Mine Water and the Environment
https://doi.org/10.1007/s10230-025-01057-w

REVIEW ARTICLE

Mine Water as an Energy Source: Overview of Technical Basics, Existing Plants, and Monitoring Results

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Received: 19 June 2024 / Accepted: 17 April 2025

Abstract
As a renewable energy source, geothermal mine water systems utilize abandoned mines for heating and cooling and contribute to the reduction of CO_2 emissions. There are five different systems for mine water heat recovery, including both open and closed types. A comprehensive review of geothermal mine water systems worldwide, both planned and existing, as well as their accompanying studies, shows that such systems have already been installed as heating and cooling applications at more than 51 sites. Approximately 85 MW of heating and 20 MW of cooling capacity worldwide are currently provided by geothermal mine water systems, and due to rising energy prices, new systems are increasingly being planned and installed. Most systems have supplied single properties with heating and cooling capacities below 200 KW; however, a trend towards larger systems that are able to provide energy for entire neighborhoods or districts can be observed. In this study, a comparison of monitoring results of four locations in Europe and North America shows that the parallel use of mine water for heating and cooling can achieve seasonal performance factors (SPF) of up to 10 for the overall system. Thus, even with high electricity prices, operational costs for geothermal mine water energy of between 5 and 10 ct/kWh heat are possible. Therefore, depending on fossil energy prices, performance factors of over 3 (Europe) or over 3.5 (USA) are feasible.

Keywords Renewable energy · Abandoned mines · CO_2-reduction · Heat pump · Mine water · Geothermal energy · District heating and cooling

Introduction

As mining geothermal systems have evolved at a relatively high annual rate, this paper updates and expands on the information provided seven years ago by Grab et al. (2018). The integration of renewable energy into the energy supply chain is currently a key issue worldwide. A substantial reduction in CO_2 emissions is required to meet climate change targets. Abandoned underground mines can play a role as a renewable energy source due to their nearly global occurrence and large water-containing cavities. Thus, they have great potential for heating and cooling as well as storing energy.

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Geothermal energy from hydrothermal sources has been used since ancient times in Greece and Japan as well as in the Roman Empire. Highly permeable rocks and geothermal anomalies caused by volcanic activity were widely utilized (Ernst and Hieblinger 1979; Oelsner 1982).

There are currently around 160,000 disused and 23,000 active metal mines worldwide (Macklin et al. 2023). In addition, coal mining has played an important role in many countries, including Germany, the UK (abandoned mines), the USA, India, and China (Jasansky et al. 2023; Oppelt et al. 2021).

Deep surface and underground mines require water management technologies and systems. Ground and surface water, which constantly flow into the mine, has to be discharged via pumps or water drainage galleries (Bernhard 1992; Dillenardt and Kranz 2010; Huber 1990; Roschlau and Heintze 1975). In some cases, this is still necessary for regional active water management many years after closure of the mine to prevent contamination of surface water and ground water. In the German Ruhr area, for example, over 92 million m^3 of water has to be pumped and, if necessary,

Published online: 15 May 2025

treated annually (Kretschmann 2020). At these locations, mine water could thus be used for heating and cooling without the need for additional pumping energy.

Flooding of abandoned mines results in large heat-transferring areas with high hydraulic conductivity and almost constant temperature stratification in the mine workings. The enormous geothermal potentials of such areas have been studied since the 1980 s, for example, in the USA (Jensen 1983) and Canada (Raymond and Therrien 2008). Energy utilization is also possible where the mines have been flooded to the level of the drainage galleries with the lowest hydraulic potential.

Integrating renewable energy into the energy supply is an important goal for achieving the decarbonization of the worldwide energy sector. Currently renewable energy sources have a global share of 12% (≈ 30 EJ) of heating energy (International Energy Agency 2024). Out of that, geothermal energy currently has a global share of about 9% in the building sector, and < 1% in industry. A decisive factor for the high share in the building sector is the Chinese market, where geothermal energy has a share of about 50% (≈ 650 PJ) (International Energy Agency 2024). In the European Union, the share is currently less than 1%, with a share of ≈ 8.5% being forecasted for 2026 (48 PJ) (International Energy Agency 2024). Most of the world's actual heating demand comes from China, the USA, the European Union, India, and Russia. Particularly the European countries, USA, China, and Russia have a considerable potential to use abandoned mines for energy recovery and could thus increase their share of renewable energies in the heating and cooling supply (International Energy Agency 2024).

This paper, based on the work of Grab et al. (2018), expands substantially on their review of 123 published geothermal mine water plants worldwide (planned, installed, closed), and addresses the main technological and economic considerations for planning geothermal mine water sites. Monitoring results from four plants in Europe and North America are used to assess the economic viability of the systems.

System-Specification

The main system parameters and possible heat extraction systems for geothermal mine water plants are presented below. Depending on the regional circumstances, the mine water can be accessed at various locations, such as pumping stations (e.g. for pumping out water to protect groundwater and surface water), water drainage galleries, ascending deep water (e.g. in shafts), or flooded underground mine workings. From an environmental perspective, several options are available for reintroducing the mine water into the water system to close the mine water cycle. These include surface water (e.g. rivers), water drainage galleries, and water-filled mine workings (return to mine).

Besides the options to collect and reinject mine water, several other site parameters are relevant for planning geothermal mine water plants (Huber 1990; Hall et al. 2011; Ramos and Falcone 2013; Preene and Younger 2014). These technical and legal parameters will be described.

Useful Energy

The usable energy or the usable heating and cooling capacity depends on the usable flow rate and the temperature level. For best operational parameters, the temperature should be as high as possible for heating and as low as possible for cooling. The key variables are therefore the maximum usable mine water volume flow, the amount of water entering the mine (mine water renewal rate or groundwater flow rate) and the maximum (heating)/minimum (cooling) usable and stable available temperature level of the mine water. Both the inflowing water and the total volume are of interest here, as the water in the mine will cool over time due to energy use if no fresh water is flowing in. The usable potential is therefore a function of the mixture of inflowing water and the total volume of water in the mine.

Effort/Losses

For the geothermal system to operate effectively, the effort required to provide energy should be kept to a minimum. For example, the pumping head should be as low as possible and the distance between energy consumers should be as short as possible. In addition, the energy end users should not be too far away. Therefore, the key variables are the vertical distance between water level (possible tapping point) and the user above ground and the length of the distribution system to the users with heating and cooling demand. The greater the distance, the greater the heat loss.

Condition of the Mine

In particular, the cost of constructing and installing a mine water geothermal system depends on the current condition of the mine. For example, an active conveyor system and/or usable access to the mine will reduce construction costs. The physico-chemical characteristics of the rock mass should also be considered, as it affects how fast heat can be transferred from the rock to the mine water, and may also affect the water chemistry. The water chemistry itself is also an important factor as, depending on the location, the composition of the water can cause fouling and clogging in the heat

