GeoScience Engineering

ANALYSIS OF THE GEOTHERMAL ENERGY UTILIZATION OF MINE WATER FROM ROŽNÁ I MINE, CZECH REPUBLIC

Michal VOKURKA[1], *Antonín KUNZ*[2], *Pavel ZAPLETAL*[1], *Marek KLIMESCH*[2],
Katarína PAULÍKOVÁ[3], *Vít SLÁDEK*[1], *Jiří SOBOTKA*[1]
1 *VSB – Technical University of Ostrava, Faculty of Mining and Geology, Department of Mining Engineering and Safety, Ostrava, Czech Republic*
2 *VSB – Technical University of Ostrava, Faculty of Mining and Geology, Department of Geological Engineering, Ostrava, Czech Republic*
3 VSB – Technical University of Ostrava, Faculty of Mining and Geology, Department of Geoinformatics, Ostrava, Czech Republic
E-mail: michal.vokurka@vsb.cz

ABSTRACT

The paper presents an analysis focused on the possibility of using geothermal energy from the Rožná I Uranium Mine through mine water as a heat source. The Rožná I Uranium Mine makes part of the Rožná deposit, whose rock mass cannot be considered homogeneous in terms of geothermal energy utilization, but heterogeneous, where there are positive and negative influences, the so-called geo-factors of geothermal energy utilization. The possibility of geothermal energy exploitation was assessed based on available materials and background information. The main parameters are the thermal conductivity coefficients of the rock mass, the ground heat flux of the area, the geothermal degree or its inverse value, the geothermal gradient. The exploitability of the geothermal potential of the mine water was determined using several calculations. This availability was assessed both in terms of the maximum achievable thermal output in combination with a heat pump and the long-term sustainability of this output.

Keywords: Geothermal energy; Heat pump; Mine water; Rožná.

1 INTRODUCTION

The current global trend is to reduce the use of traditional fossil fuels for electricity and heat generation and obtain this energy from other, more environmentally friendly sources. The European Green Deal [1] states that the switch to alternative sources is the starting point for pollution-free energy production. It makes geothermal energy utilization a viable alternative, both for industrial or non-industrial use. As for the industrial use, geothermal power plants are usually considered, for which the geological conditions in our territory are not suitable. In thermal energy production, applications for central heating of commercial or private buildings are considered on a smaller scale. So far, this application has been implemented in the Czech Republic only in several cases, e.g. in Děčín [2]. Non-industrial use, i.e. installation of heat pumps in houses or non-commercial use in industrial premises, is, on the contrary, widely supported by the state and the European Union, and the number of such installations have been around 1,400 per year [3].

In the Czech Republic, mine water is used non-commercially at sites managed by the state enterprise DIAMO Stráž pod Ralskem, e.g. at the mine water treatment plant in Příbram (ČDV Příbram II), which treats up to 70 $l.s^{-1}$ of pumped mine water. The temperature of the pumped mine water is around 21–22 °C, which is heated to an output temperature of 55 °C thanks to the installation of three heat pumps. This heating system was commissioned in 2018 [4]. Another case is the Jeremenko Shaft complex in Ostrava, where mine water from the Ostrava-Karviná

Coal District has been used for heating since 2006. Mine water is pumped in the amount of 160–170 l.s^{-1} at a temperature of 26–29 °C [5].

In 2007, an investment project was planned for the commercial use of mine water from the flooded Olší-Drahonín uranium deposit. The project envisaged the pumping of mine water through a pumping borehole and the return of this water to the underground through an injection well. This would be a closed system of mine water exploitation. The estimated amount of water pumped was projected at the level of 26 l.s^{-1} at a temperature of approximately 10–12 °C. The intention was to heat 41 houses in Drahonín. However, the project has never been implemented [6, 7].

The paper aims to analyse the usability of the geothermal potential of the mine water of the Rožná I Uranium Mine, which is close to the Olší-Drahonín deposit.

