. USA

An example of an energy recovery system installed on mine lands in the USA is the municipal building in Park Hills, Missouri [64]. The building has implemented a system designed by Caneta Research that features two 120 m wells located in a closed flooded lead mine. The mine is relatively shallow at 130 m, but nevertheless represented a viable opportunity for energy recovery. The supply well was fitted with a submersible pump, with the open loop circuit connected to a plate and frame heat exchanger. Two 17.5 kW heat pumps precondition ambient air. With a total of 9 heat pumps that have a combined capacity of 112 kW, this system is able to provide space heating to 750 m^2 of building with greater efficiency than conventional systems, albeit with a larger initial capital investment (Table 3).

6. Feasibility studies on energy recovery from flooded closed mines

Mining companies or municipalities that have access to closed flooded mines often do not have the resources or expertise needed

Table 3
Summary table of key parameters for existing geothermal energy installations.

Mine site	Water temperature	Depth	Type	System capacity	End use
Park Hills	14 °C	133 m	Coal	113 kW	Space heat
Spring Hill, NS	18 °C	1350 m	Coal	45 kW	Space heat/cooling
Shettleston	12 °C	100 m	Coal	16 houses	Space heat
Lumphinnans	14.5 °C	170 m	Coal	18 houses	Space heat
Heinrich	N/A	N/A	Hard coal	350 kW	Space heat
Zollverein	N/A	N/A	Hard coal	N/A	Space heat
Sachesen	N/A	N/A	Tin mine	N/A	Space heat
Sachesen	N/A	N/A	Tin mine	82 kW	Space heat
Folidal	N/A	600 m	Cu, Zn, S	18 kW	Space heat
Heerlen	30–35 °C or 16–19 °C	700 m	Coal	700 kW	Space heat/cooling

to assess the feasibility of geothermal energy recovery. For this reason private firms or academic researchers are typically contracted to perform such studies. Examples of their findings produced are summarized below.

6.1. Canada

A preliminary study on the Con mine, a closed and flooded gold mine was commissioned by the City of Yellowknife (Northwest Territories) in 2007 [39]. This study was to provide conceptual models, as well as discussing the potential value and different options for accessing the resource. The average yearly ambient temperature in Yellowknife is −4.6 °C.

There are a number of reasons why this project seemed attractive from the onset. Con mine's shafts are as close as 1.5 km to the center of the city, with much of the mine workings extending below the city. Additionally, further developments for the city were planned along the perimeter of the mine. In addition, 56% of the city's $114 million annual energy consumption is used for space heating, which results in 77% of the city's annual greenhouse gas emissions.

The study looked at three different sizes of installations, the key parameters of which are summarized in Table 4.

The small-scale installation would utilize a closed loop in an existing shaft, while the medium and large scenarios would drill 15 cm or 20 cm holes and use an open loop. The primary use for the system would be space heating, with any extra energy used for heating tap water, greenhouses, soil warming and/or snow melting.

Another project at Timmins (Ontario) looked to recovery energy from the water of the abandoned MacIntyre and Hollinger gold mines [65]. FVB Energy Inc. conducted the original feasibility study, which looked to provide space heating to a local arena and hospital. A well would be drilled down into the mine workings to a depth of 250 m, and would use a heat pump on the surface to upgrade the energy to suitable levels for space heating.

However, according to the city council the capital costs for the suggested system were found to be too large and so the project did not proceed. A second feasibility study then altered the parameters of the project. It instead looked to provide space heating to the Shania Twain Center. This project was deemed more favorable and could proceed if government funding or low interest loans were available to cover the $350,000 capital cost. Following payback of the loans over a 6–8 year period, it was suggested that the savings offered by the system might be utilized to develop further projects [65].

Table 4
Potential geothermal recovery installations for Con mine, Yellowknife, Canada (adapted from [39]).

Scale	Depth (m)	Temperature (°C)	Net efficiency (%)	Mine viable capacity (kW)
Small	500	15	65	300
Medium	1200	30	85	1000
Large	1700	40	90	2000

The Gaspé mines (Quebec) are abandoned flooded copper mines located near Murdochville and are 670 m at their deepest [26]. The mean water temperature was found to be 6.7 °C during testing, with a water volume of around 3,732,300 m^3. Based on these findings, the estimated energy reserve of the mines was 765 kW. With the use of heat pumps it was determined that this could provide space heating for an industrial park.

