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Geothermal energy recovery from deep flooded copper mines for heating



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ABSTRACT

Geothermal energy recovery from abandoned flooded mines provides a viable high-tech solution to reuse the abandoned mines for meeting humanity's energy needs worldwide in an environmental, economic, and reliable way. This unique energy application with mine water in the U.S., however, has not been reported. This study reports on a real geothermal energy application in the U.S. for the use of water in flooded mines for house heating. First, the site exploration of a typical flooded copper mine in the Upper Peninsula of Michigan is presented to discuss three essential components of the proposed large-scale energy application, i.e., bedrock geology, mining background, and energy reserve analyses. Then, the key technical details and data monitoring of a demonstration project for the use of mine water for heating a 15,000 ft² (1394 m²) building are introduced. For the energy reserve, energy reserve analyses were conducted considering the renewability of the thermal energy in the natural system, which was usually neglected in the literature. The analyses revealed that the annual extractable energy from the explored flooded mine with the energy replenishment is comparable to the annual energy generated by a small-scale power station, which can support over 82,000 households. The results from the demonstration project indicated that house heating with geothermal energy via the mine water is the most efficient and the second most economical heating option in very unfavorable conditions with a high electricity price and a low annual average air temperature. The intention of this study is to share the background and practical knowledge that has been learned from this ongoing project to guide future real installations in other mining areas with deep flooded mines in the U.S. and around the world.

1. Introduction

Geothermal energy, defined as heat from the Earth's core [1], is a renewable, clean, abundant, and flexible energy resource [2]. Due to these advantages, geothermal energy has been considered as a renewable resource to meet humanity's energy needs in the U.S. and around the world [3]. Among the major categories of geothermal applications [4], geothermal heat pumps that transfer heat to or from the ground are the most energy efficient means of heating and cooling buildings in most areas of the U.S. [5] and possibly the only one that can be used around the world [6]. Because of this reason, geothermal heat pumps have been receiving increasing attention [4]. Applications of geothermal heat pumps involve the extraction of energy from a low enthalpy (or roughly, temperature) source, i.e., water circulated in a closed loop, such as groundwater and surface water, to a high enthalpy fluid circulated in heat pumps, which will be later used for heating

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https://doi.org/10.1016/j.enconman.2019.01.007 Received 15 August 2018; Accepted 2 January 2019 Available online 24 January 2019 0196-8904/ © 2019 Elsevier Ltd. All rights reserved. (cooling uses an opposite process). Although less discussed for geothermal applications, water in abandoned flooded mines (i.e., mine water) has been gaining acceptance as an economically and environmentally attractive medium that can transfer geothermal energy from flooded mines for heating/cooling purposes, such as in Canada [7], Netherlands [8], and the U.S. [9]. The hypothesis of the mine water-based geothermal application is that the mine water, which is stored in deep mines and continuously heated by the Earth, can be used for heating buildings in winter and/or cooling buildings in summer. The conceptual model of this hypothesis is shown in Fig. 1. The use of the mine water for geothermal applications falls into the category of Surface Water Heat Pump (SWHP) applications. Compared with conventional Geothermal Heat Pump (GHP) applications, this SWHP application offers various remarkable advantages based on a ten-year demonstration project to be detailed later.



Fig. 1. A schematic of cooling and heating buildings with the mine water.

- 1. The mine water is mostly deemed as a useless material, therefore, the recyclable use of this material for transferring geothermal energy is sustainable.
- 2. The mine water reaches much deeper locations in the ground, which has a much higher temperature contrast with the air than surface water and near-surface pore water, and thus can transfer geothermal energy with a higher quality.
- 3. The volume of the mine water is usually large compared to the water in pipes or soil pores, which makes its energy reserve exceed that of conventional GHP applications by many orders.
- 4. It offers much better heat transfer (directly between the mine water and surrounding geologic formations) than that in Ground-Coupled Heat Pump (GCHP) systems (via heat exchangers (pipes)) and avoids the technical difficulties and environmental problems in circulating pore water in Ground-Water Heat Pump (GWHP) systems.
- 5. As abandoned mines and the mine water are existing facilities, no extra cost is needed for their construction, which saves a significant amount of expenditure compared to the other GHP applications.

The exploitation of the mine water for heating buildings has been pioneered in projects around the world. The utilization of the mine water for heating of buildings and industrial processes started officially in 1989 when the Town of Springhill developed an industrial park where companies could utilize geothermal energy supply from the local abandoned coal mines. Since this pioneering work in Canada [10], the idea of using flooded mines as natural heat exchangers has been gaining momentum worldwide. As a result, a number of demonstration projects are in progress, mostly in Europe and Canada. One example is that two typical demonstration projects are the installations of geothermal heat pumps in Germany [11] and Scotland [12]. Behrooz et al. [8] also introduced the geothermal use of an abandoned coal mine in Heerlen, Netherlands. Other sites include Freiberg in Germany [13], Czeladz in Poland [14], Folldal in Norway [15], and Shettleston in the U.K. [16]. The details and heat extraction techniques of most published real installations are reviewed and can be found in Hall et al. [15] and Ramos et al. [17], respectively.