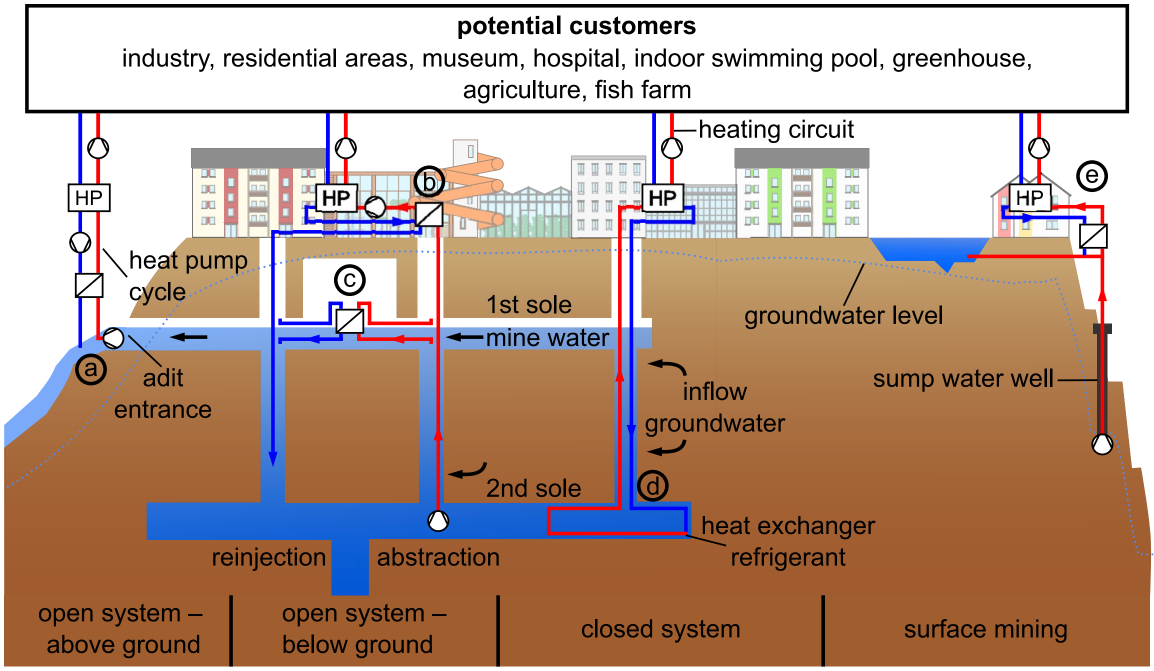

Fig. 1 Schematic structure of a mine water system with five different possible heat extraction systems with integrated heat pump stations (HP) for potential customers (a–e)

exchanger and the pipes, which affects the efficiency of the system.

Relevant in this regard are therefore the existing infrastructure (shaft hoisting system or pump station), the depth and spatial expansion of the flooded mine, the accessibility/stability of the mine area, the water chemistry (possible environmental hazards, scaling and precipitation), and the type of rock in the mine (heat conductivity and influence on water chemistry).

Legal Parameters

From a legal point of view, it has to be clear who is entitled to use the mine. Furthermore, potential limits need to be observed with regard to the chemical conditions of the reinjected water.

Further Risks

There are also cross-focus point risks, such as exploration risks. If the planned route is not hit during drilling, additional costs will be incurred. Depending on the location, it may also be important to ensure that the energy use and associated drilling does not result in an unwanted connection between the mine and the aquifer, which could contaminate drinking water, for example. Investigations are also underway into the possible seismological effects of mine water geothermal energy. Initial measurements show no connection (Nehler et al. 2023).

In addition to the exploration risks, there are also financial risks if it is not possible to extract the planned amount of heat and cold, e.g. due to an overestimation of the available volume flow or excessive fouling in the heat exchanger. In addition, for long-term economic operation, it is necessary to ensure that there are sufficient consumers in the vicinity of the mine water potential that require heating and cooling over the planned operating period (Gasperikova et al. 2024).

Therefore, the minimum and maximum temperatures of the reinjected mine water (related to water chemistry and possible scaling and precipitation) must be known, along with what the ownership structure of the site look like. Often, the temperature of the mine water is insufficient for direct heating applications. In this case, it would be necessary to use heat pumps to provide the relevant temperature.

There are several ways to use the energy of the mine water (Fig. 1). These will be explained in the following sub-sections.

a) Open System: Heat Exchanger Above Ground

In open systems, the mine water that discharges at the surface (e.g. at an adit) is pumped to a heat exchanger station where the heat is transferred to an intermediate circuit or heat pump circuit. Used water is simply returned to the pumping station outfall or the drainage adit. Main advantages of this variant are the low energy demand for the water circulation pumps and especially their easy accessibility. However, the mine water at the mine adit can have a lower temperature than other potential mine water extraction points inside the mine.

b) Open System: Heat Exchanger Located at Surface (Pumping of Mine Water Below Surface)

If an existing shaft for pumping the mine water to above ground exists, the water can be transferred into a heat exchanger (and then via an intermediate circuit to the heat pump) or directly into the heat pumps. Advantages are firstly that this water cycle can also be used for cooling and secondly, that if the water can be returned to the mine, it is also possible to recover some of the pumping energy by using the potential energy of the mine water in a generator. The recovery rate can reach 30–50% (Huber 1990). Alternatively, the water can be discharged above ground, for example into a river. Primary disadvantages of such a system are the energy consumption of the pumps (e.g. depending on the local energy price, depth) and that the direct supply of mine water to the heat pump can result in scaling. Consequently, this variant is not recommended (Huber 1990; Grab et al. 2018).

c) Open System: Heat Exchanger Located Underground (Intermediate Circuit Between Mine Water and Heat Pump)

By installing an intermediate circuit between the mine water and the heat pump, most of the scaling and corrosion in the heat pump or other components can be prevented. Furthermore, the mine water does not need to be pumped from great depths to the surface (Huber 1990; Grab et al. 2018). With a low heating and cooling rate, heat exchange with the tubing walls may be sufficient to cover demand, saving mine water pumping and leading to an even better system efficiency. Most of the drawbacks with this system concern the inaccessibility of the underground heat exchangers. Additionally, shaft refurbishments and maintenance of the underground heat exchangers might pose problems and the heat exchangers must withstand high hydrostatic pressures. Nevertheless, this system is the most frequently used (Grab et al. 2018).

d) Closed System

In a closed system, a refrigerant is transported by the thermosiphon principle. This system can also be designed as a split version with one compressor above ground (with a long suction line) or underground (with a long discharge line). If it is possible to access the water-bearing point (e.g. before flooding), a collector system can also be installed in the gallery. As these systems use relatively long piping, a large mass of refrigerant is required. While selecting the refrigerant, attention must be paid to possible environmental issues in case of leakage. If the closed system uses the thermosiphon principle, no cooling application is possible (Huber 1990; Grab et al. 2018). Besides refrigerants, water can be used in a closed system also. An additional circuit then transfers the refrigerant circuit of the heat pump. This avoids contamination of the heat pump but also reduces its efficiency.

e) Surface Mining: Using Open Pit Mine Water

Mine water pumped to drain operating mines can also be used as an energy source. As the water has to be pumped anyway, this reduces costs and the pumped mine water can be used for heating or cooling. Yet, this procedure is normally limited to the active mining period and the energy can only be used near existing pump stations and potential customers. The temperature is also often lower than in systems where mine water is used deeper in the mine.

In the following sections, details will be given expanding the information published in Grab et al. (2018) and providing a worldwide overview of currently operating and abandoned mine water geothermal systems. Furthermore, plants under construction and visibility studies will be presented. In the results and discussion section, the mine geothermal plant data is evaluated and graphically presented. In addition, monitoring data from four plants will be compared and the economic viability of these plants will be assessed and compared to using fossil fuels.

Methods

During an extensive literature review, the data provided in freely available presentations, lectures, conference proceedings, internet pages, technical literature, and published papers were compiled. In addition, plant owners were contacted and asked for plant data and corresponding characteristics for the compilation. The results are listed in Table 1.

The four plants that will be described in detail are located in Europe and North America. They are the Reiche Zeche and Ehrenfriedersdorf mines in Germany, the Markham mine in the UK, and the Butte mine in the USA.