2 LOCALIZATION OF THE ROŽNÁ I MINE

The Rožná uranium deposit is located in the central part of the Czech Republic on the edge of the Bohemian-Moravian Highlands, approximately 60 km northwest of Brno (see Fig. 1). The GEAM Dolní Rožínka spin-off plant, which is part of the state enterprise DIAMO in Stráž pod Ralskem, carries out permitted mining activities in a mining area of 8.76 km^2. From 27 October 1957 to 17 April 2017, the main activity was the underground mining of uranium ore and its subsequent processing into uranium concentrate – ammonium diuranate $(NH_4)_2U_2O_7$. Over its 60-year history, nearly 18 million tons of uranium ore containing approximately 20,000 tons of uranium metal were mined [8]. Currently, partial flooding of the mine has commenced and will be stopped below the 12th level. The unflooded mine areas will be maintained and used for research purposes for the next approximately 10 to 15 years.

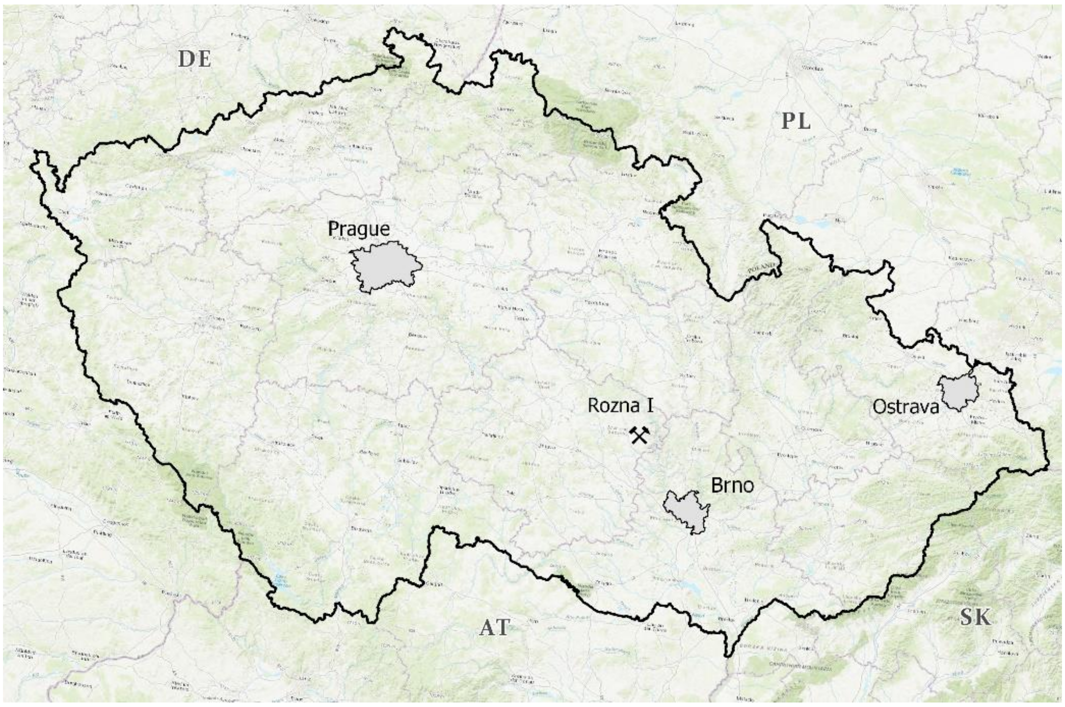

Figure 1. *Location of the Rožná I Mine in the Czech Republic* [9]

Vol. 67 (2021), No. 4
pp. 135–143, ISSN 1802-5420
DOI 10.35180/gse-2021-0059

3 MATERIALS AND METHODS

The geothermal properties of the Rožná deposit have been documented in a number of studies. The largest research of this type was carried out in the years 1975–1976. These results provided most of the input parameters for the realized analysis of the geothermal potential of mine waters. The others parameters were supplemented by operational data. The mine water inflow method determined the power of the geothermal source, and the volumetric method determined its energy supply.

4 GEOTHERMAL CHARACTERISTICS

It is well known that the temperature increases along with the depth below the Earth's surface. The most well-known temperature rise parameter in the Earth's crust is the so-called geothermal degree, which indicates the number of metres over which a temperature difference of 1 °C occurs, or its inverse, the geothermal gradient. When investigating the relationship of the temperature field to the crustal structure, the geothermal gradient parameter is replaced by the product of the temperature gradient with the thermal conductivity coefficient of the rocks. The reason is that the temperature gradient changes abruptly when different rocks come into contact with each other depending on their thermal conductivity [10]. The heat flux value indicates the amount of heat that passes through a unit area on the Earth's surface per unit of time, thus characterizing the Earth's heat economy at the point of measurement. The heat flux depends mainly on the radioactivity of the rocks. If the radioactivity of the rocks underlying the study area is known, the heat flux as a function of depth can be estimated. In addition, if the thermal conductivity coefficient of the rocks is known, the increase in the temperature with depth can be calculated [10].

