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Evaluation of heat supply with maintaining a safe mine water level during operation of open geothermal systems in post-coalmining areas

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Abstract

Purpose. Evaluation of the efficiency of open geothermal systems in flooded and drained mines of the Donetsk basin for heat supply of buildings with maintaining a safe mine water level.

Methods. Both circulation and non-return geothermal systems for the mine water heat recovery are analyzed. We proposed the energy and cost criteria for evaluating the effectiveness of open geothermal systems based on a comparison of the produced thermal energy with the energy costs for its production. The criteria use the relationships of thermodynamics, hydraulics, analytical formulas for calculation of ground water flow and methods to calculate the heat demand of indoor spaces.

Findings. The estimated ranges of thermal capacity from a few tens kW to a few MW and a coefficient of performance (*COP*) conversion factor of 3.5-6.8 achievable by geothermal systems for the studied closed mines of Donbas correlate well with the values of these indicators at open geothermal systems operated in different countries, which shows the technical and economic feasibility of the installation to cover local heat demands. The possibility to fully cover the needs for thermal energy is shown on the example of buildings with office spaces for staying of a few hundred people. We demonstrate how to preliminary calculate the parameters of mine water circulation with maintaining the safe level in terms of keeping the ground water quality in the areas adjacent to the mine.

Originality. The developed criteria and calculation methodology allow to realistically evaluate the parameters of the efficiency of operation for open non-return and circulation geothermal systems, taking into account mining, geological and technology conditions, to prioritize the exploration of geothermal resources in mines and to evaluate the parameters of mine water circulation with maintaining the safe mine water level.

Practical implications. The study showed the feasibility of installation and effective operation of open geothermal systems at the mines of the Donetsk basin for heat supply of buildings located in the adjacent areas with maintaining a safe mine water level.

Keywords: *closed mine, mine water, drainage, thermal energy, geothermal systems*

1. Introduction

In line with the requirements of international and national regulation [1]-[3]. Ukraine is gradually reducing the share of its coalmining industry. Particularly, the concept of reforming this sector [4], [5] presented in the Ukrainian parliament in January 2020 envisages the closure of 102 state-owned mines of all 148 mines in the country. Currently 67 state-owned mines are located on the territory not controlled by the government; only 4 of 33 other active mines in Ukraine are profitable, the rest will be closed in the near future. Mine closure is well-known to be a rather costly and capital-intensive process linked with the need to maintain a safe mine water level to prevent waterlogging and flooding of neighboring operating mines, and contamination of upper aquifers used for water supply. Closure of coal mines leads to local shortages of thermal energy in post-mining areas, which makes topical the searches for alternative energy sources and the methods of using the available energy resources.

Currently in some countries (Germany, Great Britain, the United States, Spain and others) almost 30 open geothermal systems operate in flooded mines producing heat for local consumers. The vast majority of these systems has a small-to-medium thermal capacity (up to 1 MW) and is used to heat one or a few buildings near to the mine [6]-[11]. In general, the world experience of mine water heat recovery demonstrates the feasibility, profitability and environmental acceptability of geothermal systems in closed mines, which can be further developed in Ukraine regarding to the existing site in Western Donbas [12]. In this regard, the purpose of this work is to assess the effectiveness of open geothermal systems in closed mines on the example of the Donetsk coal basin for heat supply of buildings with maintaining a safe level of mine water.

2. Methods

Currently, open-type geothermal systems are very common among the various methods to recover geothermal heat in closed mines. According to one of designs presented in [13] and updated in Figure 1 water is pumped out with the flow rate *Q* from flooded workings at deep horizons through

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the wells or existing mine drainage facilities. The maximum efficiency is achieved by combining the wells with the main workings like shafts. Water is raised by electric centrifugal pumps that demonstrated good performance during operation in aggressive fluids with dissolved salts, gases and mechanical impurities. Such kind of pumps is characterized by equipment simplicity, long maintenance period (2-3 years), large pumping depth (up to 4 km) and a significant maximum of the flow rate (up to 10000 m^3/day).