Reiche Zeche Silver Mine

The flooded Reiche Zeche plant in Freiberg (Germany) supplies several university buildings with heating and cooling. In general, the mine water can be used for cooling or heating. During summer, cooling is the main requirement; the ≈ 14 °C warm water from the mine's main drainage gallery can be

Table 1 Overview of existing geothermal mine water systems (a: after heat pump, b: before heat pump, c: cooling, coa: coal, d: decommissioned, h: heating, i: in, o: out, p: planned, s: study, s.w.: sump water, u.c.: under construction, w: working)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
1a	Rothschönberger Stolln/Freiberg	DE	Ag	220	14/–	–	600/800	–/–	Hospital	w. (2014)	Johnson Controls (2013), Ulbricht (2013)
1b	Rothschönberger Stolln, Reiche Zeche/Freiberg	DE	Ag	228	15|18/17|13	56	155/200	155/–	University	w. (2013)	Bauconzept Dresden GmbH (2015), Grab et al. (2010)
1c	Alter Fürstenstollen/Freiberg	DE	Ag	55	10.2/–	22	96/130	120/–	Museum	w. (2009)	Lagerpusch (2010), Hall et al. (2011), Batchelor et al. (2015)
2	Wismut-Schacht 302/Marienberg	DE	U	105	12/7	120	700–830/800–1700	–/–	Indoor swimming pool	w. (2007)	Wieber and Ofner (2008), Lagerpusch (2010)
3	Walfisch-Stollen, Weiße Villa/Pobershau	DE	Sn	12	–/–	–	–/15	–/–	Residential building	w. (2008)	Lagerpusch (2010), Mineralienatlas - Fossilienatlas (2015)
4a	Nord–West-Feld/Ehrenfriedersdorf	DE	Sn	100	10/–	–	65/95	66/–	School	w. (1994)	Wieber and Ofner (2008), Lagerpusch (2010), Debes (2012)
4b	Revier Sauberg/Ehrenfriedersdorf	DE	Sn	110	11/4	22	82/120	–/–	Museum	w. (1998)	Wieber and Ofner (2008), Kissing (2009), Lagerpusch (2010), Raube (2012)
5a	Grube Schlema-Alberoda/Bad Schlema	DE	U	90	11/5	14	100/200	–/–	School	w. (2013)	Vater (2012), Debes (2012), Wismut GmbH (2012), Ramos et al. (2015)
5b	Projekt “Leon”/Bad Schlema	DE	–	102	21/–	–	–/–	–/–	Residential building	w. (2007)	Debes (2012), Vater (2012), Landesamt für Umwelt, Landwirtschaft und Geologie (2012)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
6	–/Zwickau	DE	Co	625	24/10	30	500/600	–/–	University	w. (2018)	Röder (2012), Sunbeam GmbH (2013), Röder (2015), Sächsisches Staatsministerium für Finanzen (2018)
7	Röhrig Schacht, Segen-Gottes-Stollen/Wettelrode	DE	Ag	220	14/–	–	600/860	–/–	Museum	w. (2013)	Koch (2012), Hoffmann et al. (2015), Ramos et al. (2015)
8	Zeche Auguste Victoria/Marl	DE	Coa	700	16–21/–	–	70/–	–/–	Residential building	w. (2010)	RAG Deutsche Steinkohle (2009), Lintker (2014), Bracke and Bussmann (2015), Louie (2015), Thien (2015)
9	Zeche Robert Müser/Bochum	DE	Coa	570	20/–	40	–/690	–/–	School, Public building	w. (2012)	Raube (2012), Willmes and Bücker (2014), Bracke and Bussmann (2015)
10	Zeche Zollverein/Essen-Katernberg	DE	Coa	950	29.8/28.5	522	790/–	–/–	Museum	w. (2000)	Wieber and Ofner (2008), RAG Deutsche Steinkohle (2009), Debes (2012), Thien (2015)
11	Tagebau Hambach/Bergheim	DE	Coa	–	22–26/18	70	–/620	–/–	Buildings	w. (2014)	EnergieAgentur NRW (2014), Thien (2015)
12	Eduard Schacht/Alsdorf	DE	Coa	860	22–26/–	–	–/420	–/–	Buildings	w. (2018)	Clauser et al. (2005), Schetelig et al. (2005), Stüber (2012), GrEEN (2015)
13	Stadtstollen/Bad Ems	DE	Pb, Zn	800	25/–	100	500/600	–/–	Public building	w. (2018)	Lahntal Tourismus Verband e. V. (2020), Hickel (2018), Münch (2018)
14	–/Landsweiler-Reden	DE	Coa	800	32/24	50	450/–	–/–	Public building	w. (2012)	Rosenkreis Neunkirchen (n.D.), Frisch (2008)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
15	–/Novoshakhtinsk, Rostov Region	RU	Coa	50–150	12–13/5–7	956	7800/10900	–/–	Public buildings	w. (2007–2009)	Joint Implementation Supervisory Committee (2007)
16	Mimer mine/Norsberg	SE	Fe	300	4–7/–	–	–/180	–/–	Buildings	w. (1985)	Arkay (1993), Wolf et al. (2007)
17	–/Ljusnarsberg	SE	Cu	310	2–13/–	–	–/–	–/–	Buildings	w. (–)	Arkay (1993)
18	Kings mine/Kongsberg	NO	Ag	330	16/–	–	12/–	–/–	Festival room	s.	Banks et al. (2003, 2004), Hall et al. (2011), Preene and Younger (2014)
19	Bohrung S1-NB-II/Laskar, Novaky	SK	Coa	1851	58/11	50	2733/–	–/–	Supply mine air	w. (2001)	Halmo (2010)
20	Sobieski mine/Jaworzno	PL	Coa	500	–/–	65	–/–	–/–	Mine bath-house	w. (ca. 2006)	Karpiński and Sowiżdżał (2018), Walls et al. (2021)
21	Prokopschacht/Pribram	CZ	U	–	28/18	36	419/500	–/–	Public buildings	w. (1989)	Myslil and Frydrych (2005), Wolf et al. (2007)
22	Hachov-Plana/Marienbad	CZ	U	–	–/–	–	–/–	–/–	Mine buildings	w. (1989)	Wolf et al. (2007)
23	–/Zagorje ob Savi	SI	C	450	27.6/–	2.9	–/–	–/–	Research unit	w. (ca. 2012)	Vidrih et al. (2012), Op't Veld (2012)
24	Oranje Nassau/Heerlen	NL	Coa	700 (h), 250 (c)	28 (h)/–16 (c)/–	120(h) 230(c)	–/–	–/–	Buildings	w. (2013)	Verhoeven et al. (2013), Jones et al. (2014)
25	Ochilview/Lumphinnans, Schottland	GB	Coa	170	14.5/3	–	–/65	–/–	Residential buildings	d. (2001 ca. 2020)	Banks et al. (2003), Wieber and Ofner (2008), Preene and Younger (2014)
26	Glenalmond Street/Shettlesston, Glasgow	GB	Coa	100	12/–	10.8	–/65	–/–	Residential buildings	d. (1999–ca. 2020)	Wieber and Ofner (2008), Hassani et al. (2011), Preene and Younger (2014)
27a	"East of Wear" mine area/Dawdon, County Durham	GB	Coa	–	19/–	< 100	–/12	–/–	Office buildings	w. (2011)	Bailey et al. (2013), Preene and Younger (2014)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
