Geothermal potential, possibilities and best practices (WP2.3)

Baltic Sea Underground Innovation Network (BSUIN)

Interreg Baltic Sea Region
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
BSUIN

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1. BSUIN project introduction

The aim of the Baltic Sea Underground Innovation Network (hereinafter BSUIN) project is to make the underground laboratories (hereinafter ULs) in the Baltic Sea Region (BSR) more accessible for innovation, business development and science by improving information available about the ULs and their operation principles and opportunities therein. In addition, the BSUIN project aims to collect the safety protocols of each UL as well as experiences of their respective users to aid further development.

BSUIN is a collaboration project between 13 partners from eight (8) BSR countries. Besides project partners 17 associated partners contribute for achieving the project goals.

The BSUIN project is participated by six (6) ULs from the BSR area. Each of the ULs will be characterized and presented to potential customers in order to attract developing innovative activities and effectively activate use of those laboratories. These six underground laboratories by name are:

1. Callio Lab, Pyhäsalmi mine, Finland
2. Äspö Hard Rock Laboratory, Oskarshamn, Sweden
3. Reiche Zeche, TU Freiberg Research and Education mine, Germany
4. Lab development by KGHM Cuprum R&D centre, Poland
5. Khlopin Radium Institute Underground Laboratory, Russia
6. Ruskeala Mountain Park[1], Russia

The main outcome of the project is a sustainable network organization, which will disseminate technical, marketing, operational quality, training and other information about the BSR ULs.

Project is funded by Interreg Baltic Sea funding cooperation. Its duration is 36 months with a total budget of 3.4 M€.

2. Content of present document

2.1 Document justification

The original purpose of the WP2.3 (WP = Work Package) was to focus in structural characterization of the BSR ULs. However, due to withdraw of the company Sotkamo Silver, the focus of this WP was changed from structural characterization to a review of geothermal energy potential of underground voids and galleries, like ULs. The current

[1] The name Ruskeala Mining Park is used in some texts. Herein we will adopt the term “Ruskeala Mountain Park”.

document is based on a literature review with an emphasis on the material associated with the Callio Lab (Pyhäsalmi Mine, Finland) and Reiche Zeche (Freiberg, Germany) ULs.

2.2 About the terms “abandoned” and “closed”

Some of the closed, abandoned and flooded mines in Europe present high potential for geothermal utilisation of low-temperature (low-entalphy) water filling the underground spaces. An abandoned mine is a mine or quarry which is no longer producing or operational. It may be a hazard to health, safety or environment. Especially the abandoned mine wastes contain significant amounts of chemical elements potentially dangerous to the environment. A “closed mine” may refer to an abandoned mine, although some researchers appear to use it for descripting mines of which closure was better designed and is potentially monitored afterwards. Without such precautionary measures, it is possible that environmental effects could persist for tens of years after mine closure (Heikkinen et al., 2008, p. 14). For the sake of simplicity, we will herein use these two terms interchangeably.

2.3 Content description

The aim of this work is to give a summary of geothermal potential of closed mines and how this potential can be harnessed in places where ULs have been constructed. However, it is easier to get a hold of the concept of geothermal utilization of low-enthalpy energy trapped in the mine waters of closed mines if we first take care that the bigger picture is also understood. For this end, the **Sections 3.1** – **3.6** draw the background canvas with series of short summaries of the renewable energy in general (Section 3.1), historical perspective of geothermal energy usage (Section 3.2), current situation concerning geothermal energy production in underground mines (Section 3.3), potential of underground mines as geothermal energy sources (Section 3.4), hydrology of abandoned or closed mines (Section 3.5) and mine water chemistry in an abandoned or closed mine settings (Section 3.6). Only after these essential summaries we are ready to turn our focus to the Chapter 4 (“Experiences and practices in geothermal energy production in the ULs"). **Section 4.1** will introduce us to the results of the "Energy Mine" project that recently developed a concept for potential future geothermal energy production in the Pyhäsalmi mine (Callio Lab). In **Section 4.2** the focus is in describing the geothermal system already installed in the Castle Freudenstein, Freiberg, Germany (Reiche Zeche).

The last Chapter will summarize the main points of this report.

3. Theory

3.1 Renewable energy – needs of the society

Developed countries recognize the need to reduce emissions from the combustion of fossil fuels and the need to look for alternative energy sources. Hence, in the EU, there is a great need to shift from non-renewable fossil-fuels based energy sources towards less emissive ones or, better still, towards renewable energy (RE) sources. Wherever available, renewable energy is the preferred solution. It it thus not suprising that the use of renewable energy sources for energy generation has increased considerably in recent years (Menéndez et al., 2019). In 2017, for example, renewable energy accounted for 19.5% of the total energy used for heating and cooling in the EU.

According to Menéndez & Loredo (2019), RE sources were the third largest contributors to global electricity production in 2015. Renewable energy accounted for 22.8% of world electricity generation. This sets RE after coal (39.3%) and gas (22.9%), but ahead of nuclear (10.6%) and oil (4.1%). The vast majority of renewable electricity is produced by hydroelectrical means, generating 16.0% of world electricity, which is 70.3% of total renewable electricity. Biofuels and waste play a minor role in electricity generation, supplying 1.9% of world electricity. Geothermal, solar, wind and tide energies accounted for only 4.8% of world electricity production (21.2% of total renewable electricity) in 2015. The largest geothermal electricity producer is the United States, which accounted for 37.2% of the OECD total in 2016, with a production of 19.2 TWh. Other major producers are New Zealand (7.9 TWh in 2016, corresponding to 15.2% of total OECD production), Italy (12.0%), Mexico (11.7%), and Iceland (9.8%).

Underground waters can be considered as a potential RE (re)source generating new economic activities in the (old) mining regions. Indeed, closed underground mines and their waters are treated as an additional RE sources in creating new (heat) local energy clusters (Woźniak & Pactwa, 2019).