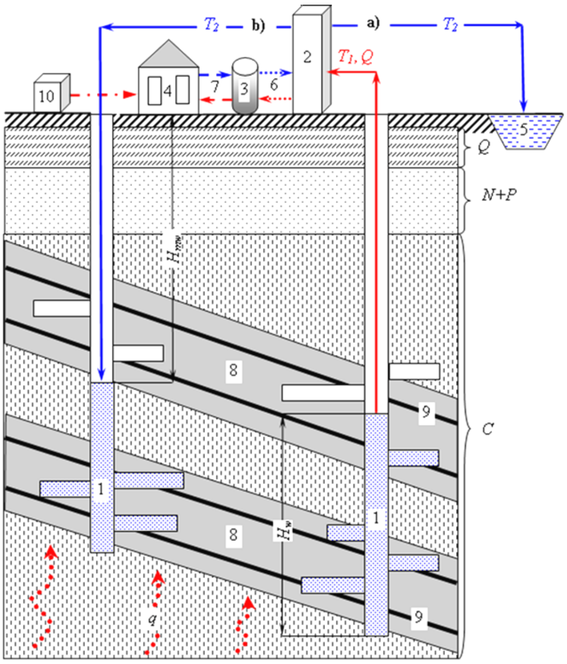

Figure 1. Design of an open geothermal system for mine water heat recovery: 1 – flooded underground workings; 2 – heat exchanger; 3 – heat pump; 4 – consumers of thermal energy; 5 – surface watercourse or reservoir; 6 (7) – direct and reverse movement of the heat transfer fluid from the heat exchanger to the pump (to the consumers); 8 – coal-bearing rocks; 9 – coal seams; 10 – boiler facility using conventional fuel during the periods of peak heat demand; (a) non-return option; b) circulation option

Raised mine water on the ground surface has a temperature T_1 close to the temperature of rocks at the pumping depth. After heat recovery in the heat exchanger by the coolant at a temperature T_2 the mine water can be treated and discharged to the hydrographic network (option “a”) or returned to underground workings of upper horizons (option “b”). The heat transfer fluid from the heat exchanger enters the inter-tube space of the heat pump evaporator where it is cooled, and then delivered back to the heat exchanger. The recovered heat is supplied to the consumers through the heating circuit and hot water supply. To cover the peaks of thermal energy consumption by buildings in winter-when the thermal capacity of the geothermal system may be insufficient – an additional boiler facility is used that runs on conventional energy sources (coal, gas). The presented design of heat recovery allows maintaining the mine water level by regulating the abstraction (flow) rate Q.

Putting this system into practice requires a feasibility study to evaluate the effectiveness by comparing the costs of system operation and the costs of produced heat energy. For a drained closed mine, the electricity consumption by water hoisting E_{wh} depending on the pumping depth and the mine water level is mandatory to maintain a hydrodynamic and environmental safety underground. From this standpoint, the additional amount of produced thermal energy from mine water U_{mw} on the ground surface before the discharge into watercourses or reservoirs (option “a” in Figure 1) does not require energy for water hoisting.

The energy criterion to evaluate the efficiency of an open geothermal system is defined as the ratio ξ_E of the thermal energy produced at the capacity $P_{hp,th}$ taking into account the losses during transportation U_{tr} to the thermal equivalent of electricity for heat pumps and electricity costs for heat transportation. An open geothermal system requires electric power to maintain heat pump operation $P_{hp,el}$ and transportation of heat to consumers $P_{tr,el}$, therefore:

$$\xi_E = \frac{P_{hp,th}\Delta t_{op} - U_{tr}}{\omega\left(P_{hp,el} + P_{tr,el}\right)\Delta t_{op}}, \tag{1}$$

where:

ω – thermal equivalent of electric energy;

Δt_{op} – operating time (during the heating season).

Hereafter the electricity required for operation is assumed to be produced with conventional fuel (coal or gas), and the thermal capacity created with mine water is compared with the thermal capacity of the respective fuel. Then the thermal equivalent ω can be calculated as:

$$\omega = \frac{\eta_h}{\eta_{TPS}}, \tag{2}$$

where:

η_{TPS} – thermal power station efficiency;

η_h – heating system efficiency.

An additional cost-related criterion for the feasibility to recover heat from mine water is defined as the relation of the difference between the costs of produced heat $C_{hp,th}$ and the losses during transportation $C_{tr,th}$ to the total cost of electrical energy spent on mine water hoisting $C_{mw,el}$, heat pump operation $C_{hp,el}$, discharge of water after its thermal use back to the mine $C_{r,el}$, and additional costs including management and maintenance C_{man}:

$$\xi_C = \frac{C_{hp,th} - C_{tr,th}}{C_{mw,el} + C_{hp,el} + C_{r,el} + C_{man}}. \tag{3}$$

System operation is economically feasible for $\xi_C > 1$.

If mine water is discharged to underground workings after thermal use and drainage is shut down (option ”b” in Figure 1), the cost of electricity for water hoisting at a constant mine water level can be optimized accordingly to heat demand near the geothermal system location. The heat recovery profitability depends on the energy balance defined as the difference between the produced thermal energy U_{mw} and the thermal equivalent of electricity used to raise water, run heat pumps and discharge water after thermal use back to the mine.

The required electric power includes the power to raise mine water $P_{mw,el}$, run heat pumps $P_{hp,el}$, transport heat to the consumers $P_{tr,el}$ and return the thermally used water to the mine $P_{r,el.}$ Then the energy criterion in Equation 1 can be rewritten as follows:

$$\xi_E = \frac{P_{mw,th}\Delta t_{op} - U_{tr}}{\omega\left(P_{mw,el} + P_{hp,el} + P_{tr,el} + P_{r,el}\right)\Delta t_{op}}. \tag{4}$$

Taking into account the additional energy costs for mine water circulation, Equation 3 can be replaced with:

$$\xi_C = \frac{C_{mw,th} - C_{tr,th}}{C_{mw,el} + C_{hp,el} + C_{tr,el} + C_{r,el} + C_{man}}, \quad (5)$$

where:

$C_{mw,el}$ – cost of electricity to raise mine water;

$C_{r,el}$ – cost of electricity to discharge water into the mine after thermal use.