The Britannia copper mine (British Columbia) is 1250 m deep at the glory hole that allows water to escape the mine [20]. The unique physical setting for this mine eliminates the need to pump water, as it flows out this hole at an average rate of 600 m^3/h. The water temperature is 15 °C, and the energy resource of the mine was estimated to be in the range of 1.2–5 MW. The two main obstacles for this system are the poor quality of the water, and the irregularity with which it flows. The low pH and high metal concentrations dictate that a closed loop system must be utilized, as well as acid resistant material for the heat exchanger. To address the variable flow rate, a fuzzy-based control system was developed utilizing historical flow data. This control system looked to optimize use of the variable flow rates to provide district heating as efficiently as possible.

6.2. Germany

A study in Germany looked at not at a single mine, but rather at a number of mines located in the Rhenish Massif region [59]. This region primarily produced iron ore, but also mined smaller quantities of sulphides of lead, zinc and copper. Eight mines that were studied and their depths and water temperatures are summarized in Table 5.

The study did not provide any detail on modeling or end use of energy, other than to say that heat pumps would be used to provide space heating of buildings. There was, however, a detailed analysis of the mine water quality and its variability with depth. The recovery of energy from these mines was considered to be a valuable resource worthy of further work.

Table 5
Characteristics of mines in the Rhenish Massif region of Germany (adapted from [59]).

Mine	Depth	Temperature (°C)
Eupel (cleft)	540 m	21.6
Georg	640 m	21.8
Neue Haardt	975 m	26.2
Pfannenberger Einigkeit	1070 m	23.6
San Fernando	930 m	26.7
Vereinigung	1000 m	31.7
Wingertshardt	700 m	30.6

6.3. Hungary

An abandoned copper mine at Recsk in northern Hungary is 1160 m deep [66]. Water sampling found that the water was 59.5 °C at its deepest and 29 °C at the water surface. The surface area exceeds 150,000 m^2 with an estimated heat flow of 0.108 W/m^2, providing a total mine resource of 2880 kW. The water exhibits high salinity and so a closed loop would need to be used with a borehole heat exchanger in the existing large diameter shaft. Heat pumps would then increase the temperature of the water, which would be primarily used for district heating. Proposed secondary uses for the energy include heating spas and swimming pools at a nearby wellness center.

6.4. Norway

A system similar to the existing Folldal mine in Norway (see Section 5.4) is being planned for the abandoned Kongsberg silver mine [41]. This mine has an operational history of several centuries, but has been used only as a tourist site since 1957. A mining museum is located on the site as well as a banquet and concert hall 342 m below the surface. Even in the summer, the air temperature in the hall does not exceed 6 °C and so a heat pump system is being designed to make use of the flooded shaft nearby. Due to concerns over water quality and its affect on the heat exchangers, the original open loop design was abandoned in favor of a closed loop system. A 130–250 m length of pipe was designed to collect 12 kW of energy, compared to the peak demand of 15 kW. Of the collected energy, 20% would be transferred to air to heat the foyer area and the remainder used directly to heat the underground hall with in-floor heating loops.

6.5. Poland

This study looked at a 660 m deep laterally distributed coal seam at Nowa Rudat [36]. The mine is closed and flooded with water at an average temperature of 21 °C. The water volume of the mine was estimated to be 5,000,000 m^3 with high salinity as well as 2–2.5 g/L of dissolved solids. The two scenarios for the study were for supplies of water at 10 L/s and 20 L/s of water. These flows were estimated to provide approximately 800 kW and 1600 kW, respectively. Heat pumps were proposed to upgrade the heat for a town less than 1 km away, although no specific description of energy end use was provided.

Modeling was performed utilizing 2D numerical models based on TOUGH2. Developed at Berkley in the USA [67], this is a general-purpose numerical simulation program for multi-phase fluid and heat flow in porous and fractured media. Results of the study were based largely on thermal modeling. They suggested that it would take 10 years following mine closure and flooding for the water temperature to approach the natural temperature. It was suggested that if heat were removed at a rate of 1.6 MW, the water temperature would drop from 23 °C to 18 °C over a period of 25 years.

This drop in temperature over time is a reminder that if energy is continually removed at a high rate from an underground reserve and is not replenished (i.e., by space cooling in summer), then the quality of the resource will degrade over time.

6.6. Scotland

A 900 m deep coal mine in Midlothian has been investigated with 37 °C water at the deepest point and 13 °C at the surface [40]. The study suggested that the 37 °C water is not suitable for direct heat recovery, but as water is continually pumped out for environmental reasons, energy from this could be extracted at the surface using a heat pump. By using a heat pump with a 450 kW compressor and a COP of 4.5–5, an estimated 3000 kW of energy could be recovered. Water exiting the heat pump would be 80 °C and would return at 40 °C. The system is anticipated to be capable of providing space heating for local dwellings, 12,000 m^2 of offices and 15,000 m^2 of a school.