In the Earth's crust, the temperature rises quite rapidly, reaching several hundred to a thousand degrees below the continents at the crust-shell interface at a depth of about 35 km. The main source of terrestrial heat is the heat released by the spontaneous decay of radioactive elements (U, Th, K^{40}) dispersed in rocks [9]. Among the other sources, which are also applied in the Earth's heat balance, is the so-called initial heat of the Earth. The Earth's initial heat is the heat that the Earth now radiates only passively. It includes the energy of solar radiation striking the Earth's surface, the heat released when the lower layers are compressed by the weight of the overlying strata, the energy released by gravitational differentiation, the energy of absorbed seismic waves, various physico-chemical exothermic reactions, the energy of crystallization and polymorphic changes, etc.

4.1 Regional geological influences affecting the geothermal character of the area

The Rožná deposit cannot be considered homogeneous in terms of geothermal energy exploitation. It is a heterogeneous rock mass with both positive and negative influences that can be characterized as geo-factors affecting the generation and transmission of geothermal energy.

Positive geo-factors:

- the presence of tectonic structures, especially faults, of a deeper extent that represent priority sections of the flow of terrestrial heat from depth,
- the varied diversity of the Moldanubian bedrock,
- the presence of granites, especially fine-grained facies, generally characterized by increased radioactivity (concentration of U = 0.0010–0.0012 %),
- the presence of vein igneous rocks that are known to have higher radioactivity,
- fossil geothermal activity, represented by hydrothermal ore veins or other ore bodies formed from ore-bearing geothermal fluids,
- the presence of metamorphites, in the bedrock of which there are granite outcrops at shallower depths of up to 1–3 km, the upper parts of which are usually associated with the occurrence of ore deposits.

Vol. 67 (2021), No. 4
pp. 135–143, ISSN 1802-5420
DOI 10.35180/gse-2021-0059

Negative geo-factors:

- a region of greater crustal thickness and greater distance from the interface between the crust and the upper mantle, the so-called Mohorovich discontinuities (MOHO interface),
- locations on slopes and upper parts of elevations in the Moldanubian bedrock,
- the presence of metamorphites (gneisses, mica schists and amphiboles) with insulating properties that have not been significantly disrupted by discontinuities, deeper fault zones, or unfavourable foliation inclinations,
- the presence of gneisses, characterized by low radioactivity.

In general, the natural conditions of the Rožná deposit can be characterized as an area with valley reliefs in granites or metamorphites, in which granites, a rock mass with fossil hydrothermal systems associated with hydrothermal ore deposits, are exposed. The area is characterized by extensive fault structures [11]. Elevated radioactivity in granites, vein structures or other rocks can be characterized throughout the area.

4.2 Temperature characteristics of the area

The coefficient of thermal conductivity of rocks characterizes the material's ability to conduct heat, and its determination is essential for determining the magnitude of heat flow. The thermal conductivity coefficient of rocks is measured in the laboratory from samples of characteristic rocks taken from boreholes in the area of interest [10]. In 1975, research was carried out on the thermo-physical parameters of rocks at selected sites of the Czechoslovak uranium industry [12]. Research on the thermal conductivity of the rocks of the Rožná deposit revealed that the thermal conductivity of rocks is conditioned by the geological structure of the deposit, where the effect of environmental anisotropy is strongly manifested. In fine-grained paragneiss, the thermal conductivity is significantly higher than in gabrodiorites. The research was complemented by Čermák in 1977, who verified the presented thermal conductivities of rocks in the laboratory [11] (see Table 1).

Table 1. *Thermal conductivity values of rocks* [11]

Depth [m above sea level]	**Rock**	**Thermal conductivity [W.m^{-1}.K^{-1}]**
-350	migmatitised gneiss	2.13
-534 to -558	amphibolite	1.43–1.70
-610 to -820	paragneiss	1.51–2.48
-943	chloritized paragneiss	2.36

The average thermal conductivity depends on the rock type and ranges from 1.5 to 2.7 W.m^{-1}.K^{-1}, exceptionally up to 3.2 W.m^{-1}.K^{-1} [13].