The thermal energy generated on the ground U_{mw} covers the local needs and, therefore, reduces the overall energy shortages near the site of system installation. The parameters in Equations 1-5 depend on many factors and should be optimized accordingly. For example, the electric power to raise mine water depends on the pumping depth and the mine water level. The deeper the pump is installed, the warmer the mine water with greater energy potential it raises, but consuming more electricity; at the same time, deeper water is more likely to have higher mineralization, which can complicate the operation of heat exchangers.

The distance to the nearest consumer is the critical parameter to evaluate the efficiency of a geothermal system. Similarly to [6] we introduce the zone of influence contoured by the maximum distance to heat consumers provided that within this zone the heat transportation losses remain acceptable. For example, the radius of this zone for 6 centralized water hoisting stations in Germany varies in the range of 500-5000 m depending on heat capacity and heat demand, these distances determine to a great extent heat transportation losses.

The contribution of the geothermal system to the local energy balance can be estimated as follows. The maximum achievable capacity with using heat pumps recovering mine water heat is calculated by the Formula [14]:

$$P_{hp,th} = Q_f C_f \rho_f \left(T_{mw,in} - T_0\right), \quad (6)$$

where:

Q_f – flow rate to the heat pump;

C_f – specific heat capacity of water per mass;

ρ_f – water density;

$T_{mw,in}$ – the temperature of the mine water being delivered to the heat exchanger;

T_0 – water temperature at the outlet of the heat pump.

The temperature $T_{mw,in}$ decreases relative to the outlet temperature of the mine water $T_{mw,out}$ when it moves from the pump to the intermediate heat exchanger and in the heat exchanger itself, therefore:

$$T_{mw,in} = T_{mw,out} - \Delta T_c, \quad (7)$$

where:

ΔT_c – the difference in mine water temperature due to cooling.

Since the duration of water rise to the ground is relatively short we assume approximately ΔT_s = 1-2ºC. If necessary, the temperature difference ΔT_s can be evaluated more accurately depending on thermodynamic and hydrodynamic relationships.

The mine water temperature T_{nat} at a depth H_z in the case of missing measurements can be estimated by a geothermal gradient [15]:

$$T_{nat} = T_{nl} + \Gamma\left(H - H_{nl}\right), \quad (8)$$

where:

T_{nl} – soil temperature in a neutral layer below the ground where annual temperature fluctuations can be neglected;

H_{nl} – depth of the neutral layer;

q – deep geothermal flux;

λ_r – average thermal conductivity of rocks.

The theoretically achievable conversion factor of the heat pump (coefficient of performance – *COP*) is calculated as:

$$COP = \eta_{hp} \frac{T_h}{T_h - T_{min}}, \quad (9)$$

where:

η_{hp} – efficiency of the heat pump;

T_h – highest temperature in the heating circuit to which the fluid has to be heated;

T_{min} – minimum temperature to which it is possible to cool the fluid in the heating circuit.

The electric power consumed by the heat pump is calculated by the Formula 10:

$$P_{hp,el} = \frac{P_{hp,th}}{COP}. \quad (10)$$

According to [16], [17] the electric power required to raise the mine water to the ground is calculated by the Formula 11:

$$P_{hp,el} = \kappa_S \frac{g\,Q\,H\,\rho_f}{\eta_p \eta_{ht}}, \quad (11)$$

where:

κ_s – safety factor that depends on the pump motor;

g – gravity acceleration;

Q – water flow rate;

η_p – pump efficiency;

η_{ht} – heat transfer efficiency.

The pump capacity required to maintain the mine water circulation is calculated by Equation 11 where the pressure H is replaced with the pump pressure H_p calculated by the Formula:

$$H_p = H_g + H_f; \quad H_f = \frac{\alpha_f L}{d} \cdot \frac{v^2}{2g}, \quad (12)$$

where:

H_g – difference between the absolute elevation of the intermediate heat exchanger and the pumping depth;

H_f – pressure loss on friction resistance;

α_f – friction coefficient;

L – path length of the cooled water;

d, S – the diameter and cross-sectional area of the pipe through which mine water is raised;

v – flow velocity in the pipe.

The total electric power consumed for the operation of an open circulation system can be calculated as the sum:

$$P_{sum,el} = P_{hp,el} + P_{mw,el} + P_{r,el}. \quad (13)$$

For option "a":

$$P_{sum,el} = P_{hp,el}.$$

The thermal equivalent of the electric capacity for geothermal heat recovery P_{th} is calculated as:

$$P_{th} = \omega P_{sum,el}. \quad (14)$$

with the parameter ω defined by Equation 2.

