https://doi.org/10.33271/nvngu/2023-2/011

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AN APPROACH FOR RANKING ABANDONED MINES BY THE EFFICIENT USE OF THEIR GEOTHERMAL POTENTIAL

Purpose. To develop an approach for ranking abandoned mines in terms of the efficiency of mine water heat recovery by geothermal systems through applying the set of basic criteria; they allow considering geological and mining conditions in first approximation and preliminary assessing the performance of the systems located on them.

Methodology. The proposed approach includes the ranking of mines by five basic indicators usually available or easily calculated such as the conversion factor of heat pumps *COP*, energy balance, thermal capacity, profit of operation, and reduction of CO_2 emissions. The energy balance introduced by the authors earlier is defined as the relation of thermal energy produced to the thermal equivalent of electricity required for operation. These indicators are integrated in the complex rank to compare the expected performance and generate the priority lists for industrial installations in mines.

Findings. We ranked 27 abandoned coal mines in Donbas with available data by five indicators separately and the complex parameter defined through averaging their contributions. The top promising sites for open non-circulation, circulation, and closed loop systems in terms of efficient heat recovery were identified. These sites refer to mostly deep mines in the central part of Donbas with the enhanced geothermal gradient over 0.03 °C/m.

Originality. Firstly, an approach to evaluate the geothermal potential and ranking the mines regarding the efficiency of thermal energy use based on existing and introduced performance indicators has been substantiated and validated for a group of abandoned mines. The developed technique allows-analyz and preliminary quantify the feasibility of geothermal installations of different design.

Practical value. The proposed approach for ranking post-mining sites enables generating the priority lists with regard to recovery of low-grade energy from mine water, thus, identifying the geothermal potential and most promising sites for further detailed feasibility studies and operation of geothermal systems of various types.

Keywords: *abandoned mines, mine water, geothermal systems, heat recovery, operation efficiency, ranking*

Introduction. The prospects and feasibility of installing open loop and closed loop geothermal systems in abandoned coal mines were discussed in previous studies [1, 2]. The effectiveness of low-grade energy recovery from mine water was confirmed through practical experiences in various countries [3, 4]. Particularly, geothermal systems of a capacity up to a few MW in post-mining areas provide heating and hot water supply for a single consumer or a group of buildings near the active mine drainage or flooded shafts [5, 6].

However, prior to installing these systems in coalmining regions of Ukraine it is first necessary to identify the most appropriate sites, which can be done by comprehensive analysis with applying the various criteria employed in different studies for evaluating the performance and the output. In this regard, there is a growing need to analyze, compare and systematize the available parameters in order to elaborate the complex evaluation criteria with most crucial factors considering specific geological and mining conditions.

Literature review. The temperature of the coolant at the outlet on the ground (or its temperature before cooling in exchangers) T_0 is the common parameter often used to make the preliminary conclusions about the expected effectiveness of operation. The open loop designs involve mine water circulation, whereas the geothermal probes as closed loop systems use mostly the ethylene glycol solution. The fluid temperature in open loop circuits commonly varies in the range 12–50 °C, whereas it ranges in the probes from 7 to 25 °C [7, 8]. In both cases, the temperature depends on both natural factors (deep flux of the Earth, rock properties) and technology features (the water withdrawal depth or deepening the probe, pumping or flow rate, and design) [9, 10] (Table 1).

The fluid temperature allows to estimate the thermal output, and is included in calculations of other important indicators [11]. However, the input temperature is just an indirect characteristic of the efficacy in the whole because it does not quantify the energy production, consumption, and balance in total.

The capacity P_{th} often used to assess the performance efficiency varies up to 3600 kW in open loop designs and up to 70 kW in the probes [8, 9]. It strongly depends on the temperature, flow rate and fluid heat capacity, and looks universal because it is applicable to any kind of circulation. However, evaluation of P_{th} turns to be challenging due to uncertainties of the fluid temperature after cooling, because P_{th} depends not only on the initial temperature T_0 but also on the specifics of heat exchange and transportation, designs of supply networks, heating and power facilities.