The geothermal grade at the Rožná deposit was determined by an average value of 55 m depth at 1 °C. The bedrock was measured in the research [12] on freshly mined faces of the R II Mine at three vertical levels (see Table 2).

Table 2. *Measured heat of rocks* [12]

Level	**Index of the working**	**Rock temperature [°C]**	**Depth [m]**
9	23-90	13.9	350
13	Z1-XIII	17.0	576
18	PS4-183	21.6	818

From the measured values, the average geothermal gradient was calculated according to relation (1) Ggr = 0.0179 °C.m^{-1}. The geothermal degree corresponding to the calculated geothermal gradient was determined according to relation (2) G_{dg} = 55.86 m.°C^{-1}. The average annual surface temperature in the Dolní Rožínka area of 7.2 °C was considered for the calculation.

$$G_{gr} = \frac{t_r - t_a}{H} \quad [°C.m^{-1}] \qquad \textbf{(1)}$$

$$G_{dg} = \frac{H}{t_r - t_a} \quad [m.°C^{-1}] \qquad \textbf{(2)}$$

where:

H ... the depth of the measurement site from the surface (m),
t_r ... rock temperature (°C),
t_a ... average annual surface temperature (°C).

The vein structure of the Rožná deposit is situated in metamorphosed rocks where the geothermal gradient is very low, and thus the heat flow is very limited. Deep disjunctive structures play an important role in the area of interest for the geothermal regime and are considered in various models of the block structure of the Bohemian Massif [14]. These may partly represent bands of discontinuities with an increased transmissivity of groundwater as heat carriers and thus fulfil the function of ground heat inputs, or conversely zones of reduced temperature with the function of thermal insulators. Equally important in this context are the surrounding basin areas with fills of Permo-Carboniferous deposits as part of the platform cover. Based on the broader geological and tectonic model, the following structures in particular encroach on the area under consideration [11]:

- *Iron Mountain Fault Zone* – is the primary tectonic line of the Sudeten NW-SE direction,
- *Boskovice Furrow* – represents a trench structure with synclinal deposition of layers in the NNE-SSW direction, formed by a continuous and lithologically varied fill of clastic Limnic Permo-Carboniferous sediments with an estimated thickness of up to 3,000 m,
- *Blansko Graben* – is a graben in the NNE-SSW direction, formed by Cenomanian and Lower Turonian sediments in the thickness of several tens to a hundred metres,
- *Blanice Forrow* – represents a trench structure in the NNE direction, formed by a disconnected fill of Permo-Carboniferous clastic sediments up to 1,000 m thick,
- *Pribyslavice Deep Fault* – is a mylonite zone in the NS direction dividing the Moldanubic area into two gravimetrically distinct sectors of the Earth's crust,
- *Carpathian Foreland* – is similar in importance to the aforementioned basin structures, reaching a depth of up to 1,200 m.

4.3 Earth's heat flow

The values of the terrestrial heat flow are relatively low in the study area. However, the wider area of the Rožná deposit has only a very limited number of in situ measurements [15]. Heat flow values on the continents range from 30–120 mW.m^{-2}, with an average temperature of about 60 ± 10 mW.m^{-2}. A close correlation between heat flow values and tectonic structure is evident. Lower heat flow is observed on old continental shields, while high heat flow is observed in areas of recent volcanic activity. Favourable heat flow values are observed in areas of smaller crustal thickness, areas with significant recent movements, and volcanic activity and post-volcanic manifestations. Suitable geothermal areas are associated with anomalous gravity fields, elevations in zones of increased electrical conductivity of rocks and sections of reduced seismic velocity in the upper mantle.

$$q = -\lambda \cdot G_{gr} \quad [W.m^{-2}] \qquad \textbf{(3)}$$

According to the available data of the average geothermal gradient G_{gr} = 0.0179 °C.km^{-1}, average thermal conductivity λ = 1.5-2.7 W.m^{-1}.°C^{-1}, the ground heat flow of the area of interest q = 27-48 mW.m^{-2} can be determined by substituting into relation (3). Thus, according to the extrapolation of values, the area of the Rožná deposit falls into the area with a lower heat flow of 20-40 mW.m^{-2}, exceptionally up to 50 mW.m^{-2} (see Fig. 2) [16, 17].