Excluding the cost of heat transportation, the criterion of thermal efficiency of an open geothermal circulation system can be defined as the ratio:

$$\xi_E = \frac{P_{mw,th}}{P_{th,eq}}, \tag{15}$$

with $P_{th,eq} = P_{th,g}$ or $P_{th,eq} = P_{th,c}$ if gas or coal is used as the fuel for electricity generation.

Criterion 15 shows how much additional thermal energy can be generated by an open geothermal system using burnt coal or gas. The higher the value ξ_E, the more thermal energy can be additionally recovered from mine water. Geothermal system operation makes sense in terms of energy production if $\xi_E > 1$ with the additional heat output defined as:

$$\Delta P_{th} = (\xi_E - 1) P_{th,eq}. \tag{16}$$

If thermally used mine water is not returned to the mine, the respective energy consumption can be neglected ($P_{el} = 0$).

The cost of produced thermal energy C_{th} and consumed electric energy C_{el} is calculated as:

$$C_{th} = a_{th} P_{mw}, \; C_{el} = a_{el} P_{sum,el}, \tag{17}$$

where:

a_{th} – tariff for thermal energy;

a_{el} – electricity tariff.

The surplus cost P obtained owing to a running geothermal system can be estimated taking into account the management and maintenance costs C_{man} as follows:

$$P = C_{th} - C_{el} - C_{man}. \tag{18}$$

The heating demand of a potential consumer can be estimated using the simplified equation proposed in [12]. The more detailed method proposed in [18] takes into account the number of people who are present or live in the indoor space. According the latter method the heat flux to maintain the room temperature is calculated as follows:

$$q_1 = q_0 \cdot k \cdot V \cdot (T_r - T_{av}), \tag{19}$$

where:

q_0 – average heating characteristics of the building;

k – coefficient that takes into account the heating system specifics;

T_r – room temperature.

The volume of heated rooms is calculated as follows:

$$V = U \cdot n_1, \tag{20}$$

where:

U – number of residents or employees in buildings;

n_1 – a standard volume per person defined as 45 m^3 for residential buildings and 13.5 m^3 for offices.

The flow rate required to provide for hot water supply is calculated by the Formula 21:

$$Q_w = U \cdot n_2, \tag{21}$$

where:

n_2 – rate of hot water consumption per person set as 0.14 m^3/d for apartments and 0.01 m^3/d for offices.

Heat flux for hot water supply is calculated as:

$$q_2 = C_w \cdot Q_w \cdot (T_h - T_c), \tag{22}$$

where:

C_w – volumetric heat capacity of water;

T_h – hot water temperature usually taken at 50-60°C;

T_c – cold water temperature taken average 6°C from October to May and 15°C from May to October.

In contrast to the cold season the most of energy during hot summer period is spent for air conditioning that can be provided by heat pumps running in the cooling mode [19]. The heat flux required to cool the indoor spaces to a comfortable temperature can be calculated as follows [20]:

$$q_3 = Q_a (h_1 - h_1), \; Q_a = U \cdot n_3; \quad h = C_a T + (q_s + C_s T)\frac{d}{1000}, \tag{23}$$

where:

Q_a – air flow;

h_1, h_2 – enthalpy of outdoor and indoor air;

n_3 – air flow rate per person (0.009 kg/s);

C_a, C_s – heat capacity of dry air and water vapor;

T – air temperature taken for outdoor air as the monthly mean value, and for indoor space as T_r;

q_s – specific heat of vaporization;

d – moisture content of air, $d = 0.6$ for outdoor air in summer, $d = 0.55$ for indoor space as the most favorable for human.

Operation of a geothermal circulation system is associated with the necessity to keep a safe mine water level in terms of maintaining ground water quality in aquifers near the points of pumping and discharge. This refers especially to vertical workings like shafts or unused degassing wells used as the ends of the mine water circuit.

If mine water mineralization does not differ significantly between the water level and pumping depth, an option of reverse discharge to the same shaft can be considered to minimize transportation losses. But this way speeds up cooling of water in the shaft, which reduces the efficiency of the heat recovery. Therefore, any available appropriate infrastructure including pipelines and pumping stations should be included to the mine water circuit to discharge thermally used water to another shaft or vertical working at a certain distance from the pumping point, which will keep a higher temperature of pumped water for a longer period.

The flow rate of mine water Q_{mw} required to provide a thermal capacity q_{th} in the heat exchanger can be preliminary calculated by the Formula 24:

$$Q_{mw} = \frac{q_{th}}{C_w \Delta T}, \tag{24}$$

where:

q_{th} – thermal capacity of the geothermal system;

C_w – volumetric heat capacity of mine water;

ΔT – temperature difference while water cooling in heat pumps, ΔT = 6ºC.

The calculated flow rate changes throughout the year proportionally to thermal capacity q_{th} that decreases in summer and increases in winter. Due to variations of flow rate of circulating mine water, the ground water level around the pumping and discharge points fluctuates within a certain interval ΔH as shown in Figure 2. The level of mine water and associated ground water with high mineralization near the discharge point may reach the bottom of an upper aquifer used for local water supply. Based on the practice of controlled flooding the mines [20][21]-[23] it is recommended to maintain the mine water level below the erosion base level or the bottom of the lowest aquifer used for water supply.