27b	Seaham Garden Village, Dawdon, Country Durham	GB	Coa	–	18–20/–	360–540	4000–6000/–	–/–	District	s.	Bailey et al. (2013), The Coal Authority (2020), Wood and Jeremy (2020)
28a	Markham Colliery Shaft 3/ Markham	GB	Coa	235	15.4/13.5	15–26	34–58/54–78	–/–	Office buildings	w. (ca. 2015)	Athresh et al. (2015)
28b	Gateshead Council, Gateshead	GB	Coa	150	–/–	–	–/6000	–/	District	W (2023)	The Coal Authority (2023)
28c	Nest Road, Gateshead	GB	Coa	131–280	13–14/–	144	–/1200	–/–	District	s.	Banks et al. (2022)
29	Hope Shaft, Caphouse Colliery/ Overton	GB	Coa	143–156	14–15/–	120	–/10.5	–/–	Museum	w. (2015)	Athresh et al. (2016), Athresh (2017), Banks et al. (2019b)
30	South Wales coal area/ Crynant	GB	Coa	65	11.5/–	7	–/35	–/–	Farm	w. (2014)	Bailey et al. (2013), Preene and Younger (2014)
31	Mount Wellington mine, St Day Cornwall	GB	Sn	–	–/–	–	–/20	–/–	Office and factory buildings	w. (2008)	Preene and Younger (2014)
32	Barredo shaft, Mieres, Central coal basin of Asturias, Asturien	ES	Coa	–	23/18	330	–/2630	–/–	Buildings, e.g. University	w. (2016)	Loredo et al. (2011), Jardón et al. (2013), Al-Habaibeh et al. (2019), HUNOSA (2019)
33	–/Springhill, Nova Scotia	CA	Coa	140	18/11 (h), 17 (c)	14.4 (h), 16.8 (c)	111/–	159/–	Factory, Restaurant	w. (1989)	Jessop et al. (1995), Banks et al. (2003), Raymond and Therrien (2008), Wieber and Ofner (2008), Herteis (2015)
34	Marvine mine pool/Scranton, Pennsylvania	US	Coa	122	14/16	–	–/–	–/–	University	w. (2010)	Korb (2012)
35	–/Kingston, Pennsylvania	US	Coa	–	16/11	20.4	130/–	–/–	Recreation center	w. (1981)	Korb (2012)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
36	Keweenaw Research Center/ Calumet, Michigan	US	Cu	90	13–18/8–13	20	–/–	–/–	–	w.	Louie (2015)
37	–/Park Hills, Missouri	US	Pb	122	14/–	16.9	–/113	–/–	Office building	w. (1995)	GeoExchange (2002), Wieber and Ofner (2008), Hall et al. (2011)
38	Henderson Molybdenum mine/Henderson, Colorado	US	Mo	–	30/4	226–285	5900/–	–/–	Heating shaft	w. (1983)	Jensen (1983)
39	Orphan Boy mine/Butte, Montana	US	Au, Ag, Cu, Zn, Mn	245	20–27(h) 24–35(c)	18–20	108/147	100/120	University	w. (ca. 2014)	Montana Department of Environmental Quality (n.D.), Thornton (2013), Malhotra et al. (2014)
40a	Zhang-shuanglou Coal mine/Xuzhou City	CN	Coa	1250–2000	11–33(h) 37–39(c)	180–1100	–/647–4750	–/649–1800	Buildings	w. (2010)	Guo et al. (2017)
40b	Jiahe mine/ Xuzhou City	CN	Coa	1000	36/–	95–135	–/3722	–/–	Heat borehole	w. (2007)	He (2009), Guo et al. (2014), Guo et al. (2017)
40c	Sanhejian mine/Xuzhou City	CN	Coa	1000	25–30/–	50–60	–/3386	–/–	Heat borehole	w. (2007)	He (2009), Guo et al. (2014), Guo et al. (2017)
41	Uranerzgrube Königstein/ Königstein	DE	U	40	13/–	–	–/–	–/–	Operation buidlings	w. (2021)	Jenk (2020)
42	Grube Schlema-Alberoda/Bad Schlema	DE	U	–	27/–	–	–/2400	–/–	Commerce and Residential buildings	s.	Vater (2012), Grab et al. (2018)
43	Schacht 383/ Aue	DE	Cu	100	20–25/11–16	100	1000/–	–/–	Industrial buildings	s.	ReSource (2011)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
44	Schlüssel Stollen/ Friedeburg, Hettstedt-Burgörner	DE	Cu	79–90	8–12/–	1200	1400/–	–/–	Industrial buildings	s.	Hoffman and Joppich (2012), Lau (2012)
45	Wiederstedter Stollen, Wiederstedt	DE	Cu	< 5	10–12/–	120	–/–	–/–	Castle	p.	Mansfelder Kupferspuren (2012); ncn KG (2012) Lau (2012)
46	Kaiser Wilhelm II Schacht/ Clausthal-Zellerfeld	DE	Pb, Zn	50–700	13/8	20	71/97	–/–	University	s.	Ramos et al. (2015)
47a	Ibbenbüren Ostfeld	DE	Coa	–	13/6	119	900/1300	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
47b	Ibbenbüren Westfeld	DE	Coa	–	13/6	457	3700/5000	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
48a	Haus Aden/ Bergkamen	DE	Coa	600	25–29/–	1440	–/–	–/–	District	p.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018), Tatenhorst (2018), Altieri et al. (2018)
48b	Haus Aden/ Bergkamen	DE	Coa	600	20/6	1100	23,600/30,600	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
49a	Zeche Dannenbaum, Mark 51°7/Bochum	DE	Coa	300 (c)–800 (h)	18/–	–	–/–	–/–	Business location	p.	Peper (2019)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
49b	Robert Müser/ Bochum	DE	Coa	445	20/6	1210	19,600/25,400	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
49c	Friedlicher Nachbar/ Bochum	DE	Coa	165	20/6	972	15,700/20,400	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
50	Prosper Haniel/ Bottrop	DE	Coa	> 1200	25–30/–	–	500/–	–/–	Commerce and residential buildings	s.	Bracke and Bussmann (2015), Bracke et al. (2015)
51a	Zeche Hein-rich/Essen	DE	Coa	280	18/6	2280	31,400/41,000	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
51b	Zeche Amalie/ Essen	DE	Coa	850–1000	26	–	–	–	District	p.	Altieri et al. (2018)
51c	Zeche Hein-rich/Essen	DE	Coa	335–480	–/–	20	6.8/–	15.2/–	Retire–ment home	d. (1984–2004)	Landesinitiative Zuku-nftsenergien NRW (2004), Wolf et al. (2007), Wieber and Ofner (2008), RAG Deutsche Steinkohle (2009), Landesamt für Natur, Umwelt und Verbraucher-schutz Nordrhein-Westfalen (2018)
52	Lohberg/ Dienslaken	DE	Coa	640	35/6	3970	128,500/157,300	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
53	Walsum/Duis-burg	DE	Coa	746	29/6	910	23,700/29,700	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
54	Garzweiler Tagebau/ Jüchen	DE	Coa	s.w	13/6	12,560	101,900/136,000	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