Vol. 67 (2021), No. 4
pp. 135–143, ISSN 1802-5420
DOI 10.35180/gse-2021-0059

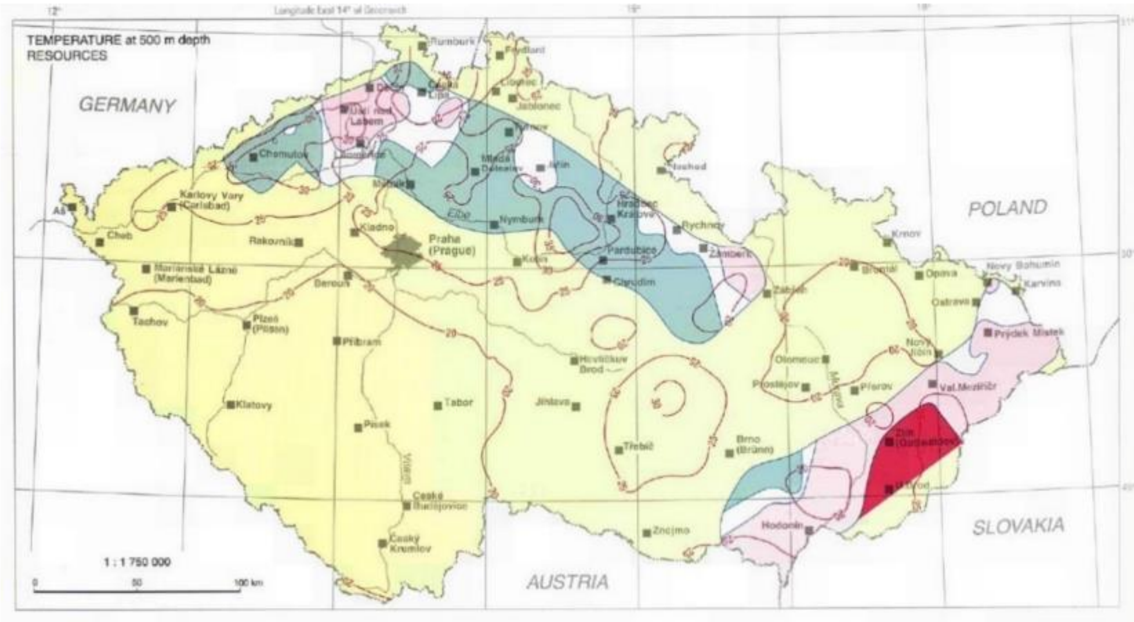

Figure 2. *Heat flow at a depth of 500 m below the surface* [17]

4.4 Radioactivity of rocks

Geothermal energy represents the thermal energy of the Earth's body, the origin of which is currently explained by, among other things, the energy released during the transformation of radionuclides [18]. The main source of the Earth's heat is the heat released by the spontaneous decay of radioactive elements (isotopes U^{235}, U^{238}, Th^{232}, K^{40}) dispersed in rocks [10]. A correlation between the total gamma activity and the heat production of rocks has been demonstrated. Within each geological structure, the linear relationship (4) applies to measurements of heat flow and radioactivity in rocks [19]:

$$Q = q_0 + bA \quad [W.m^{-2}] \qquad \textbf{\textit{(4)}}$$

where:

A ... heat production in unit volume, determined from radioactive isotopes U, Th, K ($\mu W.m^{-3}$),
q_0 *... dimension of heat flow, experimentally determined constant* ($W.m^{-2}$),
b ... length dimension, experimentally determined constant (m).

Syenites, granodiorites and igneous rocks have high heat production A ($\mu W.m^{-3}$) (5.9–2.7), while granites, pegmatites, haplites, migmatites and orthogneisses have lower values (2.5–1.4) [15].

4.5 Water as a thermal conductor

Heat transfer through groundwater is an irremovable obstacle to successful geothermal measurements in sedimentary basins. Because groundwater flow depends on rock permeability, disturbing hydrogeologic factors need not usually be considered when making measurements in igneous, metamorphosed, or even sufficiently consolidated sedimentary rocks whose permeability is low [10].