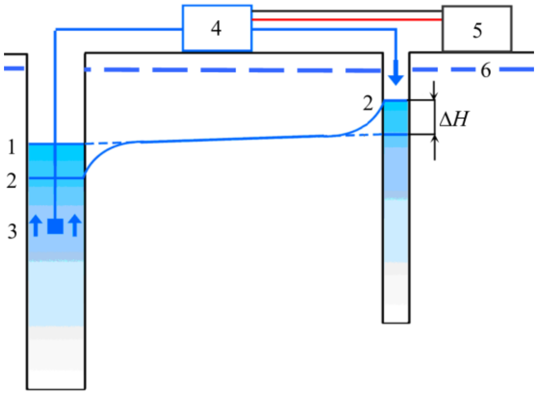

Figure 2. Sketch of mine water pumping and discharge in a geothermal circulation system: 1 and 2 – mine water level before and during the operation, respectively; 3 – pump; 4 – heat exchanger; 5 – heat consumer; 6 – maximum allowed mine water level

Maintaining the mine water level slightly below these margins minimizes pumping costs and allows avoiding of mixing ground water and mineralized mine water, as well as preventing from waterlogging in post coalmining areas after drainage shutdown [24].

In case of availability of detailed data on underground working geometry, the distribution of residual voids in mined out rocks, flow parameters, hydraulic connections with neighboring mines the mine water level and ground water level can be calculated using sophisticated numerical flow and transport models. In contrast, preliminary evaluations under parameter uncertainty can be performed by analytical relations.

The rise of the ground water level around a shaft of vertical working, through which the thermally used water is discharged back to the mine, can be calculated by the Formula of changing the ground water level near a well with the flow rate with a time-dependent stepwise pattern [25]:

$$\Delta H\left(r,t\right)=-\sum_{j=1}^{n}\frac{Q_j-Q_{j-1}}{4\,\pi\,K_{av}m_{av}}E_i\left(-\frac{r^2}{4\,a\left(t-t_{j-1}\right)}\right), \qquad (25)$$

where:

Q_j – flow rate during the time interval “j”, j = 1, 2,…n;

r – the distance from the well (shaft) axis to the calculation point;

n – number of intervals with different flow rate;

K_{av} – average conductivity of flooded mined out rocks;

m_{av} – average thickness of the flooded zone in the mine;

$a = K_{av}\, m_{av} / n_a$;

n_a – active porosity of mined out rocks.

3. Results and discussion

The operational parameters of potential open geothermal systems with active drainage were evaluated by Equations 1-18 for 9 mines in Donbas with known data [26], [27] taking minimum cooling temperature in the heat pump 6ºC, maximum temperature in the heating system 55ºC, duration of the heating season 3000 hr, heating system efficiency 0.9.

The theoretically achievable thermal capacity of an open geothermal system of a few MW (Table 1) correlates well with the actual thermal capacity of such systems currently running [6], [7]. The *COP* parameter is expected to vary within the range of 4.1-6.8. Using gas to generate electric power of a higher efficiency instead of coal enhances the overall efficiency. However, this scenario regarding current trends on the gas market in Ukraine looks rather hypothetical.

The value ξ_E depends on water temperature, the pumping depth and other indicators in Equations 6-12. The most common estimate is the values of ξ_E near 2.0 obtained for coal as a fuel; the higher values of ξ_E for mines “Novogrodivska 1-3” and “Chervonyi Profintern” are likely due to higher water temperature at a significant depth, which is characteristic for drained mines. The value $\xi_E \approx 2$ means that, for example, using 1 kWh of thermal energy in fossil fuels (coal) in a geothermal system allows obtaining surplus 1 kWh of thermal energy and getting in total 2 kWh of heat. This ratio will change in the case if alternative energy sources will be added to provide electricity for heat pumps.

Table 1. Preliminary evaluation of efficiency indicators for open non-return geothermal systems under conditions of mines in Donbas

Mines	P_{GW}, MW	*COP*	$\Delta P_{th,c}$, MW	$\xi_{E,c}$	$\Delta P_{th,g}$, MW	$\xi_{E,g}$	Rank, ξ_E
Novogrodivska 1-3	12.93	6.82	8.66	3.03	9.92	4.31	1
Artema	6.16	4.21	2.87	1.87	3.84	2.66	7
Golubovska	5.53	4.58	2.81	2.03	3.62	2.89	5
Kirova	1.74	4.50	0.87	2.00	1.13	2.84	6
Lenina	3.63	4.90	1.96	2.18	2.46	3.09	3
Vuglegirska	13.9	4.89	7.52	2.17	9.42	3.09	4
Poltavska	1.15	4.16	0.53	1.85	0.71	2.62	8
Chervonyi Profintern	18.74	6.48	12.23	2.88	14.16	4.09	2

The rank of the criterion ξ_E for the studied mines quantifies the priority or economical attractiveness to install geothermal systems in terms of maximum efficiency. The local demand on thermal energy should be taken into account with a preliminary assessment of the energy and cost criteria 3 and 5. The expected reduction in CO_2 emissions due to the operation of open systems may reach a few thousand tons per heating season.