55	Hambach Tagebau/ Niederzier	DE	Coa	s.w	22/6	37,100	664,000/856,700	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
56	Schwefelgrube Meggen/Lennestadt	DE	FeS_2,Ba–SO_4, Zn	–	17/6	194	2400/3100	–/–	–	s.	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (2018)
57	Grube St. Andreas/ Bitzen	DE	Fe	730	13/8	11	100/–	–/–	Residential buildings	s.	Wieber (2010)
58	Grube Huth/ Hamm (Sieg)	DE	Fe	465	10/5	12	69/–	–/–	Industrial, commerce and Residential buildings	s.	Wieber (2010)
59	Grube Kupferener Kessel/Seelbach bei Hamm	DE	Fe	–	10/5	13	78/–	–/–	Swimming pool	s.	Wieber (2010)
60	Grube Hohe Grete/Pracht-Wickhausen	DE	Fe	430	10/5	> 6	> 36	–/–	–	s.	Wieber (2010)
61	Grube Alte Hoffnung/ Tränke/Breitscheid	DE	Fe	200/300	10/5	> 15	> 87	–/–	Company building	s.	Wieber (2010)
62	Grube Georg, Schacht 2/ Willroth	DE	Fe	850	17–22/13–18 (h) 17–25/36 (c)	194 (h), 441 (c)	900/1200	5100/–	Comercial area, industrial buidlings	s.	Münch (2009), Münch et al. (2010), Wieber (2010)
63	Neuhoffnungsstollen/Bad Ems	DE	Pb, Zn	–	10–25, 60/–	14	–/129	–/–	Company building, Prayer house	s.	Wieber and Ofner (2008)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
64	Cherno More mine/Burgas	BG	Coa	–	16/–	–	–/70–80	–/–	ABV Furniture Factory	s.	Remining Lowex (2012), Vidrih et al. (2012), Op't Veld (2012)
65	Folldal mine/ Folldal	NO	Cu, Zn, S	600	6/–	–	–/18	–/–	Museum	d. (1998–2008)	Banks et al. (2003), Hall et al. (2011), Ramos et al. (2015)
66	Saturn mine, Pawel Shaft/ Czeladz	PL	Coa	188	12–14/–	1440	–/–	–/–	Historical mine building	s.	Malolepszy et al. (2005), Vidrih et al. (2012), Op't Veld (2012)
67a	Szombierki mine/Bytom	PL	Coa	510–630	24/19	290	1690/2250	–/–	Residential buildings	s.	Gzyl et al. (2016), Janson et al. (2016), LoCAL Deliverable 1.7 Report from Bytom (PL) predictive modelling (2017)
67b	Powstańców/ Bytom	PL	Coa	500–760	23/18	179	1040/1380	–/–	–	s.	Gzyl et al.(2016), LoCAL Deliverable 1.7 Report from Bytom (PL) predictive modelling (2017)
68	Dębieńsko/ Czerwionka-Leszczyny	PL	Coa	–	18/–	574	3340/4450	–/–	–	s.	Gzyl et al.(2016), LoCAL Deliverable 1.7 Report from Bytom (PL) predictive modelling (2017)
69	–/Nowa Ruda	PL	Coa	460/890	23/4	72	1600/–	–/–	–	s.	Malolepszy (2003)
70	Alter Stollen/ Handlova	SK	Coa	–	18/7	216	–/–	–/–	Residential buildings	s., p.	Halmo (2010)
71	–/Recsk	HU	Cu	1160	29/–	72	–/2.5	–/–	Medicinal baths, Hotels	s.	Toth and Bobok (2007), Dillenardt and Kranz (2010), Hall et al. (2011)
72	Anezka/Dolní Rychnov	CZ	Coa	24	10/2	1.2	11/–	–/–	Town hall, Welfare buidlings	s.	ENERGONPLAN s.r.o. (2011)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
73	Kimich II/ Pilsen	CZ	Coa	325	16/–	144	1660/–	–/–	–	s.	Uhlík and Baier (2012)
74	Kohlenmulde/ Fohnsdorf	AT	Coa	750	30/10	–	–/900	–/–	Residential buildings	s.	Bieg et al. (2013)
75	Trbovlje-Hrastnik coal-mine/ Hrastnik, Trbovlje	SI	Coa	–	40/14	41	–/–	–/–	Office buildings	s.	Butolen (2010)
76a	Bore KT-1/97/ Zagorje ob Savi	SI	Coa	–	425/30–32	36	–/–	–/–	Swimming pool, School gym	s., p.	Butolen (2010)
76b	Bore Fk-1/97/ Zagorje ob Savi	SI	Coa	–	180/13	40–43	–/–	–/–	–	s.	Butolen (2010)
77	Morandat mine/ Gardanne	FR	Coa	880–1109	25/–	–	–/–	–/–	Joint Development Zone	p.	Op't Veld (2012), brgm (2014)
78	Freyming-Merlebach mine/ Freyming-Merlebach	FR	Coa	1250	52/20	–	–/–	–/–	–	s.	Minewater Project (2011)
79	Monktonhall Colliery/Midlothian	GB	Coa	900	13/8	108	1150/1500	–/–	–	d.	Banks et al. (2003), Minewater Project (2011)
80	–/Mossend, North Lanarkshire	GB	Coa	–	–	–	–/–	–/–	–	d. (1992)	Banks et al. (2009)
81 a	Florence shaft, Ullcoats-Florence-Beckermet mine/ Egremont	GB	Fe	–	11–12/–	27	103/–	–/–	–	s.	Banks et al. (2019a)
81 b	Florence shaft, Ullcoats-Florence-Beckermet mine/ Egremont	GB	Fe	35	11–12/–	446	> 2000/–	–/–	–	s.	Banks et al. (2019a)
82 a	Hasketh mineshaft/Chatterley Whitfield	GB	Coa	18	12/10	144	668/–	–/–		s.	Athresh (2017)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m^3/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
82 b	Hasketh mineshaft/Chatterley Whitfield	GB	Coa	18	12/10	14.5	–/90	–/–	Enterprise centre	s.	Athresh (2017)
83	Caerau colliery/Caerau	GB	Coa	–	20/–	–	–/–	–/–	Commerce and residential buildings	s.	Braham et al. (2020)
84	Fondón shaft, Mieres, Langreo, Central coal basin of Asturias	ES	Coa	–	23/– (h) 85 (c)	–	3000/–	–/3000	University, Buildings, Football stadium, …	w. (2022)	Benito (2022), HUNOSA (2024)
85	Laciana Valley District/Villablino	ES	Coa	180	14.4/9.4	–	1072/–	–/–	buildings	s.	Matas-Escamilla et al. (2023)
86	Sierra Almagrera mines/Almeria	ES	Fe	–	75–190/25	634	38,100–120,800	–/–	–	s.	Navarro and Carulla (2018)
87	Con mine, Robertson Shaft/City of Yellowknife, Northwest Territories	CA	Au	400	35–25	21	240/300	–/–	–	s.	Ghomshei (2007)
88	Gaspé mines, Shaft P1100/Murdochville, Québec	CA	Au	670	7/3	176	765/1020	–/–	Commerce area	s.	Raymond et al. (2008), Raymond and Therrien (2008), (2014)
89	MacIntyre und Hollinger mine/Timmins, Ontario	CA	Cu	250	12–13/–	–	–/–	–/–	Arena, Hospital	s.	Hall et al. (2011)
90	Bruce mine/Lake Huron, Ontario	CA	Cu	103	8/–	14	–/–	–/–	Buildings, Green–houses	s.	Jarvie-Eggart (2015)
91	Hancock Shaft 2/Hancock City	US	Cu	60	–/–	–	–/–	–/–	–	s.	Liu et al. (2015), Bao et al. (2018)
92a	–/Kingston Pennsylvania	US	Coa	87	13/–	–	–/–	–/–	Shopping center, Radio shack	d. (ca. 1999)	Korb (2012)