Water has some physical properties that are important for geothermal processes. The specific heat capacity of water is 4.187 $kJ.kg.^{-1}.°C^{-1}$, but the reported thermal conductivity $\lambda = 0.6$ $W.m^{-1}.K^{-1}$ is very low [11].

Vol. 67 (2021), No. 4
pp. 135–143, ISSN 1802-5420
DOI 10.35180/gse-2021-0059

5 EXPLOITATION OF GEOTHERMAL POTENTIAL FROM THE ROŽNÁ I MINE

Several calculations were performed to verify the usability of the geothermal potential of the decontaminated water.

5.1 Calculation for the developed mining area only

The geothermal energy of mine water also depends on the position of the mine in the regional groundwater cycle and the area's geothermal activity [20]. The amount of usable geothermal energy, or usable power, is strongly influenced by mine water runoff and the power output can be determined by the following equation (5):

$$P_t = Q \cdot c \cdot \rho \cdot (T_2 - T_1) \quad [W] \tag{5}$$

where:

Q ... is the amount of mine water pumped ($m^3.s^{-1}$),
c ... is the specific heat of mine water, assumption c = 4.187 $kJ.kg^{-1}.°C^{-1}$,
ρ ... is the density of mine water, assumption ρ = 1,000 $kg.m^{-3}$,
T_1 ... is the mine water temperature at the outlet of the heat exchanger (°C),
T_2 ... is the mine water temperature at the inlet to the heat exchanger (°C).

On average, Q = 50 $l.s^{-1}$ is extracted from developed mining areas [11]. The temperature of the decontaminated water used is 16 °C. With an assumed heat exchange of 4 °C and an assumed distribution loss of 5 °C, a power output of 837.4 kW can be calculated.

5.2 Calculation for excavated spaces

Assuming that the excavated spaces are flooded, the thermal stratification of the ground heat into the so-called underground reservoir will occur. Assuming that some of the pits are lined with PE pipes before the mine is abandoned, it would be possible to pump water to the heat pumps as required. It would also be possible to pump water from different depths and return it to other pits.

The conventional method of estimating geothermal energy stored in flooded areas of a mine is based on the volumetric method [21]. The thermal energy available in the mine water depends on the volume of stored mine water and the temperature difference between the inlet and outlet of the heat pump. The volume of mine water stored in the flooded areas of the Rožná deposit was determined to be 12.10^6 m^3 [9]. The energy storage associated with mine water is, therefore, given by the following equation (6):

$$E_s = \eta \cdot c \cdot \rho \cdot V \cdot (T_2 - T_1) \quad [GJ] \tag{6}$$

where:

η ... conversion constant, assumption η = 2,7.10^{-4} $kWh.kJ^{-1}$,
c ... is the specific heat of mine water, assumption c = 4.187 $kJ.kg^{-1}.K^{-1}$,
ρ ... is the density of mine water, assumption ρ = 1 000 $kg.m^{-3}$,
V ... volume of mine water in flooded mine spaces (m^3),
T_1 ... is the mine water temperature at the outlet of the heat exchanger (°C),
T_2 ... is the mine water temperature at the inlet to the heat exchanger (°C).

Assuming that the temperature of the mine water drops by 4 °C as it passes through the exchanger [22, 23], and this temperature gradient is sustained at these temperatures, a recoverable amount of 200,544 GJ of geothermal energy can be calculated in the flooded mine spaces of the Rožná deposit.

Vol. 67 (2021), No. 4
pp. 135–143, ISSN 1802-5420
DOI 10.35180/gse-2021-0059

6 CONCLUSION

In line with the global trend to reduce the use of traditional fossil fuels for electricity and thermal energy generation, the use of mine water or mine sites is very efficient. Based on the calculations of the usability of the geothermal potential of mine water from the Rožná I mine, this resource can be defined as a resource suitable for utilization by heat pumps. The northern part of the village of Dolní Rožínka, where the central district heating from the central gas boiler house is currently in place, could be used to take the heat produced. Heat consumption by end-users is on average 4,500 GJ per year [24] and up to 6,000 GJ at peak times. According to the gas boiler house statistics, no more than 1 MWt of instantaneous heat output has ever been needed. By installing heat pumps with the coefficient of performance of 4, a maximum capacity of more than 1 MWt can be expected. In the case of continuous operation and pumping in amount of 50 $l.s^{-1}$, a production of 32,987 GJ of heat per year can be achieved, which exceeds the heat consumption of the northern part of Dolní Rožínka several times. A sufficient reserve of geothermal energy from the mining areas can be counted on for the long-term life of the source, which is at the level of 200,544 GJ. This reserve allows for the use of this source for 44 years with the current demand of 4,500 GJ. Before the realization of the project, it is necessary to resolve the specifics of the flooded mine, i.e. mine water management after the termination of uranium mining. It is also necessary to deal with the problems caused by the presence of contaminants (U, Ra, Fe, Mn) in mine water. In case of suitable business and investment conditions, a feasibility study would be necessary to verify the efficiency of a possible installation.