Besides the real installations and/or demonstration projects, many assessment studies have also been carried out to evaluate the potential and/or to develop preliminary plans for mine water-based geothermal applications at many sites, such as the Central Mining Institute [18], Silesian region [19], Yellowknife in Canada [20], Quebec and other Canadian provinces [7], and Rhenish Massif in Germany [21]. In addition to these isolated investigations, trust in this opportunity also prompted international efforts across countries. One example is the European project, "Minewater", for reviving old and declining mining areas by transferring geothermal energy from flooded mines via the mine water [8], in which feasibility studies were primarily conducted. Specific site studies have shown that the geothermal energy reserves in underground mines range from a few hundreds of kilowatts to hundreds of megawatts [15]. The potential of geothermal energy recovery from flooded mines has also been evaluated via field measurements of chemical concentrations and temperatures in the mine water. Monitoring data in Yorkshire revealed that chemical concentrations in the mine water were relatively stable during the six-month heat extraction period [22]. Field measurements from sixteen sites in the South Wales Coalfield [23] also showed that year-round temperatures in the mine water were stable. In addition, two real applications in the U.K. tapping geothermal energy from a single shaft in Markham [24] and Wakefield [25] demonstrated that the mine water temperature did not vary during the long-term heat extraction period. Besides that, strategies have also been proposed to reduce carbon emission and improve the performance of the proposed energy application. For example, Athresh et al. [26] proposed an approach for heating buildings with the mine water-based geothermal technology by integrating other technologies (e.g., gas engine). These existing studies have confirmed the high sustainability and remarkable benefits of the mine water-based geothermal application.

The high sustainability and benefits of the application have also been confirmed by more numerical and field studies. Andrés et al. [27] found that the mine water temperature was stable and not influenced by heat extraction in a period of 90 years after numerically studying the hydrogeological and thermal characteristics of the mine water reservoir under different scenarios of water extraction and injection. Bailey et al. [28] estimated 47.5 MW of thermal energy available in the mine water reservoir in the coalfields of Great Britain for geothermal applications based on the field data. Burnside et al. [29] observed almost no change in the isotopic variation in sampled waters and confirmed the sustainability of geothermal applications with the mine water considering the process of flooding. Jardón et al. [30] assessed a thermal energy supply capacity close to 260,000 MWh per year from the mines in central Asturias, Spain with their proposed heating systems. Based on the field and hydrochemical data, very stable pumped water temperatures, which were the temperatures of the liquid entering to the heat exchanger for heating, were also observed in the mines in Bytom, Poland [31] and in Asturias, Spain [32].

In addition to the above technical merits, historical statistics also strongly supports the proposed energy application. Fig. 2 illustrates the potential mine sites for potential geothermal use in the U.S., which lists over 23,000 past/closed underground mines according to USGS data



Fig. 2. Potential sites for the use of the mine water (USGS Mineral Resources Data System [33]).

[33]. In addition, active mines at some point will be closed so that the number of potential sites will increase. In another estimate in the U.S., there are 500,000 abandoned mines according to the abandonedmines. gov [34]. Therefore, the merits of the geothermal energy recovery from flooded mines provide a possibly viable high-tech solution to reuse these abandoned mines in the U.S.

However, a report on a real installation in the U.S. for the proposed energy application with deep mines is still lacking. The key technical details and data monitoring of a real project installation are also rare worldwide. In addition, for thermal energy reserve estimations, many existing studies, e.g., Raymond et al. [7] and Bailey et al. [28], estimated the static energy reserve with only the water temperature. However, this static energy reserve is possibly very conservative because the mine water, in fact, is similar to a big "battery", in which the heat in the mine water can be recharged by the heat from the surrounding geologic formations. According to Muffler and Cataldi [35], the energy recharge to the heat in the mine water can quickly reach over 10% of the original static thermal energy if the heat flux from the rocks is considered, which however is overlooked previously. Therefore, the renewability of the thermal energy needs to be considered to fully evaluate the potential of the energy innovation.

To fill these knowledge gaps, this study, to the best of the authors' knowledge, reports on the pioneering and first large-scale application of recovering geothermal energy in the U.S. for heating purposes and the first one with deep mines (deep copper mines located in the Upper Peninsula (U.P.) of Michigan in Fig. 2). This study covers the back-ground and practical aspects of the application, including a detailed site exploration of a typical flooded copper mine (i.e., Quincy mine) and a real demonstration project conducted at a different mine (much smaller than the Quincy mine) located within the same geologic formations. For the energy reserve assessment of the Quincy mine, the renewability of the thermal energy is considered. This study is organized as follows. In Section 2, the methods and site exploration are presented. Section 3 presents the results and discussion, including energy reserve analyses of the Quincy mine considering the energy replenishment and the results from the real demonstration project.

2. Methods and site exploration

The U.P. of Michigan shown in Fig. 2 was the first major copper mining region in the U.S., where hundreds of deep mine shafts were developed during 1840–1968. The Quincy was a typical copper mine in the area and located very close to the Hancock City of Michigan, as shown in Fig. 3. Shaft 2 of the Quincy mine reached 9260 feet (2.82 km) in depth in 1945. After the closure of mining activities in this area, the shafts and stopes of the Quincy mine were filled with groundwater within years. The water has currently filled the mine up to the seventh level and all of the lower levels (about 84 levels) are inaccessible, making the mine a possible large-scale and deep reservoir for geothermal applications with the mine water.

Due to this reason, the geothermal energy potential of the Quincy mine is assessed in Section 3.1 for the use in geothermal applications. This assessment is made with the conventional volume method and an approach considering thermal energy recharge, respectively, based on the bedrock geology and mining background. Section 3.2 presents a real demonstration project launched in 2009 by the Keweenaw Research Center (KRC), which is 6.46 km to the northeast of the Quincy mine as shown in Fig. 3, for tapping geothermal energy from a small flooded mine compared to the Quincy mine in this area. This demonstration project has been running since 2009 to provide heating to a 15,000 ft² (1394 m²) building. The heat pump system efficiency, installation cost, and water temperature stability are assessed.

In the following, the bedrock geology and mining background used for the thermal reserve estimation are presented.