Regarding geothermal heat production, different geological areas differ from each other in their respective capacities to produce energy. The ancient Precambrian shield areas, for instance, are much cooler than geologically young volcanic terrains. The Precambrian shield areas include large parts of such geographical areas as Finland, Sweden, Kola Peninsula, Russian Karelia, Northern Norway, Central and Eastern Canada, Western Australia, South Africa, Northern China and Brazil. In these areas one typically needs to get much deeper than in younger areas before ambient rock temperature reaches a viable level for geothermal energy production. In the younger terranes the situation is the opposite. Those yonger bedrock areas that currently show volcanic activity (even occasionally) are the most natural geographical areas for geothermal energy usage. These include such areas as Iceland, Yellowstone (USA), Andes, Turkey and New Zealand, just to name but a few. Highly productive geothermal areas are mostly located along plate boundaries. Geologically speaking the ancient Precambrian shield areas are said to be formed from "crystalline bedrock", which is a term used to describe recrystallized metamorphic rock. Such a rock is relatively dense and does not have porosity anymore or it is mainly of secondary origin (due to weathering, for example). Porosity has been lost in the earlier processes, like metamorphism. If secondary porosity is not counted, crystalline bedrock is "dry". In contrast, some of the younger bedrock areas comprise sedimentary rocks that may still contain a lot of pores that are often filled by water.

The presence (or lack) of porosity is important from the geothermal energy production point of view because it makes the sedimentary rocks thermally insulating. For these reasons, in Central Europe, geothermal temperatures in the sedimentary rock dominated areas reach 50-60°C already in about 1.5 km depth. In ancient shield areas temperatures are much lower in such depths.

In brief, everywhere in the world there is an upward flux of heat at the surface of the earth arising from radioactive decay in the crust and interior of the Earth. The amount of heat is hence also related to abundance of radioactive minerals in the local rocks and as certain rock types contain more radioactive minerals than others, local diffences in heat production capacities vary also in the same overall geological domain (e.g., granite produces more heat than mica schist). In addition, also climate has an affect to the temperature of the topmost part of the bedrock. For example, the permafrost reaches 570 m depth in the Lupin mine in the Arctic Canada (Ruskeeniemi et al., 2004), while in warm climates even the sun light is enough to keep the ground surface warm.

3.2 Historical perspective of geothermal energy usage

The first use of geothermal energy occurred more than 10,000 years ago in North America when American Paleo-Indians started to use water from hot springs for cooking, bathing and cleaning. The first industrial use of geothermal energy took place near Pisa, Italy, in late 18th century (Kabeyi, 2019). The first geothermal plant started operations in 1913 in Lardello, Tuscany, Italia. The first such plant in the USA started in 1922 (Kabeyi, 2019).

3.3 Current situation concerning geothermal energy production in underground mines

Conventionally, geothermal heat energy in soils and rock is exploited via drilled wells, via buried ‘‘ground collectors’’ (typically looped heat-exchange pipework), from pumped groundwater or from surface water bodies such as lakes (Preene & Younger, 2014). Geothermal energy recovery is now a well-established business and many techniques and technologies have been developed over the years. They work considerably well in traditional-type of geothermal fields. In fact, even mine water based heat systems have been operational since the 1980s (Jessop, 1995, as cited in Todd et al., 2019). However, due to the scope of the present report, it is neither possible nor necessary to review the history and current level of technology of geothermal energy exploration in underground mines in detail. A reader interested of results of different case studies and trials of such operational schemes are recommended to find any of the following papers:

- UK: Banks et al. (2009, 2017); Bailey et al. (2016); Farr et al. (2016)
- Canada: Jessop (1995)
- Germany: Wieber & Pohl (2008)

For a reader specifically interested about development of mine water heat technology the following internet pages may be a valuable source of information: https://ukgeos.ac.uk/observatories/glasgow. The Glasgow Geothermal Energy Research Field Site is one of two new UK Geoenergy Observatories that specifically focus in research of the mine water environment as a test and developing site for mine water heat technology (Monaghan et al. 2018).

Table 1 represents key features of some low-entalphy geothermal energy installations.

Table 1. Summary table of key parameters for some geothermal energy installations. Note that this table is extracted from Hall et al. (2011) and there probably exists many newer installations around the world.

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

3.4 Potential of underground mines as geothermal energy sources

A geothermal system typically requires significant up-front capital cost to construct the necessary geothermal wells or ground collectors. This is probably one of the factors why geothermal systems have not been implemented in a wider range of settings and by a wider range of organisations than they are (Preene & Younger, 2014). However, in the case of the mining industry, much of the work required to establish geothermal infrastructure is already there, even if it is originally established for other purposes. An abandoned (i.e., closed) mine consists of either an open pit or a network of underground galleries and roadways, or both. These artificial water features are typically flooded. Another notable aspect having a positive impact to geothermal projects is that almost all mines are or were used to pump groundwater as part of their dewatering operations.

An abandoned or closed underground mine forms an artificial water reservoir. When a mine is in operation pumps are used to keep it dry. However, when a mine is abandoned the pums are typically switched off. This eventually leads to fill of the main roadways, galleries and fractures by groundwater. Flooded underground mines provide an innovative opportunity to extract low-entalphy geothermal energy. The potential for closed mines as a local source of geothermal heat energy is significant both locally and globally since it has been estimated that there are well over 1 million abandoned mines throughout the world (Hall et al., 2011). It would be a significant step towards sustainable mining if even a fraction of those abandoned mines could be brought back to life as geothermal energy enterprises. Such an alternate use of mine infrastructure following closure would contribute to the community by offering jobs and providing energy and economical well-being, both locally and regionally. Moreover, the greater the number of abandoned mines that recover geothermal energy the less fossil fuel would be needed. In other words, greenhouse gas emissions would be reduced. According to Bailey et al. (2016), the flooded mines throughout Europe have a range of 3000 MW potential available from heat trapped in such mines.