ACKNOWLEDGEMENTS

This research was supported by the VSB – Technical University of Ostrava under Project SP2021/10 “Analysis of the use of the energy potential of mine water for central heat supply”.

REFERENCES

[1] Climate Action: EU Climate Action and the European Green Deal. *European Commission* [online]. 2021 [cit. 2021-04-11]. Available from: https://ec.europa.eu/clima/policies/eu-climate-action_en

[2] Geotermální zdroj v Děčíně [Geotermal Source in Děčín]. *MVV Energie CZ* [online]. Praha [cit. 2021-10-04]. Available from: https://www.mvv.cz/geotermalni-zdroj-v-decine.html

[3] BUFKA, A., J. VEVERKOVÁ, M. MODLÍK and J. BLECHOVÁ-TOURKOVÁ. *Obnovitelné zdroje energie v roce 2019 [Renewable Energy Sources in 2019]*. Prague: Ministry of Industry and Trade, 2020. Available from: https://www.mpo.cz/assets/cz/energetika/statistika/obnovitelne-zdroje-energie/2020/9/Obnovitelne-zdroje-energie-2019_2.pdf

[4] KRAMÁŘ, L. Nasazení tepelných čerpadel na ČDV Příbram II [Deployment of Heat Pumps at ČDV Příbram II]. *Diamo*, 2019, XXIV(4), pp. 2. Available from: https://www.diamo.cz/storage/app/media/obcasnik/4_19%20net.pdf

[5] TÍŽKOVÁ, V. *Využití odpadního tepla z čerpaných důlních vod vodní jámy Jeremenko pro vytápění [Utilization of Waste Heat from Pumped Mine Water of the Jeremenko Shaft for Heating]*. Technical report. Ostrava: IVT Tepelná čerpadla s.r.o., 2007. Available from: https://portal.cenia.cz/eiasea/download/RUlBX01TSzU0MV9vem5hbWVuaURPQ18xLnBkZg/MSK541_oznameni.pdf

[6] OPRAVIL, J. *Průvodní zpráva projektu “Využití důlních vod pro vytápění a přípravu teplé vody v obci Drahonín [Accompanying Report of the Project “Utilization of Mine Water for Heating and Preparation of Thermal Water in Drahonín”]*. Technical report. Brno: KP Klima, 2007.

[7] PECHERT, I. *Technická zpráva projektu “Využití důlních vod pro vytápění a přípravu teplé vody v obci Drahonín” [Technical Report of the Project “Utilization of Mine Water for Heating and Preparation of Thermal Water in Drahonín”]*. Technical report. Brno: KP Klima, 2007.

[8] VOKURKA, M. *Likvidace dolu Rožná I, jeho historie a možnost využití důlních prostor po ukončení těžby uranové rudy [Liquidation of the Rožná I Mine, its History and the Possibility of Using the Mining Areas after the End of Uranium Ore Mining]*. Ostrava, 2018. Diploma thesis. VSB – Technical University of Ostrava, Faculty of Mining and Geology, Department of Mining Engineering and Safety. Available from: https://dspace.vsb.cz/handle/10084/129855

[9] VOKURKA, M. and M. HUMMEL. Current issues of the Rozna I mine dewatering due to its flooding process, Czech Republic. *International Journal of Advances in Science, Engineering and Technology*. 2021, vol. 9(2), pp. 50–56. ISSN 2321-9009. Available from: http://www.iraj.in/journal/journal_file/journal_pdf/6-727-162876305250-56.pdf

[10] ČERMÁK, V. *Problémy geotermického výzkumu zemské kůry [Issues in Crustal Geothermal Research]*. *Geologický průzkum*. 1972, vol. 158(2), pp. 6–8.