2.1. Bedrock geology

Bedrock geology provides the properties of rocks, e.g., specific heat and density, to evaluate the energy reserve and renewability of the geothermal energy for the proposed application (see Section 3.1.2 for the evaluation). In the following, the key geologic information is collected with an emphasis on the Quincy mine.

The first copper mines in the U.P. were located in the Portage Lake Lava Series (PLLS) known as the Portage Lake Volcanics. As shown in



Fig. 3. Location of the Quincy mine close to the Hancock City in the U.P. of Michigan [Google Earth].

Fig. 4, a major geologic feature of this area is the Keweenaw fault that formed on the southeast flank of the Lake Superior Basin. All of the native copper mining was conducted in the PLLS, mostly in the basaltic flow tops but also in some of the interbedded sediments. 380 million tons of copper ores were mined from the PLLS [36].

The Quincy mine is primarily made up of conglomerates (sedimentary rock) and amygdaloidal basalts (igneous rock). These two types of rocks are the geologic formations to hold and consequently heat water in the mining spaces. According to Robertson [38], the specific heat is 0.93 (kJ/(kg $^{\circ}$ C)) and 0.85 (kJ/(kg $^{\circ}$ C)) for conglomerates and basalts, respectively. For the density, the two rocks have a bulk density of 2.95 g/cm³ and 2.98 g/cm³, respectively [39]. In the rocks, the permeability dictates the ability of water seeping into mines through the rocks. Fissures/faults have the highest permeability and primarily determine the ability of the geologic formations around the mining spaces to transport water and energy. Due to the fact that the



Fig. 4. Bedrock geology in the U.P. for copper mining areas [revised after Bornhorst and Williams [37]].



Fig. 5. Layout of underground mining spaces of the Quincy mine [developed with Google map according to Plate#36 [40]].

Keweenaw fault runs through the entire length of the Keweenaw Peninsula, as shown in Fig. 4, the area in the PLLS contains many faults and fissures. Among them, the Hancock fault reaches 2000 feet (610 m) in depth and runs through Shaft 7 of the Quincy mine (see projection in Fig. 5) at the Portage Lake level.

2.2. Background on the Quincy mine

The layout of the underground mining spaces of the Quincy mine is shown in Fig. 5. The 3D underground mining structures are projected to the map for visualization. Most roads and buildings in the downtown of Hancock are distributed on the bottom of the map. The black lines are the major mine shafts (projection). The red curly lines are the horizontal drifts (projection), which are approximately parallel to each other and perpendicular to the shafts. The shafts are connected by the horizontal drifts. The projection of the mining structures on the horizontal plane manifests itself as an interconnected net because most of the shafts are inclined and dip to the northwest.

The Quincy mine consists of several major mine shafts, i.e., Shaft 2, 6, 7, and 8, and some unlabeled shafts adjacent to these major shafts. According to Butler and Burbank [40], Shaft 8 consists of 75 drifts and reaches a depth of 6600 feet (2012 m). Shaft 6 has a depth of 7650 feet (2332 m) and 81 drifts. The distance between Shaft 6 and Shaft 2 is 1890 feet (576 m). Shaft 2 was the deepest shaft worldwide in 1945, whose depth is 9260 feet (2.82 km) along the dip of the deposit on a 55degree inclination with 85 drifts. Shaft 7 has a depth of 6130 feet (1868 m) and consists of 70 drifts. Those unlabeled shafts, which include approximate 35 drifts for each, have a relatively smaller depth than the major ones. Most of the deep copper mine shafts are inclined at an angle, ranging between 28 and 73°. Fig. 5 also shows some fissures. One of the marked fissures cuts through Shaft 8 at 290 feet (88 m). Another marked fissure cutting through Shaft 6 starts at Shaft 2 and moves downward. Many drifts of Shaft 6, such as Drifts 9 and 13, are cut through by this fissure. These fissures provide pathways for water and heat transporting into mines. Due to the depth of the lodes, copper mines in this area are often deeper than other types of mine shafts in the U.S., leading to a reachable depth with a very high-quality geothermal field.

It was estimated that about 43 million tons of copper ores have been

mined from the Quincy mine [36]. Besides that, there were about 3 million tons of waste rocks (rock without copper) extracted from the mine [36]. Most of the rocks were either placed on the ground surface in "poor rock piles" or hauled away for road constructions in the region [41]. The above mined ores and rocks result in a potential underground mined volume of $1.55 \times 10^7 \,\mathrm{m^3}$. After the closure of the mine, groundwater started to fill its underground mining spaces. To date, the water level is stabilized on the 7th level, where an adit was developed for drainage; therefore, about 95% of underground mining spaces of the mine is filled with water, leading to a great amount of mine water (around $1.47 \times 10^7 \text{ m}^3$) stored in the mine. The top layer of the mine water is influenced by the air temperature. But when this top layer reaches a specific depth, i.e., 200 feet (60 m), it is reasonable to assume that water therein is independent of temperature variations in the atmosphere. According to Van Orstrand [42], the geothermal gradient in this area was around 0.015 °C/m. The temperature of the mine water at 60 m is about 9 °C according to the measurement in another mine connected with the Quincy mine at the lower portions of the shafts in the area [9]. As the depth further increases, the water temperature tends to be more influenced by geothermal gradients. The temperature at the bottom of the Quincy mine (2.82 km for Shaft 2 with a 55-degree inclination) thus is approximate 43.7 °C. According to the local miners, the bottom temperature could possibly reach as high as 50 °C. It is therefore predicted that a tremendous amount of geothermal energy is reserved in water in the abandoned mining spaces of the Quincy mine, making it a potentially high-quality and low-enthalpy geothermal reservoir. Motived by this fact, the following Section 3.1 will target at answering the most urgent question for the large-scale exploitation, namely, the thermal energy reserve in the mine water. The analysis of the energy reserve will be conducted based on the above geologic and mining conditions.