6.7. USA

In the Pittsburg (Pennsylvania) coal seam a study revealed that currently 5000 km^2 out of 13,000 km^2 are flooded, with water temperatures ranging from 10 to 13 °C [21]. The volume of water was estimated at 5.15×10^{12} L, with both treated and free discharges totaling 2.0×10^{11} L per year. The energy reserves of the flooded coal field were predicted to be the equivalent of 437,000 MWh. The quality of the water poses a minimal threat for scaling, but there exists a high potential for corrosion. The suggested use for the energy is space heating, but minimal modeling has been done thus far.

7. Conclusions

The planning, construction, operation and closure of underground mines are extremely capital intensive. However, despite this investment very few mines are regarded as having a “useful” life after core extraction activities have ceased. Whereas, with increasing pressure to reduce fossil fuel consumption, mines can be considered for their ability to provide renewable geothermal energy from warm mine water. Despite estimates of an excess of a million disused mines worldwide, there are, however, still only a very limited number of operations that look to exploit this opportunity. Creating value as net energy generators would extend return on the mine investment. It could also continue to help offset greenhouse gas emissions produced as a consequence of previous mining activities.

This survey of both existing and proposed installations demonstrates that utilization of a mine site post-closure can build energy resilience into local communities. In particular, use of geothermal energy extraction loops coupled to heat pumps to provide local communities with a sustainable source of heating and cooling. Other possibilities also exist, ranging from snow melting to maintenance of ponds to cultivate microalgae. Mining operations leaving a legacy that demonstrates integration of beneficial contributions to sustainability and job creation are likely to be regarded more favorably by investors, community, insurers and legislative bodies.

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References

[1] Natural Resource Canada, Office of Energy Efficiency. Table 3: secondary energy use and GHG emissions by industry, http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/agg_ca_3_e_4.cfm?attr=0.
[2] Hilson G. Barriers to implementing cleaner technologies and cleaner production (CP) practices in the mining industry: a case study of the Americas. Minerals Engineering 2000;13:699–717.
[3] Hilson G. Defining “cleaner production” and “pollution prevention” in the mining context. Minerals Engineering 2003;16:305–21.
[4] Durucan S, Korre A, Munoz-Melendez G. Mining life cycle modelling: a cradle-to-gate approach to environmental management in the minerals industry. Journal of Cleaner Production 2006;14:1057–70.
[5] Norgate T, Haque N. Energy and greenhouse gas impacts of mining and mineral processing operations. Journal of Cleaner Production 2010;18:266–74.
[6] Gunson AJ, Klein B, Veiga M, Dunbar S. Reducing mine water network energy requirements. Journal of Cleaner Production 2010;18:1328–38.