The binary geothermal power plant technologies require almost 200°C water temperatures to be able to generate over 10 bar steam pressures needed for good operating efficiencies (Ahonen et al., 2020). However, the operating efficiencies are lower for water temperatures less than that and it is rare that a mine has an access to water hot enough (>85°C) to generate electricity using binary power plants[2] (Preene & Younger, 2014). Some electricity can still be generated from waters having temperatures

[2] By usign binary geothermal power plant technology the geothermal water loop and power cycle are completely separated. Geothermal fluid is typically gathered by using "doublets" (one production well and one injection well), "triplets" or even multi-well schemes (several doublet or triplet modules).

in the range of 70-120°C by applying the so-called Organic Rankine Cycle (ORC) technology (e.g., see https://climeon.com). However, most geothermal systems associated with abandoned mines represent low-enthalpy systems of which water temperatures are too low even for ORC-based technologies. However, these low-entalphy mines can be exploited for direct heating/cooling purposes by applying other types of technical solutions.

Preene & Younger (2014) recognize three types of aspects that act as drives for exploiting mining-related geothermal energy:

1. ***Financial savings***. All mining operations use heat energy, to a lesser or greater degree influenced by the local climate and the type of mining and processing operation. The energy costs associated with heating maybe substantial. Geothermal energy can potentially provide heat at lower unit costs than conventional fuels, thereby reducing operating costs.
2. ***Environmental benefits and corporate social responsibility (CSR)***. Geothermal systems are classified as low carbon energy sources. Typically heat from geothermal systems will be used to displace heat derived from conventional fossil fuel sources. Use of geothermal energy will hence reduce carbon emissions, which is in line with typical CSR objectives.
3. ***Gaining benefit from closed and legacy mines***. Flooded mine workings and open pits can be significant reservoirs of geothermal heat. If these heat reservoirs are exploited this can generate new revenue streams for mining companies, and potentially support the sustainable development of communities associated with closed mines.

Figures 1 A and 1 B schematically illustrate open and closed loop geothermal systems, respectively.

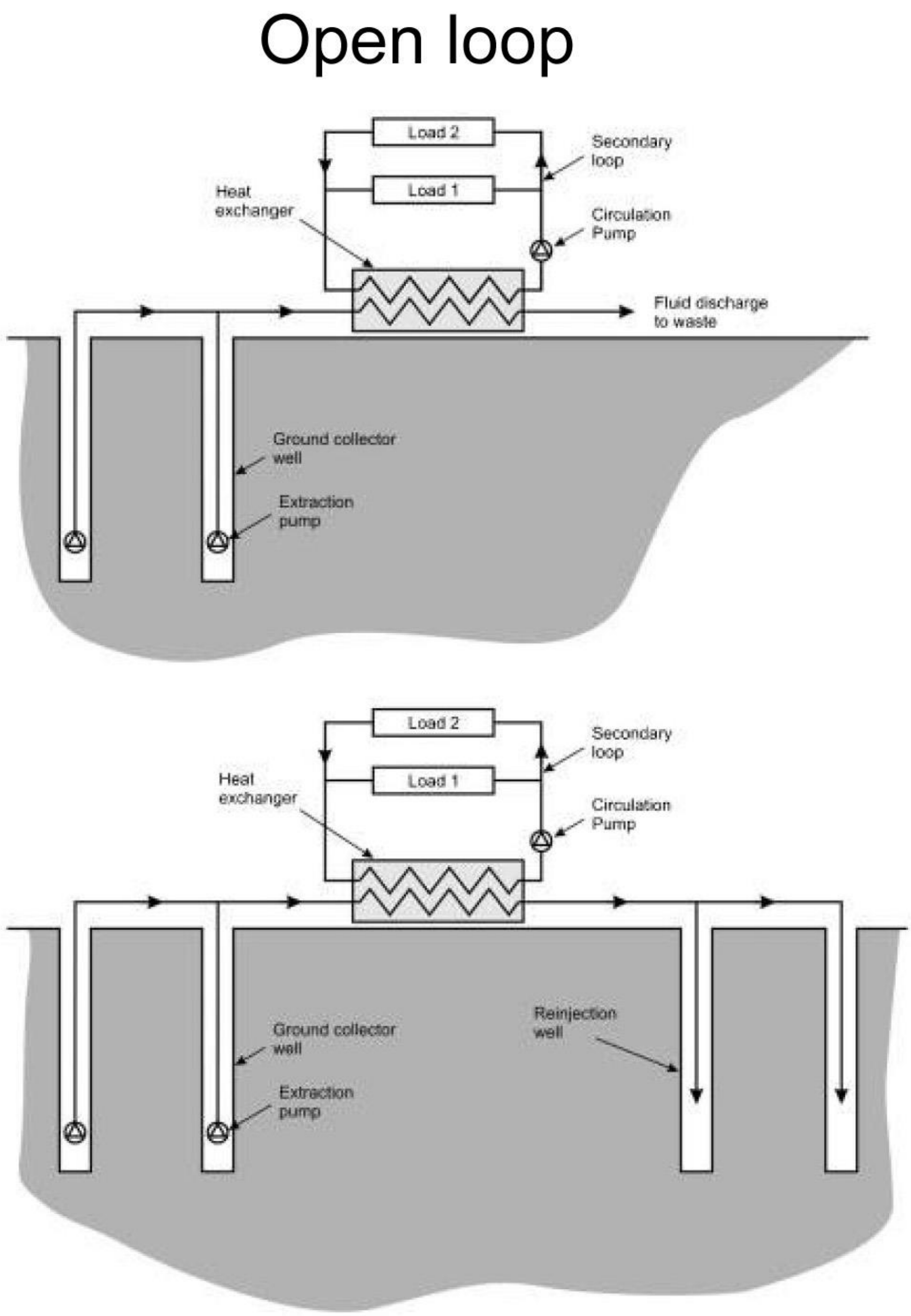

Fig. 1 A. Conceptual sections through an open loop geothermal system. After Preene & Younger (2014).