3. Results and discussion

This section first presents energy reserve estimates of the Quincy mine considering the energy replenishment and then reports the results from a real demonstration project conducted at a different mine (much smaller than the Quincy mine) located within the same geologic formations.

3.1. Analysis of thermal energy reserve in the Quincy mine

In the following sub-sections, the geothermal energy reserved in water in the Quincy mine is estimated with the conventional volume method and an approach considering thermal energy recharge, respectively.

3.1.1. Estimation with conventional volume method

The conventional way to estimate the thermal energy reserved in the mine water is the volume method [43]. Such a method is used for static energy reserve evaluations, in which the energy recharge from the rocks is not considered. As mentioned in Section 2.2, the volume of the mine water V in the Quincy mine was estimated to be 1.47×10^7 m³. With such a volume, the static energy storage of the mine water can be estimated using the following equation

$$E_s = \eta c \rho V \left(T_h - T_c \right) \tag{1}$$

where E_s is the static energy (kWh); $\eta = 0.0002778$, which is the unit conversion factor (kWh/kJ); *c* is the specific heat of the mine water (kJ/ (kg °C)); $T_c = 1.4$ °C is assumed for a typical heat pump in heating, which is the mine water temperature after heat extraction via a heat exchanger sending back to the mine; T_h is the temperature of the mine water at the bottom; and ρ is the density of the mine water (kg/m³), which is assumed to be 1000 kg/m³. T_h can be estimated using the local geothermal gradient (i.e., 0.015 °C/m [42]) based on the depth of the mine shafts. In the following, Shaft 2 was adopted for analyses. As explained in Section 2.2, T_h differs from different estimations. Therefore, four temperature differences between T_h and T_c in Table 1 were assessed for the energy reserve evaluation to consider the situations where T_h could approximate to a high temperature (e.g., 50 °C) or a relatively low temperature (e.g., 39 °C).

The thermal energy reserved in water in the Quincy mine is huge and highly desirable for the proposed energy application. Table 1 shows the estimated thermal energy with Eq. (1) and its equivalent heat content in terms of other energy resources. The thermal energy reserve can be as high as $8.23\times 10^8\,k\text{Wh}$ with a temperature difference of 48 °C in Case 1. Such thermal energy is comparable to the heat content from 2.81×10^9 ft³ (7.96 $\times 10^7$ m³) of natural gas, 5.98×10^7 gallons $(2.26 \times 10^5 \text{ m}^3)$ of petroleum, or 4.27×10^5 tons of coal. According to the U.S. Energy Information Administration, the annual energy consumption for a U.S. residential utility household is 10,000 kWh. Therefore, the amount of energy in Case 1 can satisfy 82,300 residential utility customers for a year. The thermal energy reserves are also good in Cases 2-4 with lower temperature differences that were estimated when T_h is relatively lower than 50 °C. These energy reserves are in the same order as that in Case 1. It is clear that a tremendous amount of thermal energy reserved in water in the Quincy mine is available but has not been exploited by the local communities.

3.1.2. Estimation considering thermal energy recharge

The above static energy reserve estimation with Eq. (1), which was conventionally used in existing mine water-based geothermal studies, is possibly very conservative. As explained in the Introduction, water in the Quincy mine is similar to a big "battery". The heat in the mine water thus can be recharged by the heat from the surrounding geologic formations. However, this fact is not considered in the static energy reserve. This section thus considers the Thermal Energy Recharge (TER) for fully evaluating the potential of the energy innovation.

To include the TER, the dynamic energy recharge from the rocks and from the flow transport through the rocks was considered. For the TER estimation, Muffler and Cataldi [35] discussed the dynamic TER considering these two types of the TER for a high-enthalpy geothermal reservoir (e.g., borehole or well) rather than large bodies of water in a mine. The following paragraphs thus discuss the dynamic TER for the large-scale mine water in the natural mine water-geologic formation system according to Muffler and Cataldi [35]. For this purpose, Fig. 6 shows the conceptual geometry of a representative shaft with the above two major types of the TER. The geometry of the mine water is thus needed to calculate the TER. However, the structure of the Quincy mine is extremely irregular. To solve this, the mine shaft and drifts were assumed to be cylindrical according to previous studies, such as Hamm and Sabet [44], in which the mining spaces were assumed as interconnected cylinders. To compute the TER, nine shafts in the Quincy mine were adopted according to Butler and Burbank [40]. The TER to the heat in the whole mine water is equivalent to the sum of the TER to the heat in water in each shaft. The total thermal energy reserve E_{tot} for large bodies of water in the natural mine water-geologic formation system is

$$\begin{aligned} E_{tot} &= H_s + H_d^{rock} + H_d^{flow} \\ H_s &= \sum_{i=1}^m c\rho V^i (T_h^i - T_c) \\ H_d^{rock} &= \sum_{i=1}^m (\phi_q \pi D_1^i Z_1^i + n^i \phi_q \pi D_2^i Z_2^i) t \\ H_d^{flow} &= \theta c_r \rho_r V_3 (T_r - T_c) \end{aligned}$$

$$(2)$$

where H_s is the static thermal energy calculated using Eq. (1); H_d^{rock} is the dynamic TER conducted from the rocks (Fig. 6a); H_d^{flow} is the dynamic TER convected by water flows through the rocks (Fig. 6b); t is the time (s); ϕ_a is the conductive heat flux from the rocks (W/m²); n^i is the number of horizontal drifts (the superscript means the i^{th} shaft); D_1^i and D_2^i are the diameter of a shaft and a drift, respectively; Z_1^i and Z_2^i are the length of a shaft and a drift, respectively; θ is the rechargeable factor; $c_r = 0.89$ (kJ/(kg °C)) and $\rho_r = 2970$ (kg/m³) are the specific heat of rocks and the density of rocks, respectively, which were determined based on the average values detailed in Section 2.1; V^i (m³) is the volume of the mine water in the i^{th} shaft and its drifts; V_3 is (m³) the volume of the rocks; T_r is the temperature of rocks (°C) at the bottom; m is the number of shafts and m = 9 was determined for the Quincy mine according to Butler and Burbank [40]; and T_h^i is the bottom temperature, which can be estimated with the depth of each shaft and the geothermal gradient.