Table 1 (continued)

No	Name/place	Country	Raw material	Depth in m	t_i/t_o in °C	$\dot{V}$ in m³/h	$\dot{Q}_{b,h}/\dot{Q}_{a,h}$ in kW	$\dot{Q}_{b,c}/\dot{Q}_{a,c}$ in kW	Customer	Status (year)	Source
92b	–/Kingston Pennsylvania	US	Coa	–	–/–	–	–/–	–/–	Medical center	d. (2000 s)	Korb (2012)
93	–/Carbondale	US	–	–	–/–	–	–/–	–/–	–	d. (1990 s)	Korb (2012)
94	–/Hill District, Pittsburgh	US	Coa	–	14/–	23	–/–	–/–	Church	d. (2009)	Ove (2008), Burtner et al. (2009), Korb (2012)
95	Panther Creek mine #2/ Springfield, Illinois	US	Coa	–	–/–	18	–/–	–/–	Head-quarters	s.	Illinois Department of Military Affairs (27.04.15)
96	Britannia Copper mine/Britannia Beach, British Columbia	CA	Cu	1250	15/7.5	600	960–4000/1200–5000	–/–	–	s.	Hall et al. (2011), Grasby et al. (2012)
97	–/Saint–Bruno–De. Montarville	CA	–	–	–/–	–	130–190/–	–/–	Apartments	d. (2006–?)	Raymond and Therrien (2008)
98	Blahodatna/ Western Donets Basin	UA	Coa	–	17/–	200	–/800	–/–	–	w. (2011)	Rudakov and Inkin (2022)
99	Xiezhuang mine/Taian Shandong	CN	Coa	–	9–12/–	426	–/4343–5227	–/–	Mine air supply	w. (2006)	Yu et al. (2008)
100a	Zhaolou mine/ Shandong	CN	Coa	860–1000	26	800	–/7500	17,000/–	Mine air supply	w. (2014)	Yi (2015)
100b	Jisan mine/ Shandong	CN	Coa	556	22	583	8700/12,200	–/–	Mine air supply	w.	Feng et al. (2018)
101	–/Pingsingsham, Henan	CN	Coa	s.w.	15	500	–/5000	–/–	Buildings	w. (2016)	Wang et al. (2018)

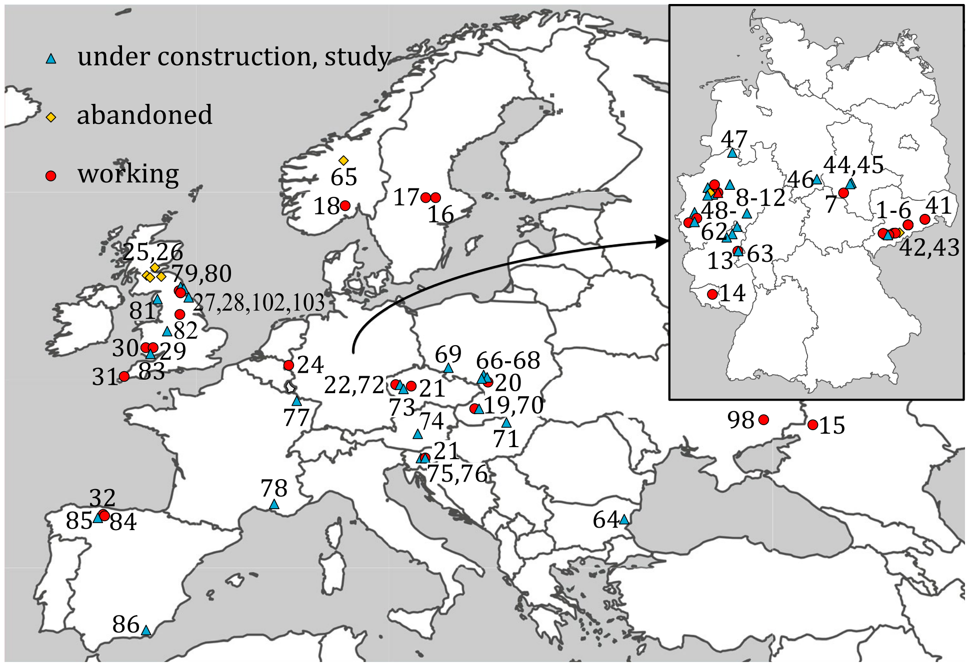

Fig. 2 Planned, working and abandoned mine water geothermal plants in Germany and Europe, according to Grab et al. (2018) and Oppelt et al. (2023) (Δ: under construction/study, ◊: abandoned, o: working)

used. When the heating demand is greater during winter, 19 °C rising deep mine water can be utilized. In total, a heating capacity of 175 kW and a cooling capacity of 100 kW can be provided (Oppelt et al. 2021, 2023).

Ehrenfriedersdorf Mine

Tin, lead, iron, and silver were mined at the abandoned German Ehrenfriedersdorf mine since the thirteenth century. When the mine was closed in 1990, it was flooded and since then the mine water has been available at a temperature of 10–12 °C. Since 1998, this mine water has been used to heat the rooms of the visitor mine with a heat pump and a heating capacity of 120 kW (Hösel 1994; Rottluff 1998).

Markham Mine

In Markham (Wales, UK), water from the flooded coal mine has been used for heating since 2012. A 20 kW heat pump is used to increase the initial mine water temperature of 13–14 °C to 55 °C, which is then used for heating. Designed as an open system, mine water is pumped to the surface, where heat is transmitted to a heat exchanger (Athresh et al. 2015; Burnside et al. 2016a, b; Banks et al. 2019a, b).

Butte Copper Mine

Butte (Montana, USA) began flooding its former coal mining area in 1982. In 2011, a mine water geothermal system was built that uses water from the Orphan Boy shaft to supply a

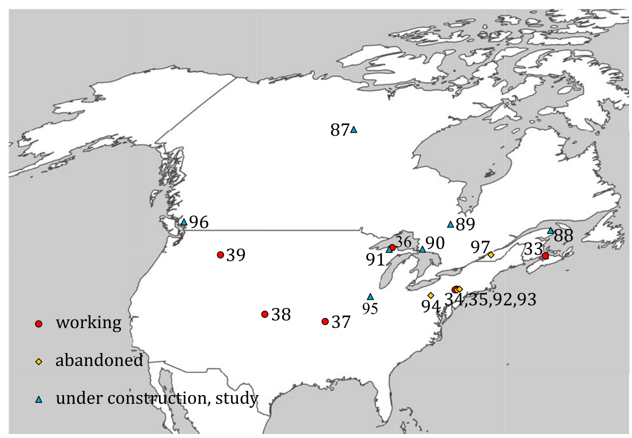

Fig. 3 Planned, working and abandoned mine water geothermal plants in North America, according to Grab et al. (2018) and Oppelt et al. (2023) (Δ: under construction/study, ◊: abandoned, o: working)

175 kW heat pump (Gammons et al. 2006; Malhotra et al. 2014; Liu et al. 2016).