Closed loop

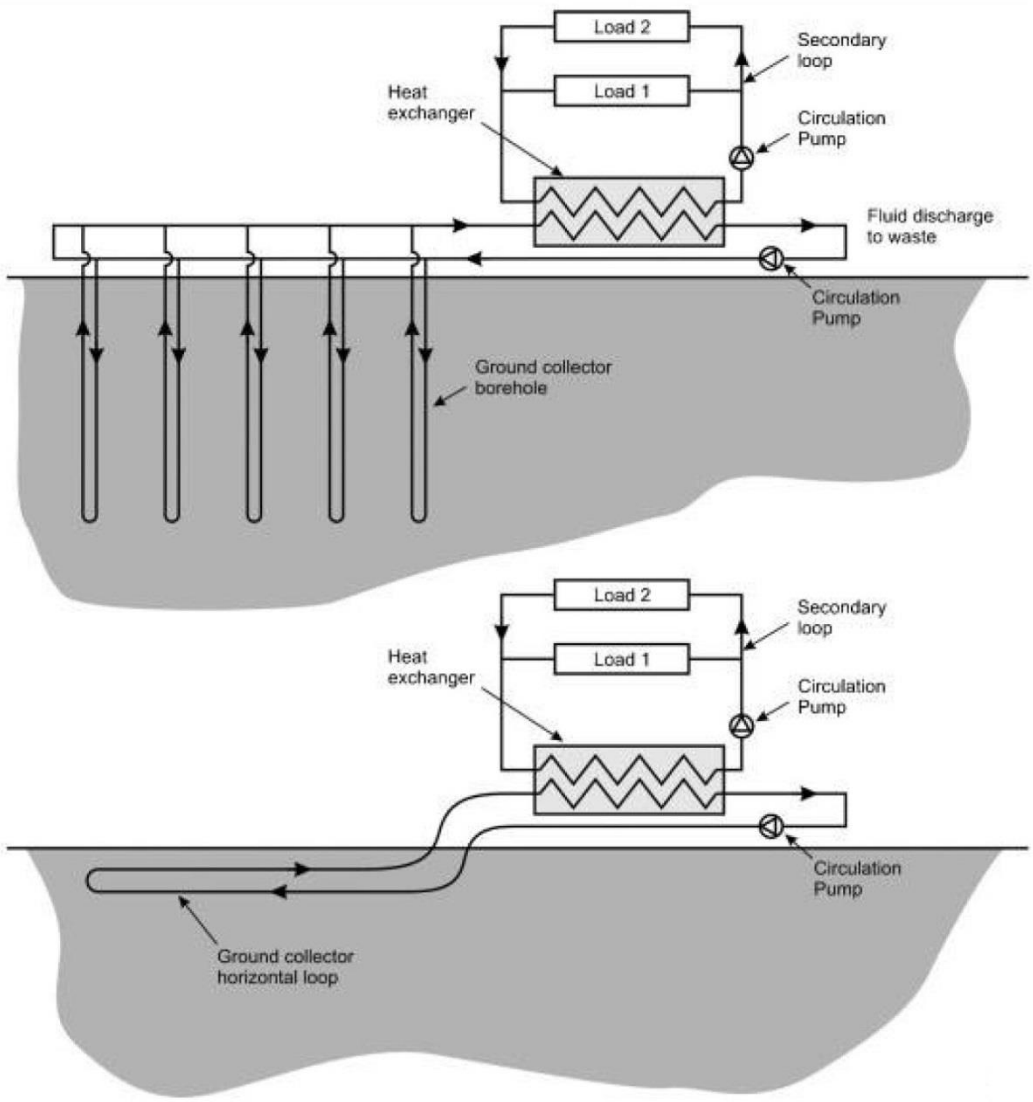

Fig. 1 B. Conceptual sections through a closed loop geothermal system. After Preene & Younger (2014).

3.5 Hydrology of abandoned or closed mines

For most operating mines dewatering of the underground space by pumping water from inside the mine to the surface is a must. Mines which only have low grade ore reserves left, may occasionally cease their operational activities in an attempt to wait for higher ore prices. Such mines are said to be in a maintenance mode. These mines will also continue to be dewatered to maintain stability and safety. Most fully closed mines do not continue their dewatering schemes. In these cases the water levels typically continue to rise until the mine is flooded (there is of course a strong climate control affecting to the outcome). Water permeates into mines from surface, aquifers, bed separation cavities, solution cavities and old mine workings (Hall et al., 2011).

3.6 Mine water chemistry in an abandoned or closed mine settings

It is important to know and often monitor mine water chemistry in geothermal projects. Many ore deposits contain minerals that release harmful components when they are oxidized. One source of harm is that some of these harmful components may cause clogging issues in the filters, pumps, heat exchangers, pipelines and reinjection wells (Banks et al., 2017). In such cases the maintenance costs may get higher than expected if the mine water chemistry is not monitored. Another source of harm is those mine waters that are chemically harmful but the geothermal system is still based on open-loop princinple (Fig. 1 A). According to Banks et al. (2017), such thermally spent water may need some form of treatment before it is disposed to surface water (or, sometimes, to the sea). Possible disadvantages of open-loop schemes in these cases include: the cost of treatment and the potential for pumps, pipelines, heat exchangers and reinjection boreholes to become fouled with chemical precipitates. According to Kranz & Dillenardt (2009), mine water monitoring should be focused on the water–rock-interaction zones since they influence mine water composition.

4. Experiences and practices in geothermal energy production in the ULs

4.1 Callio Lab (Pyhäsalmi Mine, Finland)

The Pyhäsalmi mine is located in a geological domain called the Vihanti-Pyhäsalmi belt, Central Finland. The mined deposit belong to the so called volcanogenic massive sulphide (VMS) deposit class and it has (or rather had before extensive mining) a flat, subvertical shape that was reminiscent of an elongated French bread with a thick potato-shaped lower part. The original ore deposit was composed of large amounts of sulphide minerals (like pyrite, sphalerite, chalcopyrite and pyrrhotite), but most of the ore is now gone due to long history of mining. The mine is expected to end its mining operations in a year or two due to depletion of ore-grade material. However, what remains is a wide network of tunnels and open underground space, the some of which are in the use for the Callio Lab. As part of the closure plan for the current mine, the company operating the mine (Pyhäsalmi Mine Oy), the local community and several stakeholders such as a group of research organisations and private companies have done co-operation for finding post-mining use for the underground facilities in Pyhäsalmi. One of the research targets has been the geothermal potential of the mine. The following results are based on the report of Ahonen et al. (2020) that examines the potential future usage of the Pyhäsalmi mine as a geothermal energy source.