To evaluate H_d^{rock} , $Z_1^i = 5Z_2^i$ was assumed and n^i for each shaft was chosen according to the underground mining spaces introduced in Section 2.2. Also, $5D_1^i = D_2^i$ was assumed because of the relatively large dimensions of stopes in the Quincy mine according to Butler and

Table 1

Estimation of the static thermal energy in the mine water in the Quincy mine.

Parameter	Unit	Case 1	Case 2	Case 3	Case 4
Temperature difference Specific heat	°C kJ/(kg °C) m ³	48 4.2 1.47 $\times 10^{7}$	45	40	38
Energy Household (10000 kW h/year)	kWh	$1.47 \times 10^{\circ}$ 8.23×10^{8} 8.23×10^{4}	7.72×10^{8} 7.72×10^{4}	6.86×10^{8} 6.86×10^{4}	$6.52 imes10^8\ 6.52 imes10^4$
Heat conversion to other energy resources	natural gas [m³] petroleum [m³] coal [tons]	7.96×10^{7} 2.26×10^{5} 4.27×10^{5}	7.45×10^{7} 2.12×10^{5} 4.01×10^{5}	$6.63 \times 10' \\ 1.89 \times 10^5 \\ 3.56 \times 10^5$	$6.29 imes 10' \ 1.80 imes 10^5 \ 3.38 imes 10^5$

Note: The heat conversion of the thermal energy reserved in the mine water was made according to the U.S. Energy Information Administration.



Fig. 6. Conceptual view of the thermal energy recharge from (a) the rocks and (b) flow transport through the rocks.

Burbank [40]. The ratio between H_d^{rock} and H_s thus can be calculated to evaluate the rate of the TER regarding H_d^{rock} with respect to time using the following equation based on Eq. (2)

$$\frac{H_d^{\text{rock}}}{H_s} = \sum_{i=1}^m \frac{(\phi_q \pi D_1^i Z_1^i + n^i \phi_q \pi D_2^i Z_2^i)t}{c\rho V^i (T_h^i - T_c)} = \sum_{i=1}^m \frac{4\phi_q t (1+n^i)}{c\rho D_1^i (1+5n^i) (T_h^i - T_c)}$$
(3)

where $V^i = \pi D_1^{12} Z_1^i / 4 + n^i \pi D_2^{12} Z_2^i / 4$. Fig. 7 shows that H_d^{rock} / H_s varies as a function of t and ϕ_q when $D_1 = 5$ m. Five typical ϕ_q values were adopted according to Muffler and Cataldi [35]. As can be seen, the ratio of H_d^{rock} / H_s linearly increases with time. In addition, the rate of the recharge increases with an increase in ϕ_q . H_d^{rock} / H_s can reach 10% within 4 years if $\phi_q = 0.063$ W/m². When ϕ_q increases from 0.063 W/m² to 0.84 W/m², H_d^{rock} / H_s can reach 10% within 1 year. These observations reveal that ϕ_q is a key parameter to determine the rate of recharging such a big "battery" (i.e., mine water) via the energy from the surrounding rocks.

It is seen that the TER can easily reach the static reserve estimate determined with the conventional method within a few years even with only H_d^{rock} . That is, the energy reserved in the mine water can be replenished in a few years even without considering H_d^{flow} , which can possibly further expedite this replenishment. Therefore, it is very necessary to consider the TER for the evaluation of the geothermal energy reserved in the mine water.

The energy from the flows through rocks, i.e., H_d^{flow} was further considered. This is because the flow transport through the permeable rocks, especially fissures and faults introduced in the geologic



Fig. 7. H_d^{rock}/H_s is a function of t and ϕ_q when $D_1 = 5$ m.

conditions in Sections 2.1 and 2.2, can contribute the TER to the heat in the mine water via the convective heat flux. Similar to H_d^{rock} , H_d^{flow} was evaluated with the reference to H_s . According to Muffler and Cataldi [35], the influence of H_d^{flow} can be formulated using a rechargeable factor θ with the following equation

$$\frac{H_d^{flow}}{H_s} = \frac{\theta c_r \rho_r V_3 (T_r - T_c)}{c \rho V_{tot} (T_h - T_c)} = \frac{c_r \rho_r}{c \rho} R \theta$$
(4)

where V_{tot} is the total volume of the mine water; $T_r = T_h = T_{h|max}$ (T_h is from Eq. (1)), where $T_{h|\max}$ is the bottom temperature of the mine water of the deepest shaft; and $R = V_3/V_{tot}$. In general, it is difficult to determine the rechargeable factor θ , which depends on the rock and flow conditions (e.g., rock permeability and flow velocity). Fig. 8a plots H_d^{flow}/H_s as a function of θ with three values of R. H_d^{flow}/H_s linearly increases as θ increases. When $H_d^{flow}/H_s = 10\%$, which is the lower limit of the energy replenishment that is of practical significance for the real application according to Muffler and Cataldi [35], θ decreases with the increase of R (see Fig. 8b). This is because, while heat is eventually from rocks, a larger rock volume provides a stronger recharge, leading to the higher TER. In a small range of R, e.g., R = 1, θ is equal to 18%. However, this value of R seems geologically unreasonable because the volume of rocks should be larger than that of the mine water. When $R = 10, \theta$ is approximately equal to 1.8%. To understand the TER due to H_d^{flow} , Fig. 9 shows the TER in the static energy reserve for Case 1 in Table 1 considering H_d^{flow} . It is seen that this TER is obvious. Among them, the TER is 47 GWh, 116 GWh, and 233 GWh at θ = 5% when *R* is equal to 2, 5, and 10, respectively. Therefore, the TER due to H_d^{flow} cannot be overlooked either because it will be significant in this largescale natural system at reasonable values of R.