Results and Discussion

Fifty-one active plants for regenerative mine water heat supply were identified in Europe and North America. The locations of these operating plants, including plants that are closed, planned or under construction, are tabulated and compiled in maps (Table 1; Figs. 2, and 3). In addition, seven plants were identified in China. Most of the listed plants are located in Germany, the UK, and the USA. However, similar

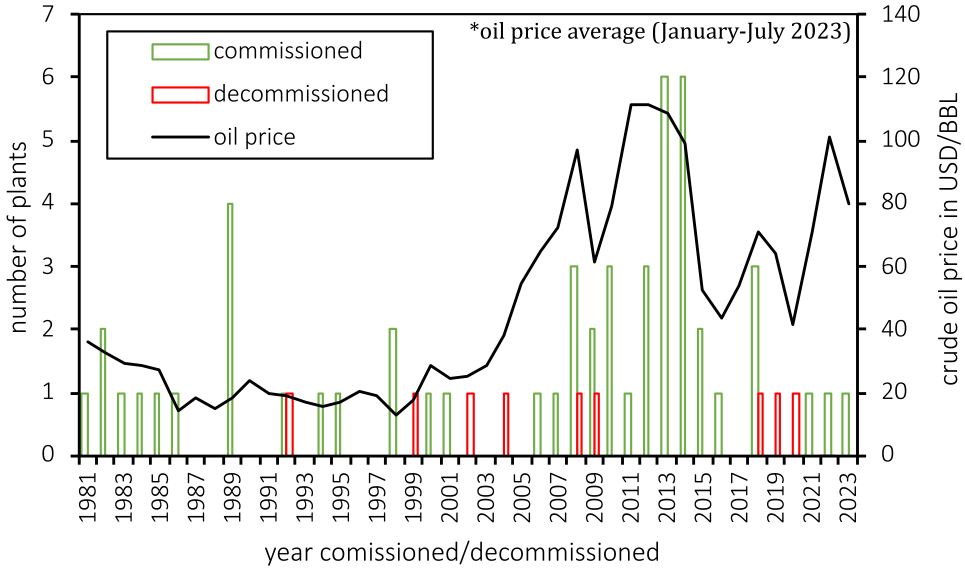

Fig. 4 Development of the implemented or abandoned mine water systems worldwide compared to the oil price over time. Values oil price: (OPEC and IEA 2020), according to Oppelt et al. (2021)

studies on the reuse of old mines have likely been carried out in other countries, but not yet published in the international literature.

A principal reason for the concentration of mine water geothermal plants in central Europe can be the long history of mining as well as the high population density, meaning that there is an appropriate heat demand by customers. Yet, there are many locations in Eastern and Southern Europe, with obstacles, such as a lack of customer structures and potential investors for providing financial support. Another potential area to conduct further research is North America, as there are many closed and flooded mines. However, the low population density (e.g. Canada) and thus missing customer structures at former mining sites represents a major barrier to operate mine water geothermal plants.

For historical reasons, mines in Eastern Germany (e.g. Erzgebirge) were closed and flooded earlier than the hard coal mines in the Western German Ruhr area. Consequently, this resulted in the implementation of one of the first plant concepts in the Erzgebirge region in the 1990 s whilst most of the Ruhr area is in the early stages of structural change. Initial studies (Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen 2018) provide insight into the large mine water geothermal potential to supply energy, which will result in the planning of further mine water plants. However, despite the long period of active mining, there were also small projects in the Ruhr area in the 1980s that used mine water for energy generation (e.g. 51c, Zeche Heinrich/Essen).

Globally, there are 51 active mine water geothermal plants, and 61 planned or ongoing studies on the subject. Eleven plants have been closed down or are out of operation. However, there is no evidence from the sites surveyed that there is a general requirement to decommission plants after a certain (short) lifetime. For example, the systems in Ehrenfriedersdorf (4a and 4b) have been in continuous operation for more than 25 years, while the plant in Folldal (63) was decommissioned after 10 years due to a heat pump defect (Ramos et al. 2015).

Economic criteria need to be established to support the use of mining infrastructure for both heating and cooling. As the renewable energy source is in competition with fossil fuels such as oil and gas, their economic viability is still largely reliant on the volatile prices of fossil energy sources. However, the oil price (and therefore the general energy prices) has been rising steadily from 1998 to 2012 (Fig. 4). From 2007 onwards, at least two new mine water geothermal plants were put into operation each year, with the peak being reached in 2013 and 2014 with six new plants annually.

This analysis highlights the escalation in energy prices, which is leading to extended planning and delayed deployment of mine water systems. It is not yet possible to predict the influence of the sharp rise in energy prices in 2022. However, it is expected that more plants will be commissioned, supported by the political decision to reduce gas imports to Europe. How fossil fuel prices affect the economic viability of mine water geothermal plants is discussed below.

Most of the currently installed plants have a heat output of less than 200 kW, as mine water has mainly been supplied to individual consumers (Fig. 5). However, there is a trend towards larger plants. This can be seen for the heat output of the Mieres plant (32 and 84), (Loredo et al. 2011; Al-Habaibeh et al. 2019; HUNOSA 2019; Benito 2022) and the Gateshead (28b) plant (Coal Authority 2023), which both have a capacity of 6 MW. In the German Ruhr area, an entire urban district close to the former “Haus Aden” mine will require the active management of mine water, which can be

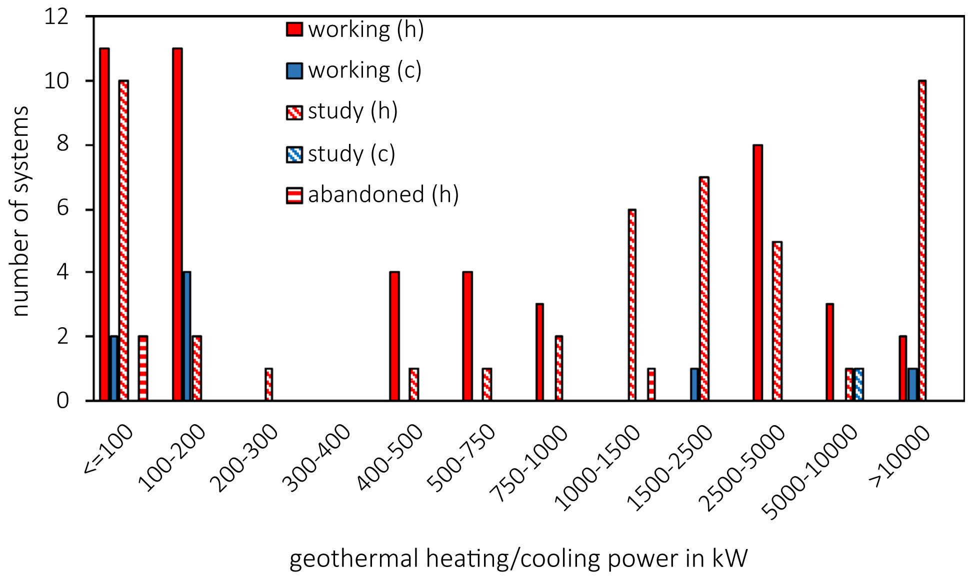

Fig. 5 Researched and calculated geothermal power for heating and cooling of the working, planed, abandoned mine water systems and studies (h: heating, c: cooling), according to Oppelt et al. (2023)

Table 2 Comparison of the monitoring key performance indicators of four operational mine water geothermal plants in Europe and North America

	Reiche Zeche Freiberg (GER, 1b)	Ehrenfrieders-dorf (GER, 4b)	Markham (GRB, 29)	Butte (USA, 39)
Temperature mine water in °C	19/14	12	13.3	20–27
Operating modes	Winter (more heating)/summer (more cooling)	Heating	Heating	Heating
Heating (cooling) power in kW	200 (155)	120	20	175
SPF_{H1} (heat pump)	3.6/–	3.8	3.6	4
SPF_{HC4} (total system)	4.2/7	3.6	1.6	3.5
Full-time hours per day in h	4.0	3.3	5.5	5.8

Data: own monitoring and Athresh et al. (2015) (h: heating, c: cooling)

used for heating and cooling purposes (48a and b) (Altieri et al. 2018).

Supplying many consumers at one location requires a heating or cooling network, which involves further investment costs. As the review shows, only a few plants provide cooling, and it is rarely considered in the researched studies. Yet, adding cooling to a mine water geothermal plant could be essential for its economic efficiency, since mine water can be used for cooling without installing heat pumps. In the case of a combined heating and cooling system, the fluid that has cooled down after being used for heating can then be used for cooling, which provides an extra benefit with very little additional expenditure (e.g. for pumps).