The aforementioned project was commenced in the latter part of 2017 and it ended in February 2020. The project was lead by Geological Survey of Finland (GTK) with a strong input from the Kerttu Saalasti Institute of the University of Oulu, Finland. The total budget of the project was 407 000 €. The project's Finnish name was "Energiakaivos", which translates as "Energy Mine". The projects' aims were to:

- Investigate the potential of the Pyhäsalmi mine as a geothermal energy provider
- Investigate how the mine could work as a platform for increasing know-how for usage of geothermal low-temperature heat
- Investigate how much bedrock-stored geothermal energy can be exploited from the local underground levels from 500 – 2500 m
- Investigate the different technical and technological solutions that could be used to exploit the geothermal energy from the said levels
- Investigate whether or not the exploited geothermal energy could be directly used by the existing local energy infrastructure and if the answer is "yes", are the local solutions directly applicable in other places with similar underground facilities
- Develop a universally applicable concept for geothermal underground plant

- Investigate the business opportunities regarding exploitation of geothermal energy in closed underground mine settings by (i) examining the existing technologies applicable to exploitation of geothermal energy in underground settings in general, (ii) examining the service concepts developed in other similar places and cases, and (iii) examining the interest levels of the local energy providers for utilizing the Pyhäsalmi mine for geothermal energy production

The bedrock at Pyhäsalmi represents metamorphosed crystalline bedrock. The rocks surrounding the Callio Lab can be classified to three simplified rock classes: mafic volcanic rocks[3], felsic volcanic rocks[3] and granitoids. The thermal properties of these three rock classes are different from one another (Table 2). For example, the mafic volcanic rocks have a greater density than the other two rock classes, which in turn means they have a higher thermal capacity than the other two rock classes.

The Pyhäsalmi mine provided a 3D model of the mine for the project. The data contained geological information about the local rock types as well as technical information about the boreholes (e.g., collar locations and borehole directions, dips and changes in directions and dips along the borehole traces). During the project, a representative sample set of different rock types was collected from the drill cores. These samples were subsequently studied in a petrophysical laboratory for physical characterization of the different rock types. The measured parameters included heat conductivity and heat capacity. Mine geologists provided unwrote information about structures in the mine that are known to be a major source of water. In addition, in situ rock temperatures in the mine were measured in several places during the project. These measurements were conducted in deep boreholes by applying optical sensor cables (Distributed Temperature Sensing, DTS) (Ahonen et al., 2020).

To keep the mine dry, the mining company pumps about 1 million cubic meters of water per year from the mine. This water has a temperature of 17°C. If the geothermal energy contained by this water would be exploited by cooling its temperature to 7°C, about 10

[3] Mafic and felsic volcanic rocks are often informally called “mafic volcanites” (“emäksiset/mafiset vulkaniitit” in Finnish) and “felsic volcanites” (“happamat/felsiset vulkaniitit” in Finnish), respectively. However, these terms are not scientifically accepted nor recommend. Mafic rocks always contain less SiO_2 than felsic rocks. All rock types in the Callio Lab area are metamorphosed, but for the sake of simplicity the prefix “meta-“ commonly used for such rocks types is omitted (e.g., “mafic volcanic rock” is in fact “mafic metavolcanic rock”).

GWh energy would be generated each year (c. 1 MW average power output, 31 kg/s water). However, as the pumping consumes energy (several hundreds kilowatts) the total yield would be less than that. Currently the heat contained by mine water is salvaged by using a condenser (i.e., heat exchanger), after which the generated energy is used to warm the fresh ventilation air that is transferred to the underground mine. The exhaust air ventilated from the mine contains about 2–3 MW energy (assuming an air with the following parameters: 100 m^3/s, 17°C and Relative Humidity of 80%).

Based on an initial analysis, two different approaches for geothermal energy recovery were chosen for further investigation in the Energy Mine project:

1. Circulation of underground water through natural fracture networks between two ore more boreholes
2. Geothermal well(s)

In the former solution the heat collecting would be arranged by using two or more boreholes and by circulating water between them for transferring geothermal heat. In the latter case, however, there are additional technical aspects to consider depending on whether the solution involves one or two boreholes. If there is only one borehole, the cold downgoing water would be physically close to the warm upgoing water. However, if two holes are used, the cold downgoing and the geothermally heated upwards going water would be distinctly separated. The differences between the two technical solutions are hence fundamental.

It was noted early on that exploitation of heat from natural fracture networks in the local crystalline bedrock is really challenging. To start with, it is difficult to predict or even study where such fracture networks go and how well they are connected. It is also true that a single planar fracture network connecting two boreholes is just not enough for geothermal energy production. Therefore, if the aim is to produce geothermal energy in economically viable quantities, the volume of rock the water is circulated through needs to be as large as possible. In addition, also the surface area water is in touch with needs to be extensive. Based on these arguments it was soon established that, at least in the case of the Pyhäsalmi mine, the only geothermal energy exploitation technique that would work – both theoretically and practically – would be based on the geothermal well(s) concept.

The results and other key points of the project Energy Mine can be summarized as follows:

- Geothermal gradient in the Pyhäsalmi mine increases about 13°C by each kilometer downwards (12°C for the first 1 km, 14°C for 1 – 2 km depth range)
- Currently the mine is kept dry by pumping each year about 1 million m^3 of water from the underground spaces. This water has a temperature of 17°C. By cooling it to 7°C, about 10 GWh energy would be generated annually
- The Pyhäsalmi mine is deeper than most mines and offers an excellent opportunity for exploitation of geothermal heat. Geothermal well concept is the most viable technique in Pyhäsalmi
- Two options were recognized for implementing the geothermal wells concept in Pyhäsalmi: (1) The wells are drilled to reach as deep levels as possible (for reaching higher water temperatures; unfortunately, in such cases also higher expenditures will be witnessed); (2) A lot of shallow wells in a volumetrically small area (this would lead to rather quick cooling of the targeted rock volume, but on the other hand it could be easily heated again with external waste heat; this would mean that the volume could be used as a source of heat in the winter time)
- Required investments are about 1 M€/MW plus the original construction costs for the heat exchange line from the bottom of the mine to the surface

Table 2 shows the physical parameters of the three dominant rock classes in Pyhäsalmi. Figure 3 depicts bedrock temperatures in the Pyhäsalmi mine as measured from various deep boreholes with the DTS cable. Figure 4 illustrates a conceptual model for geothermal energy production in Pyhäsalmi.