A more quantitative understanding for evaluating the energy reserve can be obtained by comparing the annual energy that can be extracted from the mine considering the energy recharge with that produced by existing power stations. The annual energy produced by a power station can be estimated using the following equation

$$G = 365Ch \tag{5}$$

where *G* is the annual electricity generation produced by a power station (GWh); *C* is the power capacity (GW); and *h* is the working hours per day (hour) and h = 12 was assumed in this study. For comparison, three power stations in Michigan, i.e., GM Pontiac, White Pine, and Escanaba Paper, were adopted, which have the power capacity of 29 MW, 40 MW, and 54 MW, respectively (U.S. Energy Information Administration).

The annual energy that can be extracted from the Quincy mine considering the renewability of the energy is comparable to that produced by a small-scale power station. Fig. 10 shows the energy comparison. In this comparison, the total thermal energy reserved in the mine water estimated based on Case 1 in Table 1 was used. This total thermal energy was divided by the duration of time in Fig. 7a under three different ϕ_a to obtain the annual energy. As can be seen, the



Fig. 8. Estimation of H_d^{flow} : (a) H_d^{flow}/H_s as a function of θ and R and (b) θ vs R when $H_d^{flow}/H_s = 10\%$.



Fig. 9. TER to the static energy reserve considering H_d^{flow} with three different R at three different θ .



Fig. 10. Comparison between the annual energy that can be extracted from the mine with three different ϕ_q and those produced by three power stations in Michigan.

annual extractable energy from the Quincy mine with the renewability is approximately one half of that produced by the White Pine power plant when $\phi_q = 0.21 \text{ W/m}^2$. As ϕ_q increases to 0.84 W/m², the annual extractable energy from the Quincy mine with the renewability exceeds that produced by the Escanaba Paper power plant. The results from Figs. 9 and 10 clearly show that the TER to the heat in the mine water leads to a significant increase in the potential of geothermal energy for the application, and thus, cannot be neglected.

3.2. Demonstration project

A demonstration project launched by the KRC, to the best of the authors' knowledge, is the pioneering and first one in the U.S. to explore the possibility of using geothermal energy from a flooded mine. This demonstration project is introduced in this section. The goal is to gain lessons and experiences for guiding the future large-scale installation in the Quincy mine.

In this demonstration project, geothermal energy was tapped from the New Baltic No. 2 mine shaft, which is about 90 m far from the KRC building as shown in Fig. 11, to provide heating for a 15,000 ft² (1394 m^2) building with the mine water. The quality of the pumped mine water was examined before the application. Field inspections indicated that the mine water at the locations, where the mine water will be pumped, has a high quality close to the local surface water in the area. Therefore, blockages in the pipes, which will happen and be a big concern if the pumped mine water is muddy, can be avoided. The shaft is inclined with an angle of 30-degree and a depth of 1900 feet (580 m) along the shaft, which is much shorter than most of the shafts in the Quincy mine. A submersible pump went down a depth of 91 m at a 30degree angle in a 6-inch casing. The pump extracts the mine water from the shaft, sends it to the building, and then returns it to the shaft near the shaft head (see Fig. 11b) after heat extraction. Two thermal insulated pipes were embedded in the ground for water transport between the shaft and the building.

3.2.1. Heat pump system installation and workflow

The air conditioning of the KRC building is composed of two systems, as shown in Fig. 12. The mine water-based heat pump system is primarily used for heating, while the natural gas-based system is a backup heating system for unexpected conditions, for example, when the temperature of the pumped mine water is lower than the design temperature (i.e., 4.4 °C). The geothermal system installation consists of 14 heat pumps placed in 14 different rooms in the building with a nominal heating capacity of 440 MBTU/hr (129 MW), as shown in Fig. 12.

A 90 gpm (0.0057 m^3/s) pump pulls the mine water from the shaft and sends it through a big Accu-Therm Plate Heat Exchanger (model number AT40) with a maximum flow rate of 1150 gpm (0.073 m^3/s), as shown in Fig. 13a. In this process, the temperature of the mine water from the shaft and that of the mine water after heat extraction are monitored with temperature indicators. This heat exchanger has double walls inside: one wall is always open for the mine water to circulate through, while the other wall is closed and a back-up loop if the mine water through the former wall is frozen. The purpose is to ensure that the pumped mine water can always return to the shaft. Through this



Fig. 11. Use of the mine water for heating the KRC building: (a) location of the KRC and the shaft and (b) layout of the shaft.

heat exchanger, the mine water heats a closed loop system. Special attention is paid to ensure that water moves smoothly in the closed loop system. The water always moves inside the pipes and is mixed with glycol (type: DOWTHERMTM SR-1 Fluid) to avoid freezing. This water-glycol mix can obtain the freezing point of 20 °F (-7 °C) when the mix has an Ethylene Glycol volumetric concentration of 16.8%. At a temperature of 25 °C, the density, viscosity, thermal conductivity, and specific heat of this mix are around 1023.9 kg/m³, 1.34 mPa s, 0.515 W/m K, and 3.877 kJ/kg K, respectively. On the building side of the heat exchanger, as shown in Fig. 13b, a 160 gpm (0.01 m³/s) pump makes this water-glycol mix circulate through the heat exchanger to all of the 14 heat pumps in the rooms.