Thermal capacity of open geothermal circulation systems can be calculated by Equations 8-14 similarly to the systems that discharge pumped water to surface watercourses. Evaluations in Table 2 show the feasibility to install geothermal systems in the flooded mines of the Selidovo group in Donbas where there are potential local consumers of thermal energy. In calculation we set the flow rate of 250 m^3/d. In case of pumping water at the mine water level the thermal capacity is expected to insufficient due to low water temperatures of 10-12ºC; however, thermal capacity can be significantly enhanced by deepening the pumps as shown in Figure 3. Therefore, it might be reasonable, depending on local conditions, to pump mine water below the water level to increase *COP* and produce more thermal energy. Key limitations to deepen the pumps are technical capabilities of submersible pumps and growing mineralization with depth.

Table 2. Evaluated efficiency indicators for an open circulation system on mine water heat recovery for mines of the Selidovo group in Donbas

Mine	H_g, m	$T_{mw,out}$, ºC	P_{mw}, kW	*COP*	ΔP_{th}, kW	ξ_E
Selidivska	41.5	10.9	60.1	3.64	17.6	1.41
Novogrodivska 2	83.6	12.2	75.4	3.74	19.6	1.35
D.S. Korotchenka	30	10.6	55.9	3.61	17.1	1.44

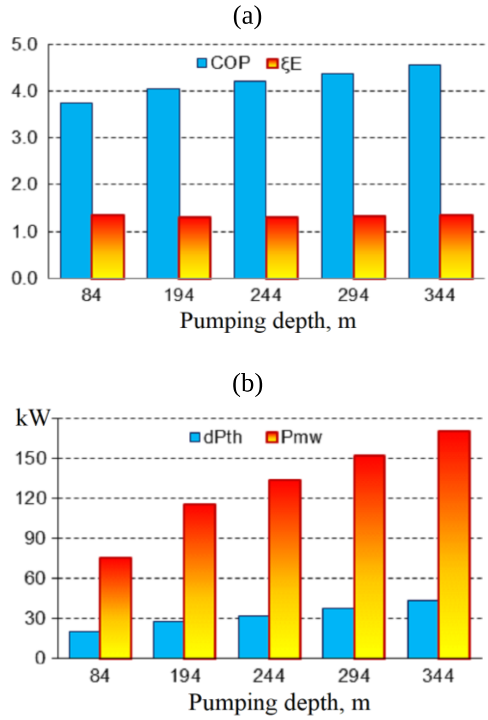

Figure 3. Evaluated thermal efficiency indicators of an open geothermal system under conditions of mine "Novogrodivska-2" versus pumping depth

Starting from Tables 1 and 2 it is possible to evaluate the site-specific potential of geothermal system operation. The operation efficiency depends on sound balancing between the thermal capacity and local demand on heating and hot water supply, which varies throughout the year. According to actual requirements in Ukraine [27], [28] heating of civil and industrial facilities should start if air temperature drops below 8ºC. Taking into account the annual cycle of the average air temperature [29], [30] the heating period in the Donbas region should last approximately 150 days, whereas the period of cooling in summer roughly 60 days.

Figure 4 shows the expected monthly consumption of thermal energy by office spaces in houses or office buildings with a total heating area of 3240 m^2 and a volume of 8100 m^3 where up to 600 people may be inside. This is applicable to the buildings of closed mine services located in the vicinity of the shaft or water hoisting where open geothermal systems can be installed.

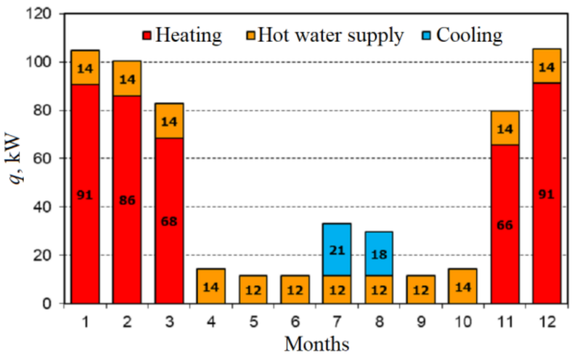

Figure 4. Evaluated thermal energy consumption by buildings with office spaces for up to 600 people for the conditions of Donbas

In calculations the outside air temperature was set according to [29], [31]; the other parameters were set as follows: q_0 = 1254 J/(m^3·h·ºC); T_h = 55ºC; C_w = 4183 MJ/(m^3·ºC); C_a = 1006 kJ/(kg·ºC); q_s = 2500 kJ/kg; κ = 1.15, C_s = 1.87 kJ/(kg·ºC). The most of the produced thermal energy is spent on heating (67%) and hot water supply (26%), while the energy consumption for cooling is insignificant (7%).