Table 2. A summary of different physical parameters of the three dominant rock classes in the Pyhäsalmi mine, which is the location of the Callio Lab UL, Finland.

	Sample count	Density	Thermal conductivity	Thermal capacity	
		D	λ_m	C_m	C_V
		kg/m^3	W/m/K	J/ kg/K	kWh/m3/K
Mafic volcanic rocks	22	2975±76	2.27±0.16	682±22	0.56
Felsic volcanic rocks	21	2708±46	3.40±0.44	681±24	0.51
Granitoids	14	2639±18	2.24±0.22	685±33	0.50
All samples	57	2794±156	2.92±0.61	682±25	0.53

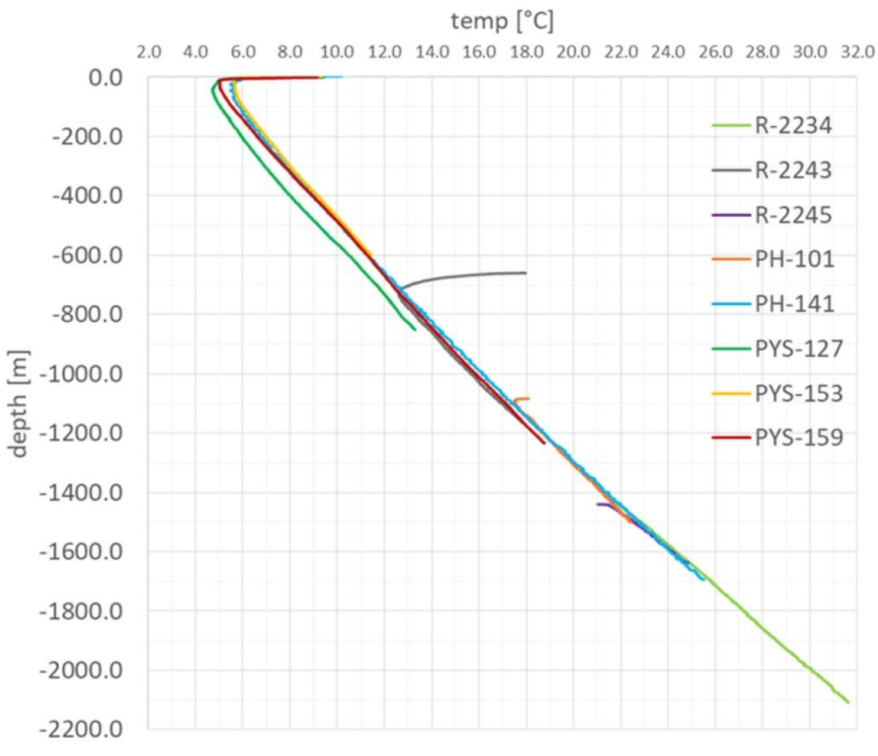

Fig. 3. Temperatures in the bedrock as measured from different boreholes by a DTS cable.