[7] Stern D. The contribution of the mining sector to sustainability in developing countries. Ecological Economics 1995;13:53–63.
[8] Thompson S, Duggirala B. The feasibility of renewable energies at an off-grid community in Canada. Renewable and Sustainable Energy Reviews 2009;13:2740–5.
[9] Dawson S. CMJ's top 10 Canadian junior mining companies. Canadian Mining Journal 2004. http://www.canadianminingjournal.com/issues/story.aspx?aid=1000143885&type=Print%20Archives [accessed September 3rd 2010].
[10] Ontario Mining Act. Ontario Regulation 240/00, mine development and closure under part VII of the act, financial assurance; 2010. http://www.e-laws.gov.on.ca/html/regs/english/elaws_regs_000240_e.htm [accessed August 8th 2010].
[11] Demollin-Schneiders E, Malolepszy Z, Bowers D. Potential use of geothermal energy from mine water in Europe for cooling and heating. In: Passive and low energy cooling for the built environment. 2005.
[12] Wolkersdorfer. Water management at abandoned flooded underground mines: fundamentals, tracer tests, modelling, water treatment. Heidelberg: Springer; 2008. p. 465.
[13] Evans DJ, Stephenson M, Shaw R. The present and future use of 'land' below ground. Land Use Policy 2009;26S:S302–16.
[14] Evans DJ. An appraisal of underground gas storage technologies and incidents, for the development of risk assessment methodology. report by the british geological survey to the health & safety executive (HSE). HSE Research Report Series, vol. RR605; 2009. p. 350.
[15] Scott JA, Hall A, Shang H, Hall S. The potential for sustainable energy recovery form a working mine. In: Proceedings 48th annual conference of metallurgists. 2009. p. 23–6.
[16] Shang H, Scott JA, Ross GM, Shepherd SH. A dynamic temperature model for mine water fed raceways for microalgae biofuel production. Environmental Progress and Sustainable Energy 2010;29(4):510–6.
[17] Shang H, Scott JA, Shepherd SH, Ross GM. A dynamic thermal model for a microalgae incubator using smelter off-gas. Chemical Engineering Science 2010;65:4591–7.
[18] Raymond J, Therrian R, Hassani F. Overview of geothermal energy resources in Quebec (Canada) mining environments, project summary. McGill University; 2008.
[19] Molson J, Fala O, Aubertin M, Bussiere B. Numerical simulation of pyrite oxidation and acid mine drainage in unsaturated waste rock piles. Containment Hydrogeology 2005;78:343–71.
[20] Ghomshei M, Meech JA. Usable heat from mine water: coproduction of energy and minerals, from "Mother Earth". In: Meech JA, Kawazoe Y, Kumar VJ, Maguire J, Wang HP, editors. Intelligence in a materials world: nanotechnology for the 21st century. CRC Press; 2003. p. 5.
[21] Wazlaf G, Ackman T. Underground mine water for heating and cooling using geothermal heat pump systems. Mine Water and the Environment 2006;25:1–14.
[22] Lawson DC, Sonderegger JL. Report (geothermal data-base study). Butte (USA): Montana Bureau of Mines and Geology; 1978. p. 40.
[23] Bridgwood E, Singh R, Atkins A. Selection and optimization of mine pumping systems. International Journal of Mine Water 1983;2:1–19.
[24] Morton K, Mekerk F. A phased approach to mine dewatering. Mine Water and The Environment 1993;12:27–34.
[25] Diersch H. FEFLOW finite element subsurface flow and transport simulation system. In: Reference manual. Berlin: Institute for Water Resources Planning and Systems Research; 2005.
[26] Raymond J, Therrien R. Low-temperature geothermal potential of the flooded Gaspé mines, Quebec, Canada. Geothermics 2008;37:189–210.
[27] Van Hooydonck J, Prado M, Guiguer N, Bittencourt C. Tools to calculate groundwater inflow to underground mines: a comparative assessment. Environment 2009. Santiago, Chile.
[28] Royle M. Giant mine: identification of inflow water types and preliminary geochemical monitoring during reflooding. Mine Water and the Environment 2007;26:102–9.
[29] Metesh J. Using a water balance to determine the source of water in the flooding underground mine working of Butte. Mine Water and the Environment 2006;25:108–13.
[30] O'Hara G. Water management aspects of the Britannia mine remediation project, British Colombia, Canada. Mine Water and the Environment 2007;26:46–54.
[31] Coulton R, Bullen C, Dolan J, Hallett C, Wright, Marsden C. Wheal Jane mine water active treatment plant – design, construction and operation. Land Contamination and Reclamation 2003;11(2):245–52.
[32] Hamm V, Sabet B. Modelling of fluid flow and heat transfer to assess the geothermal potential of a flooded coal mine in Lorraine, France. Geothermics 2010;39:177–86.
[33] Kruse NA, Younger PL. Development of thermodynamically-based models for simulation of hydrogeochemical processes coupled to channel flow processes in abandoned underground mines. Applied Geochemistry 2009;24:1301–11.
[34] Rodriguez R, Diaz M. Analysis of the utilization of mine galleries as geothermal heat exchangers by means a semi-empirical prediction method. Renewable Energy 2009;34:1716–25.