The heat demand throughout the year varies from 17 kW to 117 kW, which is achievable for open circulation geothermal systems under the conditions of mines of the Selidovo group (Table 2). The flow rate of mine water will vary from 58 m^3/d in summer to 401 m^3/d in winter. These margins look realistic for mines of the Selidovo group (Table 2, Figure 3) in case of the pumps are positioned at the depths 200-300 m below the mine water level.

As an example we calculated the rise of the water level and the risk of reaching the bottom of the upper aquifer under the geological conditions of the flooded mine "Novogrodivska 2" in Donbas. The average values of ground water flow parameters were evaluated by inverse modeling for the period of mine water rebound [31], [32]: K_{av} = 0.08-0.1 m/d, m_{av} = 400-550 m, n_a = 0.05-0.08. According to the latest data [26], the mine water level rose to 83 m below the ground surface and exceeded the mark +121 m a.s.l. by 2019.

We analyzed the influence of pumping depth with changing thermal capacity throughout the year (Table 3) on fluctuations of the ground water level. Pumping from the mine water level with a temperature of 12.2ºC (option 1) allows reaching a thermal power of 150 kW. A deeper position of the pump below the mine water level with a water temperature of 18.5ºC (option 2) allows increasing the thermal capacity to 300 kW. In Table 3 ΔH_{max} denotes the elevation of the ground water level at a distance of 20 m from the discharge point by the end of period with a maximum flow rate (March); $\Delta H_{max,s}$ does the same indicator by the end of period with a maximum flow rate (October).

We used the minimum values from the range of parameters K_{av}, m_{av}, and n_a to calculate the ground water level fluctuations at different horizontal distances from the discharge point throughout the year assuming "pessimistic scenario" (Fig. 5).

Table 3. Calculated maximum elevation of the ground water level at the discharge point of thermally used water

	H_p, m	T_{mw}, ºC	q_{th}, kW	Q_{mw}, m^3/d	Months	ΔH_{max}, $\Delta H_{max,p}$, m
Option 1	84	12,2	150	515	Nov – Mar	8,1
			20	70	Apr – Oct	1,8
Option 2	294	18,5	300	1030	Nov – Mar	16,1
			40	140	Apr – Oct	3,7

Discharge of thermally used water through the well or the shaft leads to temporary rising the water level during the heating season, after which it gradually drawdowns to the previous position but does not reach it by the end of the annual cycle. The evaluated ground water level under option 1 by 12 m (Fig. 5a) will not reach the overlying bottom of the aquifer above the coal-bearing rocks because currently the groundwater level at the mine "Novogrodivska 2" occurs at 121-125 m a.s.l. [33] and the bottom of the aquifer at 150-160 m a.s.l. [27].

More intensive pumping (option 2, Fig. 5b) leads to rising the ground water level up to 24 m that may reach the bottom of the lower aquifer but only within the near vicinity (up to 20 m) of the discharge point.

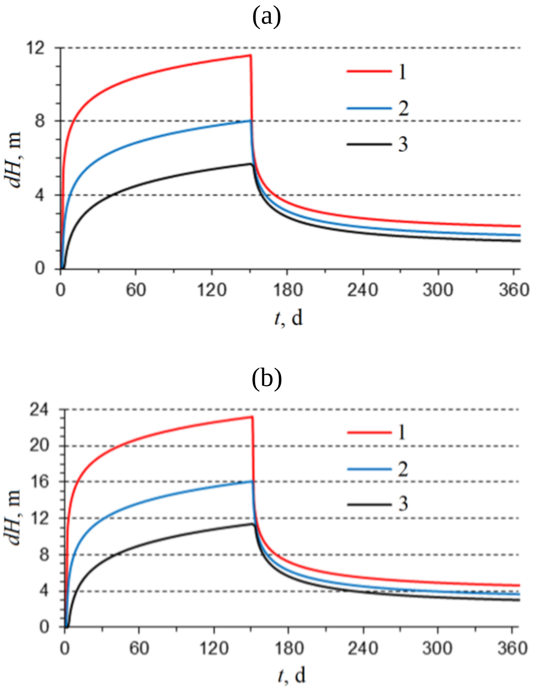

Figure 5. Annual variation of the groundwater level at the distance l_d from the discharge point: 1 l_d = 5 m; 2 l_d = 20 m; 3 l_d = 50 m; (a) option 1; (b) option 2

Regarding the localized area of the rising ground water level and flow parameters assumed for a "pessimistic scenario" preliminary we can make a conclusion that the ground water level under flow rates as in options 1 and 2 won't rise to the upper aquifer bottom, thus, preventing from mixing of more mineralized mine with water of this aquifer. Due to a usually lower demand in thermal energy in March and November in comparison to the winter, the flow rate can be reduced these months by 15-25%, which minimizes ground water rise. The final conclusion on whether the fluctuations of mine water and ground water due to water circulation at the site be acceptable in terms of environmental impact should be drawn based on 3D numerical simulation of coupled flow, heat and mass transfer taking into proper account rock heterogeneity, operation modes, locations of pumping and discharge.