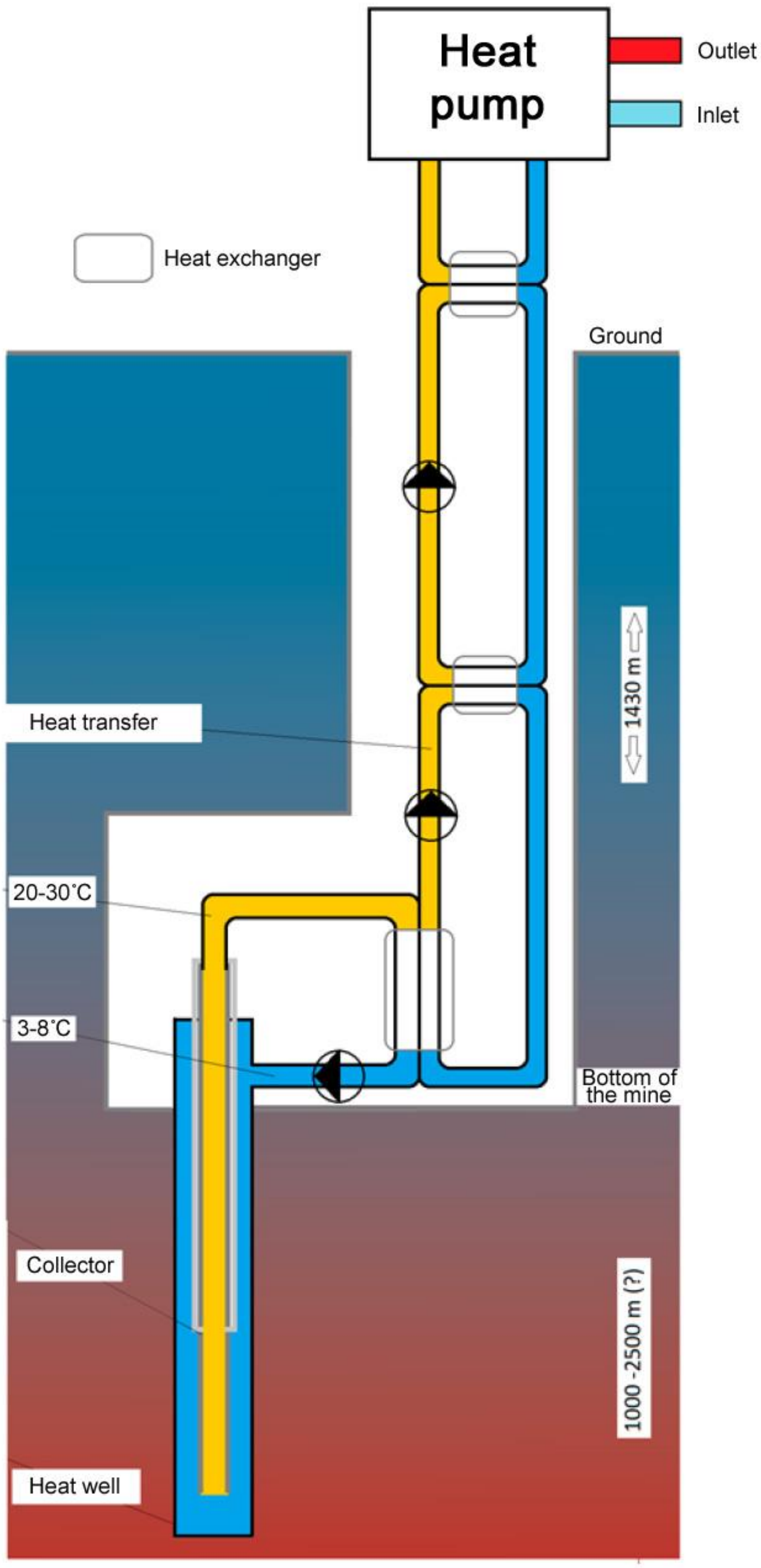

Fig 4. A conceptual model for the proposed geothermal energy production in the Pyhäsalmi mine. Modified from Ahonen et al. (2020).

The Energy Mine project concluded that the Pyhäsalmi mine offers an excellent opportunity for exploitation of geothermal heat.

4.2 Reiche Zeche (Freiberg, Germany)

The Freiberg/Saxony mining district is located in the northern part of the eastern Ore Mountains in Saxony, Germany, and is famous as a traditional silver mining district and an important geosciences centre of Europe (Kranz & Dillenardt, 2009). According to Ramos et al. (2015), Freiberg has two geothermal projects that have been presented in the literature. One has been implemented for the local Castle Freudenstein and the museum it houses, while the second one supplies heat to buildings belonging to the Freiberg University of Mining and Technology. Herein we will discuss about the former installation.

The geothermal system installed at the Castle Freudenstein supplies the base requirements of the infrastructure in the castle and the associated museum, while a conventional system covers the peak load and the special air conditioning requirements. The low-enthalpy heat energy is harnessed from the water flowing in the Alter Tiefer Fürstenstollen gallery that is located at a depth of 60 m. Mine water is at a constant 10.2°C and is accumulated to this gallery by a dam (Kranz & Dillenardt, 2010). The water level was raised approximately 1.8–1.9 m in the gallery that was about 200 m long and 1 m wide. Two submersible rotary pumps raise the water to a height of about 50 m to the shaft head, where is a heat exchanger that finally returns water back to the gallery. The mine water has a neutral pH, an electrical conductivity of 0.9 ms cm-1, and a relatively low Fe and Mn content. Hence, it is usable without conditioning. Figure 5 depicts this geothermal open loop system as a schematic representation. The system was installed in spring 2009.

Bedrock at the site is composed of the so-called “Freiberg grey gneiss”, which comprise in fact two rock types: biotite-plagioclase-gneiss and metagranite. The thermal and hydraulic properties were found to be influenced by the orientation of the gneiss foliation, i.e. anisotropy in the rock.

Kranz & Dillenardt (2009) conclude that one should study and compare samples drilled parallel and perpendicular to the foliation of the rock (if foliation exists) since this allows one to consider how much the rock anisotropy fabcrics have effect in permeability. In their Freiberg-based study the samples drilled perpendicular to the rock foliation plane had lower permeabilities than those drilled parallel, which was an expected property of the rock. They also recognized that thermal conductivity in Freiberg was anisotropic and that it was higher in samples drilled parallel to the foliation than in those drilled perpendicular to it.

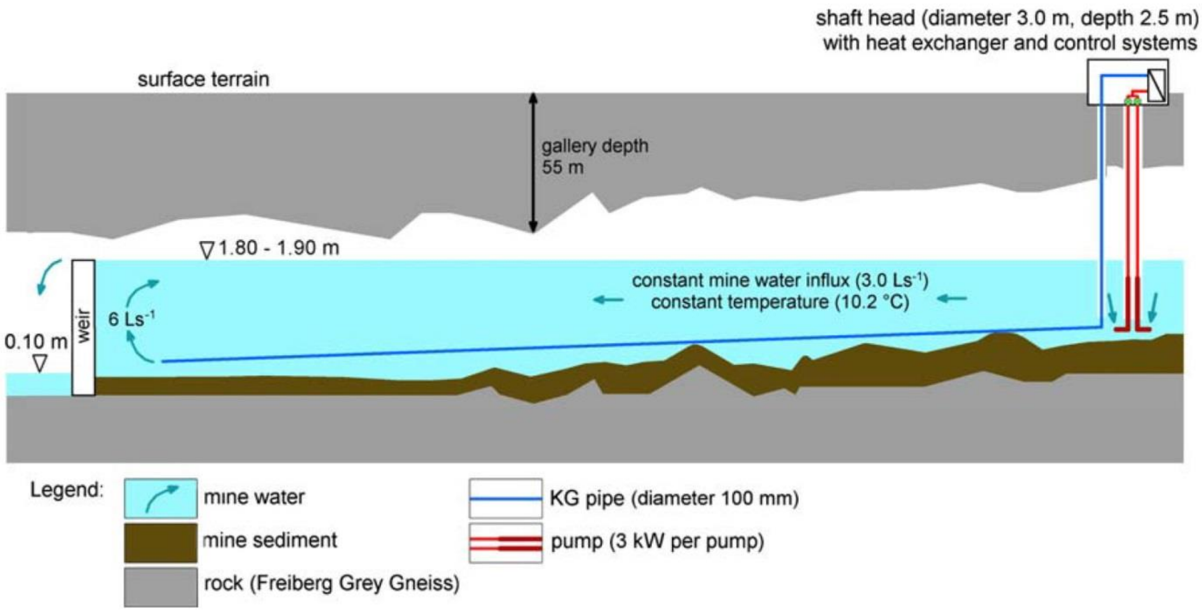

Fig. 5. Schematic representation of the geothermal open loop system in the Geothermal Project for the Castle Freudenstein in Freiberg. The heat exchanger captures the heat and transfers it to a secondary loop, which at the same time transfers the heat to a two-stage heat pump located 230 m away from the shaft at a building behind the castle. The heat pump has a maximum heat capacity of 130 kW with a net consumption of 29.24 kW. For more details concerning the heat pump technology, see Banks (2008). From Kranz & Dillenardt (2009).