[35] Milenić D, Vasiljević P, Vranješ A. Criteria for use of groundwater as renewable energy source in geothermal heat pump systems for building heating/cooling purposes. Energy and Buildings 2010;42:649–57.
[36] Malolepszy Z. Low temperature, man-made geothermal reservoirs in abandoned workings of underground mines. In: 28th workshop on geothermal reservoir engineering. 2003.
[37] Ontario provincial water quality, objectives, temperature criteria, http://www.ene.gov.on.ca/envision/gp/3303e.htm#20.
[38] Haehnlein S, Bayer P, Blum P. International legal status of the use of shallow geothermal energy. Renewable Sustainable Energy Reviews 2010;14:2611–25.
[39] Ghomshei M. Geothermal energy from Con mine for heating the city of Yellowknife, NWT. Norman B. Keevil Institute of Mining Engineering; 2007.
[40] Mine water as a renewable energy resource, project report, www.minewaterproject.info.
[41] Banks D, Skarphagen H, Wiltshire R, Jessop C. Heat pumps as a tool for energy recovery from mining wastes. Energy, Waste and the Environment: a Geochemical Perspective Geological Society, London, Special Publications 2004;236:499–513.
[42] Holmgren K, Gebremedhin A. Modelling a district heating system: introduction of waste incineration, policy instruments and co-operation with an industry. Energy Policy 2004;32:1807–17.
[43] Thorsteinsson H, Tester J. Barriers and enablers to geothermal district heating system development in the United States. Energy Policy 2010;38:803–13.
[44] Ozgener L, Hepbasli A, Dincer I. A key review on performance improvement aspects of geothermal district heating systems and applications. Renewable and Sustainable Energy Reviews 2007;11:1675–97.
[45] Godwin KS, Hafner SD, Buff MF. Long-term trends in sodium and chloride in the Mohawk River, New York: the effect of fifty years of road-salt application. Environmental Pollution 2003;124:273–81.
[46] Iwamoto K, Nagasaka S, Hamada Y, Nakamura M, Ochifuji K, Nagano K. Prospects of snow melting systems using underground thermal energy storage in Japan. Hokkaido University; 1997.
[47] Vutukuri V, Singh R. Recent developments in pumping systems in underground metalliferous mining. Mine Water and the Environment 1993;12:71–94.
[48] Miller D. Using aquaculture as a post-mining land use in West Virginia. Mine Water and the Environment 2008;27:122–6.
[49] Mahmoudi H, Spahis N, Goosen M, Ghaffour N, Drouiche N, Ouagued A. Application of geothermal energy for heating and fresh water production in a brackish water greenhouse desalination unit: a case study from Algeria. Renewable and Sustainable Energy Reviews 2010;14:512–7.
[50] Renaud L, Scott JA, Shang H, Salt B, Loken M, Ross GM. Microalgae and the mining industry: a research review. In: Maintenance engineering mine operators conference. 2010.
[51] Harun R, Singh M, Forde G, Danquah M. Bioprocess engineering of microalgae to produce a variety of consumer products. Renewable and Sustainable Energy Reviews 2010;14:1037–47.
[52] Ward O, Singh A. Omega-3/6 fatty acids: alternative sources of production. Process Biochemistry 2005;40:3627–52.
[53] Hossain A, Salleh A, Boyce A, Chowdhury P, Naqiuddin M. Biodiesel fuel production from algae as renewable energy. American Journal of Biochemistry and Biotechnology 2008;4:250–4.
[54] Dane J, Voorhees K. Investigation of nitro-organic compounds in diesel engine exhaust. National renewable energy laboratory, June 2010; 2010.
[55] Department of Energy US. Energy efficiency and renewable energy. Clean cities fact sheet, June 2009; 2009.
[56] United steelworkers, health, safety, reducing diesel emissions in mines. http://www.uswa.ca/program/content/982.php.
[57] Jessop A. Geothermal energy from old mines at Springhill, Nova Scotia, Canada. In: Proceedings world geothermal congress. 1995. p. 463–8.
[58] Geothermal mine water as an energy source for heat pumps. Cadet Energy Efficiency, October 1992.
[59] Wieber G, Pohl S. Mine water: a sources of geothermal energy – examples from the Rhenish Massif. In: 10th international mine water association congress proceedings. 2008.
[60] Matthes R, Schreyer J. Remediation of the Old Wismut-Shaft 302 in Marienberg and installation of a technical plant for geothermal mine water use. In: IMWA symposium 2007: water in mining environments. 2007.
[61] Kranz K, Dillenhart J. Mine water utilization for geothermal purposes in Freiberg, Germany: determination of hydrogeological and thermophysical rock parameters. Mine Water and the Environment 2010;29:68–76.
[62] John Gilbert Architects. Glenalmond street project, www.johngilbert.co.uk.
[63] John Gilbert Architects. Lumphinnans sustainable housing project, www.johngilbert.co.uk.
[64] Municipal building, Park Hills, Missouri – technical report, Caneta research, 1997.
[65] Louiseize K. Siemens. Chamber warming it up, up, up, Northern Ontario Business. February 2005, http://www.nob.on.ca/DisplayArticle.aspx?id=16942&LangType=1033&terms=louiseize%20siemens.
[66] Tóth B, Elemér. A prospect geothermal potential of an abandoned copper mine. In: 32nd workshop on geothermal reservoir engineering. 2007.
[67] TOUGH2 Homepage; http://esd.lbl.gov/TOUGH2/.