[11] MYSLIL, V. and V. FRYDRYCH, V. *Výpočet zásob ložiska uranu Rožná – Hydrogeologická charakteristika ložiska Rožná [Calculation of Reserves of the Rožná Uranium Deposit – Hydrogeological Characteristics of the Rožná Deposit]*. Technical report. Prague: Geomedia, s.r.o., 2004.

[12] BLACHOWICZ, J. *Výzkum tepelně-fyzikálních parametrů hornin podle jednotlivých lokalit uranového průmyslu [Investigation of Thermo-physical Parameters of Rocks According to Individual Sites of Uranium Industry]*. Technical report. Kamenná: Development plant of the uranium industry, 1975.

[13] BLACHOWICZ, J., P. GLOGAR and M. ŠKUBAL. Zemský tepelný tok v dobývacím prostoru UD – Dolní Rožínka a UD – Příbram [Ground Heat Flow in the UD – Dolní Rožínka and UD – Příbram Mining Area]. *Rudy*. 1976, vol. 1976(8), pp. 237–238.

[14] SUK, M. *Geological History of the Territory of the Czech Socialist Republic*. Prague: Academia, 1984.

[15] HAZDROVÁ, M. et al. *Geotermální energie a její využití [Geothermal Energy and its Utilization]*. Prague: Academia, 1981.

[16] BLAŽKOVÁ, M. *Metodika k hodnocení geotermálního potenciálu v modelovém území Podkrušnohoří [Methodology for the Assessment of Geothermal Potential in the Podkrušnohoří Model Area]*. Technical report. Ústí nad Labem: J. E. Purkyně University, 2010. Available from: https://prvnigeotermalni.cz/upload/4084e9a33cc28c0fe8e25501a8bcbc01/metodika_ujep_4.pdf

[17] MYSLIL, V., J. BURDA, J. FRANCŮ and M. STIBITZ. National Geothermal Resource Assessments: Czech Republic. In: HURTER, S. and R. HAENEL (eds.). *Atlas of Geothermal Resources in Europe*. Belgium: European Commission Research Directorate, 2002.

[18] ČERMÁK V. Využití zemského tepla [Utilization of the Earth's heat]. In: *Proc. 3rd Conference on Biosphere: Utilization of primary energy sources.* Prague: ČVT Technology house, 1971, pp. 100–122.

[19] ČERMÁK, V. Tepelný tok a stavba zemské kůry [Heat Flow and Crustal Structure]. *Geologický průzkum*. 1972, 158(2), pp. 33–37.

[20] BAJTOŠ, P. Low Enthalpy Geothermal Energy from Mine Waters in Slovakia. In: *Proceedings of International Scientific Conference "Geothermal Energy in Underground Mines", November 21–23, 2001, Ustroń, Poland*. Krakow: Polska Akademia Nauk, 2001, pp. 77–80. Available from: https://www.geothermal-energy.org/pdf/IGAstandard/Poland/2001/a11.pdf

[21] RAYMOND, J. and R. THERRIEN. Low-temperature Geothermal Potential of the Flooded Gaspé Mines, Québec, Canada. *Geothermics*. 2008, 37(2), pp. 189–210. ISSN 0375-6505. DOI: 10.1016/j.geothermics.2007.10.001

[22] BAO, T., J. MELDRUM, C. GREEN, S. VITTON, Z. LIU and K. BIRD. Geothermal Energy Recovery from Deep Flooded Copper Mines for Heating. *Energy Conversion and Management*. 2019, 183(1), pp. 604–616. ISSN 0196-8904. DOI: 10.1016/j.enconman.2019.01.007

[23] BANKS, D., A. FRAGA PUMAR and I. WATSON. The Operational Performance of Scottish Minewater-based Ground Source Heat Pump Systems. *Quarterly Journal of Engineering Geology and Hydrogeology*. 2009, 42(3), pp. 347–357. ISSN 2041-4803. DOI: 10.1144/1470-9236/08-081

[24] SATT, a.s. *Celkové spotřeby tepla zákazníků v Dolní Rožínce v období 2016–2020 [Total Heat Consumption of Customers in Dolní Rožínka in the Period 2016–2020]*. Žďár nad Sázavou: SATT, a.s., Heat Division, 2020.