Mine water in this area is of low-to-medium mineralization below 3.5 g/dm^3 [31], [32]; this allows making a preliminary conclusion on the acceptability of using mine water as a heat transfer fluid. This conclusion should be analyzed in more details when designing the mine water circuit on site.

Pumping from the shaft leads to a drawdown close to the values of ΔH_{max} (Table 3, Fig. 5), which increases the hydraulic gradient on the flow line between the points of pumping and discharge, thus, intensifying the flow of cooled discharged water to the pumping point. For this reason the distance between the points of pumping and discharge should be estimated taking into account the circulation rate to cover the local demand on thermal energy, maximum acceptable drawdown and mineralization at the pumping point.

4. Conclusions

In this paper we analyzed the widely used in post-mining practice open geothermal systems in terms of efficiency operation and environmental safety. We proposed energy and cost criteria to preliminary evaluate the efficiency of these systems through the comparison of the produced thermal energy and energy costs needed for operation. The criteria allow prioritizing of the installation of geothermal systems among a significant number of potential sites.

The expected thermal capacity of non-return open geothermal systems that can be installed at closed coal mines in Donbas is evaluated at a few MW with the *COP* in heat pumps of 4.1-6.8, which correlates well with the reports on similar systems currently operated abroad and in Ukraine. The thermal capacity of suggested open circulation geothermal systems for flooded mines of the Selidovo group in Donbas with the existing demand on thermal energy ranges of a few dozen kW and *COP* of 3.5-4.5 in the case of pumping at the mine water level and can be doubled by deepening the pumps to the depths up to 200 m below at the same pumping rate.

To assess the applicability of suggested geothermal systems we compared their expected thermal capacity with the needs of local consumers of thermal energy in the climatic conditions of the Donetsk basin. It was shown that the heat flux required throughout the year in buildings with office spaces for up to 600 people and the area of more than 3000 m^2 can be fully covered by geothermal systems that can be installed at the flooded mines in Donbas. In summer, it is reasonable to operate heat pumps in the cooling mode with pumping cooler mine water from the upper part of the shaft replacing conventional air conditioning.

For the circulation geothermal systems we proposed the formulae to evaluate the pumping rate needed for a required thermal capacity and the respective rise of the ground water level near the discharge point. On the example of flooded mine "Novogrodivska 2" in Donbas it was preliminary evaluated that the rising ground water level due to discharge of thermally used water to the mine will not reach the bottom of the upper aquifer, thus, not threatening the ground water quality.

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Оцінювання теплозабезпечення з підтримуванням безпечного рівня шахтних вод при експлуатації відкритих геотермальних систем у районах колишнього вуглевидобутку

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Мета. Оцінка ефективності роботи відкритих геотермальних систем на затоплених та дренованих шахтах Донецького басейну для забезпечення теплом будівель при підтримуванні безпечного рівня шахтних вод.

Методика. Розглянуто як циркуляційні, так і безповоротні геотермальні системи з використання тепла шахтних вод. Запропоновано енергетичні та вартісні критерії оцінювання ефективності відкритих геотермальних систем на основі порівняння виробленої теплової енергії з енергетичними витратами на її виробництво. Критерії використовують співвідношення термодинаміки, гідравліки, аналітичних формулах розрахунку фільтрації підземних вод та методиках розрахунку теплових потреб приміщень.

Результати. Оцінені діапазони теплової потужності від кількох десятків кВт до кількох МВт та коефіцієнту перетворення *COP* 3.5-6.8, що можуть бути досягнуті геотермальними системами для досліджених закритих шахт Донбасу, добре корелюють зі значеннями цих показників на працюючих в різних країнах відкритих геотермальних системах, що показує техніко-економічну доцільність їх встановлення для забезпечення місцевих потреб у тепловій енергії. Показана можливість повного забезпечення потреб у тепловій енергії на прикладі будівель з офісними приміщеннями для перебування кількох сотень осіб. Показано порядок розрахунку параметрів відбору шахтних вод із забезпеченням їх безпечного рівня з точки зору підтримування якості підземних вод на прилеглих до шахти територіях.

Наукова новизна. Розроблені критерії та методика розрахунку дозволяють реалістично визначати параметри ефективності експлуатації відкритих безповоротних і циркуляційних геотермальних систем з урахуванням гірничо-геологічних і технологічних умов, визначати пріоритетність освоєння геотермальних ресурсів шахт та оцінювати параметри циркуляції шахтних вод з підтримуванням їх безпечного рівня.

Практична значимість. Дослідження продемонструвало можливість створення та ефективної експлуатації відкритих геотермальних систем на шахтах Донецького басейну для забезпечення теплом будівель розташованих на прилеглих до них територіях та підтримання там безпечного рівня шахтних вод.

Ключові слова: *закрита шахта, шахтні води, водовідлив, теплова енергія, геотермальні модулі*