5. Concluding remarks

The underground facilities surrounding ULs form an obvious opportunity to use these engineered features also for many other purposes. Exploitation of heat energy from the local geothermal source is one of such opportunities. The capital and operational costs needed for building a geothermal energy system at old mine sites are much lower than normally for these types of projects as the mine infrastructure is already there and, if maintained, is in good shape. Understandably at least the facilities used by the operating ULs are in good shape by necessity.

Based on literature, the benefits of using mine water as a low-temperature heat source include:

1. **Economic benefits**:
    - No geothermal exploration stage needed
    - No geothermal holes (drilling) needed
    - Mines are a constant source of sustainable energy, protected from the energy price fluctuations
    - Mines provide business oppurtunites for local cheap, low-carbon energy
2. **Ecological benefits**:
    - The emissions affecting the local climate are reduced
    - Draining mines also provide protection against groundwater pollution
3. **Social benefits**:
    - Heat consumers save on fees (reduction of energy costs)
    - Using mine waters as a low-T heat source changes the image of the mine from the environmental pollutant to the responsible entity being the source of “green” energy

It follows from the above that using the geothermal potential of mines is not only acceptable, but also advisable. Additional benefits include creation of new stable jobs. This is especially valuable in mining areas that are often economically depressed after closing of the local mining projects.

Additional notes and recommendations:

- There is always the temptation to extract more heat out of the system than is available by recharge, thereby depleting the resource. Prevent this to happen by modelling and monitoring

- If the mine water has a heavy sediment load, then removal systems may be needed to avoid reducing the life of the pumping equipment (Vutukuri & Singh, 1993; Hall et al. 2011). Closed loops could be also used if the water quality is too poor

The key results of the "Energy Mine"project from the Pyhäsalmi mine, Finland, can be summarized as follows:

- With its 1460 m depth, the Pyhäsalmi mine is deeper than most mines. From a geothermal point of view, this is a notable advantage comparing to shallower mines in similar bedrock areas
- The mine is closing its operations in the near future. Three options remain for the future after its mining operations end:
    1. The mine is totally abandonded and allowed to be filled by water
        - This option could provide a very limited amount of heat energy from the water filling the tunnels. The energy could be used for heating the surface buildings
        - However, the operating efficiency of the heat pump would gradually deteriorate (notably already in the first ten years)
    2. The mine is used as a major source of geothermal heat by following any of the guidelines provided in the final report of the project (Ahonen et al., 2020)
    3. The mine is used as a demonstration place for carbon neutral energy production

If the option two is the one that is to be adopted, the process for constructing the geothermal heat facility should follow these steps, given in the order of first to last:

- The needs of the system are decided first: how much heat is wanted and what water temperature is required to achieve this goal
- Next, the decisions are made regarding (i) the depths of the geothermal wells to be drilled, and (ii) what type of heat collectors are constructed

- Testing the heat production in a pilot geothermal well. Does the results correspond the modelling results? If not, circulation of water in the wells is optimised
- Technical plan for the construction project is completed. This will provide an estimate of the expenditures for constructing a heat exchange line from the bottom of the mine to the surface
- The heat exchange line and heat pump station are built. The geothermal well(s) are drilled. The heat collectors are installed. The wells are connected to the heat exchange line
- On the ground, a heat center transfers warm mine water to heat pump station or directly to the customers. The heat pump station produces heat required by its customers, while the price of the provided heat depends on the required temperature. The heat pump station can also receive excess heat (waste heat) from various sources and then transfer it to the bedrock

The preliminary calculations show that the Pyhäsalmi mine could be used as a source of geothermal energy with competitive prices.

If the option three is chosen, the mine can be developed in a manner after which it could change the whole community for one that is carbon neutral. In this vision, the local houses can install solar panels and then transfer renewable solar energy to the heat pump station at the mine site, which then can transfer it to the bedrock. The stored energy could then be reused in the winter (each house would get a discount for their winter heating costs). Usable waste energy is produced also by the local indoor ice rink and the cold storage space in the local markets.

The key results[4] of the "Castle Freudenstein"geothermal project in Freiberg, Germany, can be summarized as follows:

- The knowledge of the specific heat capacity, the thermal diffusivity, and the thermal conductivity is important for the characterization of a geothermal system

[4] Some of the findings are from the literature reviewed by Kranz & Dillenardt (2009).

- The heat transport in a geothermal system depends on the composition and geometry of the rock matrix, the porosity, and the pore medium (i.e., mine water)
- Thermal conductivity:
    - In contrast to several volcanic and plutonic rocks, the thermal conductivity of many metamorphic rocks is strongly anisotropic and influenced by the dominant mineral phase. The local geology must hence be known (at least in a rudimentary level)
    - Thermal conductivity of igneous and metamorphic rocks decreases with decreasing quartz content and increasing feldspar content. Consequently, gneiss, in general, has a low thermal conductivity
    - Thermal conductivity decreases with increasing temperature, but the decrease for quartz-poor metamorphic rocks is rather weak compared to quartz-rich ones
    - Structural anisotropy (like foliation) has a negative impact on thermal conductivity
    - Thermophysical rock properties – especially thermal conductivity – should be measured in situ as they may differ significantly from laboratory values
    - With increasing pressure, fractures and microcracks in rocks begin to close, which leads to reduction in porosity. Hence pressure can considerably affect thermal conductivity
- Since the heat transfer within the geothermal system is affected by thermal and hydraulic rock parameters, such as thermal conductivity, heat capacity, porosity and permeability, in situ rocks were sampled to allow laboratory determination of these parameters
- The laboratory measurements indicated that the local bedrock at Freiber (the Freiberg grey gneiss) has high thermal conductivity and normal radiogenic heat production. The Freiberg grey gneiss is hence suitable for the near-surface geothermal energy use
- The geothermal project was successfully carried out in an open-loop system in spring 2009. The installed geothermal system is especially energy-efficient and

inexpensive due to its two-fold use for heating and cooling (160–180 kW heating capacity, 120 kW cooling capacity)

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