The primary temperature conditioning need in the U.P. is heating. The multiple heat pump systems, which were installed and controlled separately in each room, can heat different rooms in the building simultaneously. Each heat pump transfers the heat from the water-glycol mix in the closed loop system to the air from the air handling unit. The heated air is sent to each room for the purpose of space heating via forced convective air (see Fig. 12) through the air duct (see Fig. 13c). In this heating process, 85% of the air collected from the building is reused; while 15% of the air, which is almost from restrooms, is exhausted. To provide 15% of the air supply, the outside air is added through the air intake duct, as shown in Fig. 12. Such a workflow can ensure that the air for heating in the building is always fresh.

3.2.2. Heat pump system efficiency

The efficiency of the heat pumps was evaluated with the

temperature of the mine water entering the heat exchanger and the pumping rate to assess its performance. As shown in Fig. 14, the efficiency of the heat pumps is significantly influenced by the temperature of the mine water entering the heat exchanger. The initial heating design point was based on an entering water temperature of 4.4 °C and a leaving water temperature of 1.4 °C, which is typical for a geothermal heat pump. The initial designed pumping rate was 13 gpm (0.00082 m³/s). This design can obtain an air heating capacity of 35 MBTU/hr (10.26 MW), which can be calculated using the following equation [45]

$$E_{out} = \dot{m}c_p \Delta T \tag{6}$$

where E_{out} is the rate of the output energy for heating; \dot{m} is the water mass flow rate; c_p is the water specific heat; and ΔT is the water temperature difference between entering and leaving the heat exchanger. The higher the air heating capacity, the better the performance. When the entering water temperature turned out to be near 12.8 °C, which is the annual average temperature of the mine water in the shaft, the heat capacity of the heat pumps increased by 20%. Another related factor in Eq. (6) is the pumping rate. An increase in the pumping rate from 5 gpm (0.00032 m³/s) to 11 gpm (0.00069 m³/s) will also result in a 6% increase in the heat capacity at an entering water temperature of 12.8 °C, which is, however, less significant than that with the entering water temperature and will increase the electrical cost of pumping water. Because of the higher actual entering temperature (12.8 °C) than the designed entering temperature (4.4 °C), the initial pumping rate (13 gpm) can be reduced to be less than 10 gpm (0.00063 m³/s) to save



Fig. 12. Overall system in the KRC for heating with the natural gas-based system and the mine water-based heat pump system.



Cold mine water F to mine shaft

Plate heat exchager

Fig. 13. Geothermal system installation in the KRC.



Fig. 14. Performance of the heat pump with entering water temperatures and pumping rates with an air mass flow rate of $1350 \text{ cfm} (0.64 \text{ m}^3/\text{s})$ and an air entering temperature of 21 °C through the air handling unit.

the electrical cost of pumping water in achieving the originally designed air heating capacity.

To further improve the efficiency by reducing the running cost (i.e., electricity), the KRC also installed the automation devices with logic and automatic controllers to manage the whole heat pump system, as shown in Fig. 15. The devices can automatically optimize the motor based on the heating demands of the building to make the system productive. For the efficiency, a higher energy output-input ratio indicates a higher efficiency, which can be calculated using the following equation

$$\beta = \frac{E_{out}}{E_{in}} \tag{7}$$

where β is the efficiency; E_{out} is the output energy rate calculated with Eq. (6); and E_{in} is the input energy rate. For the heat pumps (model number: ENVISION NS042), the typically consumed energy rate (input) is 7600 BTU/hr (2.23 kW). The efficiency of the use of mine water therefore can be calculated with Eqs. (6) and (7) using an annual average mine water temperature of 12.8 °C and a low pumping rate of 3.5 gpm (0.00022 m³/s), in which this low pumping rate was used to



Fig. 16. Comparison of efficiencies between mine water and other energy resources.

obtain the initial designed air heating capacity with an entering water temperature of 12.8 °C for saving the running cost. To illustrate the performance, the efficiency comparison between the mine water-based geothermal application and other typical energy resources for house heating in the U.P. is presented in Fig. 16. In this comparison, the output heating values of the other energy resources in the U.P. were estimated based on the local experience with the use of an electric heater or a furnace in the U.P. as follows: electricity (kWh) = 3412BTU; oil (gallon) = 119 MBTU; propane (gallon) = 77.6 MBTU; and natural gas (Therm) = 87 MBTU. The heating values of the above energy resources (input) were determined according to the U.S. Energy Information Administration [46] as follows: electricity (kWh) = 3412 BTU; oil (gallon) = 140 MBTU; propane (gallon) = 91.3 MBTU; and natural gas (Therm) = 100 MBTU. Eq. (7) was used to calculate the efficiency of these energy resources. It is clearly seen in Fig. 16 that the use of the mine water for heating has a much higher efficiency than that of the other energy resources, making the use of the mine water for transferring geothermal energy from flooded mines remarkable for the application. More than that, the input energy for the geothermal option to run the pumps is only electricity. The environment, therefore, will benefit from house heating with the mine water due to the much less carbon emission than the other energy resources.

3.2.3. Cost comparison

The KRC geothermal heat pump system cost is approximately \$100,000 when it was installed during the building's construction



Fig. 15. Automation systems for efficiency and cost control: (a) Allen-Bradley PowerFlex for the shaft pump and (b) VLT AutomationDrive for the loop pump.