This can specifically be seen when comparing the four plants' performance factors (Table 2). The performance factor is an indication of how much useful energy (heating and cooling) can be generated from a kilowatt hour of energy used to operate the system (see Gehlin et al. 2022). The higher this parameter, the better the system runs. Of the four, only the Reiche Zeche plant has an additional cooling option. As a result, the entire system, including all mine water and intermittent circulating pumps, attains a seasonal performance factor (SPF) greater than 7 during summer. High performance factors for the whole system are also possible in winter because, in addition to using mine water for heating, laboratories and server rooms are cooled. Comparing the performance factors of the heat pumps shows that Butte and Reiche Zeche have the highest SPFH (Seasonal Performance Factor Heating), which is partially due to the high temperature of the mine water. In these two systems, the temperature increase that is required to supply the heating system is lower and consequently results in higher system efficiencies. The geothermal system in Markham has the lowest SPF because it actively pumps water above ground, and the pumping costs therefore make it harder for the plant to operate economically.

A comparison of the four plants' full load hours shows that they either run only a small part of the day or only at partial load. Therefore, there is a future development potential to increase the plant's operating hours by suppling additional consumers.

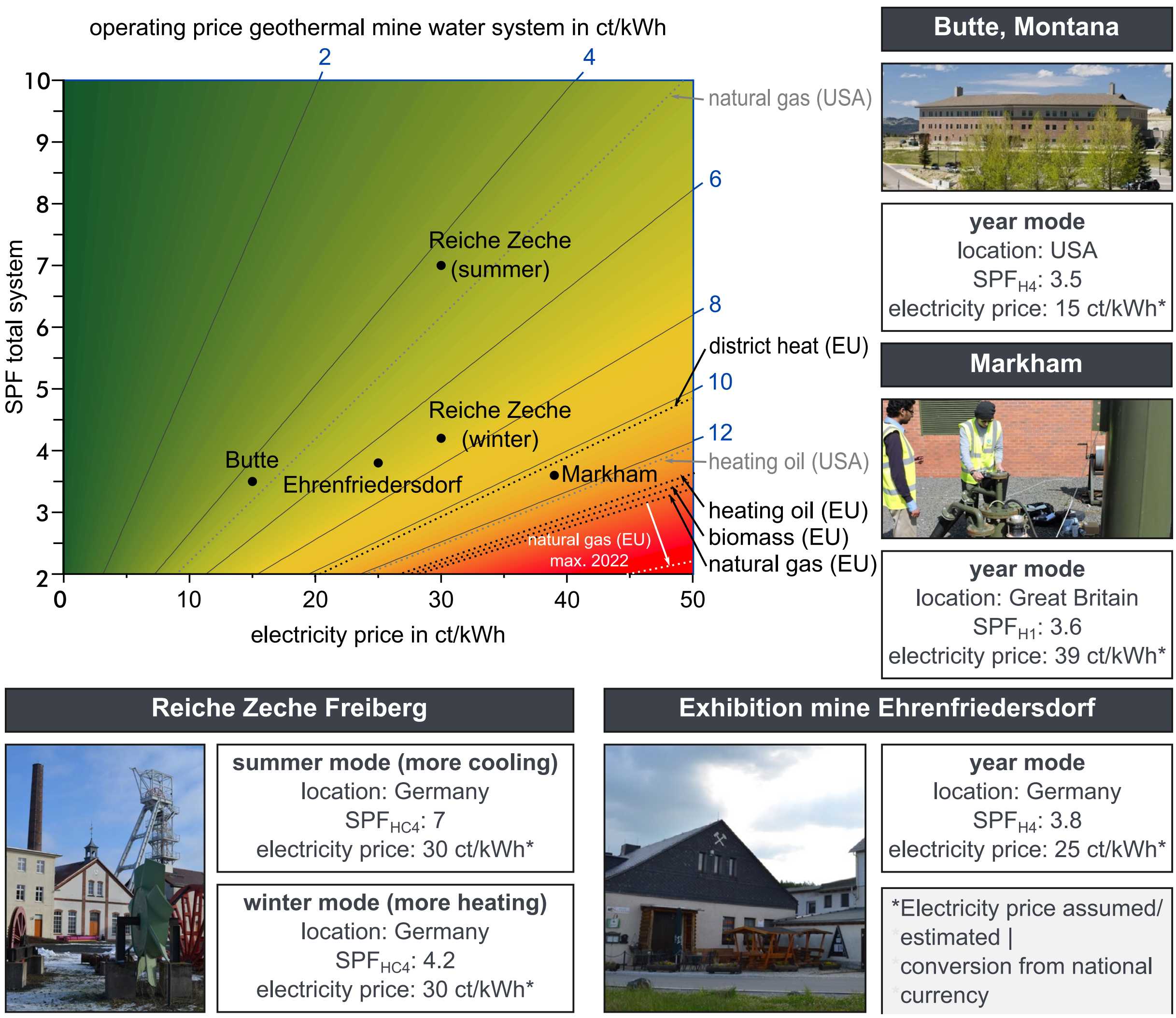

Fig. 6 Operating costs of a geothermal mine water system as a function of SPF and electricity price for various example plants compared to costs of other energy sources in the USA (grey dotted lines) and Europe (black dotted lines). Data, pictures: Malhotra et al. (2014), Burnside et al. (2016b), Banks et al. (2019b)

In order to assess the economic viability of the four investigated mine water geothermal systems, the production costs for one kWh of heating or cooling from the mine water were calculated. These costs include the cost of electrical energy used (e.g. mine water pumps, compressor heat pump), the performance factors of the whole system and the costs for maintenance or service. As can be seen, these vary considerably, specifically as electricity prices or SPSs of the whole system vary (Fig. 6).

Conclusion

A total of 123 mine water geothermal plants and studies were reviewed. Most of these plants are in Europe and North America and have a capacity of less than 200 kW. However, there is a clear trend towards plants with a capacity of more than 1 MW. A comparison of the average crude oil price per year with the number of mine water geothermal plants built shows that an increase in the cost of fossil fuels will lead to an increased expansion of mine water geothermal energy systems. The effects of high gas prices in 2022 and 2023 is not yet apparent. However, it is expected that more mine water projects will be realized, as many countries have legal requirements to increase the use of renewable energy.

Comparing the monitoring data from four mine water geothermal plants in Europe and North America shows that performance factors above 7 are possible when heating and cooling is combined. For heating only, performance factors above 3.5 are possible over the whole season. If mine water has to be pumped from greater depths, the efficiency of the system decreases. An analysis of operating costs shows that in Europe, an SPF for heating and cooling of at least 3 is required to be cheaper than fossil fuels. In contrast, in the USA, which has lower energy prices, a performance factor of more than 3.5 is required. This comparison also shows that the four systems rarely run at full load, which allows for an increase in running time by adding more energy consumers. If the systems are run efficiently, both CO_2 emissions and costs can be reduced. If the electricity to power the pumps and heat pumps is also generated locally, for example by photovoltaic systems, emissions can be reduced even further.

In conclusion, combining the use of mine water geothermal systems for both heating and cooling is highly recommended. If the operating hours of the systems are also increased, they can work more effectively and thus more economically than fossil energy systems.

Acknowledgements Thanks to all the technicians and students involved in this project, especially Julia Balski and Undine Fleischmann. We also thank the German Federal Ministry of Education and Research and the project management organisation Jülich for their financial support of the MineATES (03G0910 A) project.

Funding Open Access funding enabled and organized by Projekt DEAL.

Availability of Data and Materials Raw data were monitored and analysed at TU Bergakademie Freiberg. Derived data supporting the findings of this study are available from the corresponding author Lukas Oppelt on request.

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