Table 2

Residential heating cost comparison for the Upper Peninsula of Michigan.

Electric Heating \$ 58.61 Electrical rate of \$0.20 Heating Oil \$ 30.19 #2 Fuel Oil at \$3.54/g Propane \$ 28.62 \$2.25/gallon Mine Water Geothermal \$ 11.72 \$0.20/kWh, electricity Natural Gas \$ 8.24 \$0.70/Therm)/kWh 3allon

Note: The price of the energy resources was adopted according to the U.S. Energy Information Administration for the U.P. of Michigan. The electricity price referred to the KRC building's electricity bills.

phase. Based on the condition of its service, it was estimated that a payback period is three to five years and the lifespan of the major geothermal equipment is 20–25 years. Because of these benefits, the KRC is intended to expand this mine water-based geothermal on the site to install a new and smaller system in a separate building.

The U.P. has a primary need of heating with a low annual average temperature, so it possibly represents an extreme situation that is less economical. Despite this extreme situation, the results of this project still indicate that heating using the mine water is very economically attractive. An estimate of economic benefits was made and is shown in Table 2. The estimate of cost (M) was calculated using the following equation

$$M = \frac{rE}{\beta} \tag{8}$$

where *r* is the dollar per unit consumption of a heating resource, e.g., β (gallon for oil; *E* is the needed energy (1 MMBTU (293.3 kWh)); and β is the efficiency obtained in Fig. 16. For heating, the financial benefit of the geothermal application with the mine water in the U.P. is better than heating with electricity, propane, or diesel fuel. This table was made under the condition that the western portion of the U.P. has the second highest electrical price in the nation and a very low cost of fuel. As most of the cost of the mine water-based geothermal system occurs during the installation and later system operation using electricity, a lower electrical price could significantly reduce the cost, making the application of the technology in other parts of the U.S. a possibly even much more economical option.

3.2.4. Temperate monitoring

The temperature of the mine water monitored with temperature indicators (see Fig. 13a) is a key parameter to determine the performance of the heat pump system, and especially to tell if house heating with the mine water in winter is reliable. To evaluate the temperature variation of the mine water, the temperature data plotted in Fig. 17 was continuously collected during the period of April 5, 2018 to April 10, 2018, which is a typical working cycle in winter. In general, the heat pump heating system in the building is turned on at 6 am on weekdays and at 9 am on weekends. At 6 pm, the system is turned off



Fig. 17. Temperature variations of mine water and the air in the intake duct.

automatically. The temperature of the mine water entering the heat exchanger (i.e., inlet) almost remains a constant of 8.8 °C. This temperature value, in fact, is much lower than that during most time of the year (the average is around 12.8 °C). This is because the cold water from the melting snowpack on the cold surface is flowing into the shaft during this period, leading to a smaller inlet mine water temperature compared to the average value of 12.8 °C in a year. A significant drop in the outlet mine water temperature occurs at the time when the system is turned on, which implies that the heat is extracted from the inlet mine water through the heat exchanger. At the same time, the extracted heat during this process warms the air in the intake duct supplied from the outside (i.e., 15% air supply in Fig. 12), leading to a distinctive increase in the temperature of this air.

As the building gradually warms up in a day, the outlet water temperature approaches the inlet temperature and the heat extraction becomes negligible. After the system is turned off, the air temperature in the intake duct decreases significantly because no heat is extracted from the mine water to warm that air. In this collocated data period, the air temperature hits the lowest point about -10 °C on Monday morning, however, the inlet mine water temperature remains very stable at 8.8 °C. This temperature has the lowest value in this working cycle and represents one of the typically highest heating demands in the whole year, which indicates that the KRC heating with the mine water is very reliable.

The project has been running well for heating the KRC building. The effort of this project is of great significance as it proved the feasibility and reliability of recovering geothermal energy from this mine in this area. More than that, it has offered us more confidence to implement real installations in the Quincy mine explored in Section 2, where the scale of the mine and the potential of the energy are much more remarkable. The effort also has a scientific and practical significance beyond the territory of the area to guide future real installations.

4. Conclusions

This study presents a real geothermal energy application in the Upper Peninsula (U.P.) of Michigan in the U.S. for the use of water in deep flooded copper mines for house heating. The site exploration of a typical flooded copper mine in the U.P. was presented to discuss three essential components of the proposed large-scale energy application, i.e., bedrock geology, mining background, and energy reserve analyses considering the renewability of the energy. Dynamic energy reserve analyses revealed that the explored mine has a huge potential to provide the annual extractable energy comparable to the annual energy produced by a small-scale power station, which can support over 82,000 households. The key technical details and data monitoring of a demonstration project for the use of mine water for heating a 15,000 ft² (1394 m²) building were introduced. The results from the demonstration project indicated that house heating with the mine water is the most efficient and the second most economical heating option in very unfavorable conditions with a high electricity price and a low annual average air temperature.

The KRC mine water-based heat pump system installation is one of the limited numbers of real projects in the world for geothermal applications with mine water in deep hard-rock mining and a groundbreaking one in the U.S. The effort of this study is of great significance because it not only proved the feasibility and reliability of recovering geothermal energy from deep abandoned mines in the U.P. but also set up a paradigm to guide future real installations in other mining areas with abandoned flooded mines in the U.S. and around the world. It is the first time that the economic value of this energy renovation is validated by comparing against other heating options based on a real demonstration project on the site and that the high power and reliability of this type of low-enthalpy geothermal energy reservoir are investigated and reported for deep flooded mines.

Conflict of Interest

The authors declared that there is no conflict of interest.

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