For open systems that discharge cooled water to surface watercourses (non-circulation design) it is necessary to maximize extraction of thermal energy by cooling the fluid to the temperature of 6 °C; the unused low-grade heat is considered irrevocably lost. For open and closed loop designs with fluid circulation it is necessary to optimize temperatures for each case considering specific geological conditions and physicochemical reactions during operation.

On the one hand, the maximum possible decrease in the fluid temperature on the ground allows to gain additional energy; simultaneously, it leads to an increase in water density, thus, to growing the hydrostatic pressure in the injection well, which is called as the “thermal press effect”. On the other hand, excessive cooling of the circulating fluid increases its viscosity and may lead to salt precipitation. Hence, the temperature of the cooled fluid should be limited with a point below which there are no cost-effective ways of energy extraction under local climatic conditions.

The effectiveness of vertical and horizontal probes of different designs is often assessed with the specific extraction rate q_s defined as the heat extracted per a running meter; it depends on the same factors as the capacity, but it is applicable only to closed circuits. The value of q_s varies from 20 to 100 W/m depending on surrounding rock properties and the geothermal gradient [12]; besides, q_s may significantly vary along the probe length due to temperature variability in depth. This indicator does not directly quantify the energy effectiveness of heat recovery. Apart from q_s, the energy yield measured in kWh/(m · a) is

Table 1

Parameters to evaluate the efficiency of mine water/rock heat recovery by different geothermal systems

Parameter	Notation	Unit	System type (open loop, closed loop)	Influencing factors		Benefits	Parameter feature
				Natural	Technological		
Initial fluid temperature	T_0	°C	Both types	Heat flux, rock thermal conductivity	Withdrawal depth, flow rate, design	Applicable to all designs	Single
Thermal capacity	P_{th}	W	Both types	The same as above	Withdrawal depth, flow rate, design	Applicable to all designs	Single
Specific heat extraction rate	q_s	W/m	Closed loop	The same as above	Heat flux, flow rate	Simple evaluation of thermal capacity by the probe length	Single
Coefficient Of Performance	*COP*	–	Both types	Coolant temperature	Coefficient of pump efficiency, temperature in the heating system	Quantifies heat pump performance	Complex
Thermal and hydrodynamic efficiency	E	–	Closed loop	Heat flux, rock thermal conductivity	Withdrawal depth, flow rate, design	Quantifies the ratio of thermal energy produced und spent	Complex
Efficiency coefficient	η	–	Both types	The same as above	The same as above	Quantifies the share of thermal energy recovered	Complex
Energy ratio	ξ_E	–	Both types	The same as above	The same as above	Quantifies the energy efficiency of heat recovery	Complex
Cost difference between the energy produced and electricity spent	P	Monetary unit	Both types	The same as above	The same as above	Estimates the economic effect	Complex
Reduced CO_2 emission	E_{CO_2}	ton	Both types	Properties of fossil fuels	The same as above	Estimates the environmental effect	Complex

also employed in geothermal assessments; it can be easily calculated by multiplying q_s with appropriate coefficients.

The performance efficiency can be roughly assessed by the Coefficient of Performance (*COP*) that depends on the temperatures of the fluid in exchangers and in the heating circuit of buildings; in practice, *COP* varies from 2.5 to 6 [13, 14]. Although *COP* refers mostly to heat pump operation; it allows also comparing the performance of different geothermal systems operated under the same temperature in heating circuits.

Additionally, the efficacy of closed loop circuits can be quantified by the thermal and hydrodynamic efficiency E, which is often employed in calculations of heat exchangers [15]. It is defined as the ratio of two terms; the first one is the heat transferred to the fluid through the surface of the probe, the second one is the power spent to overcome the flow resistance in probe tubes. The denominator is expressed by the product of the volumetric flow rate and resistance.

The higher the value of E is, the more efficiently the probe is running and extracting heat from its surface, assuming other things being equal. The ratio E is dimensionless, so the numerator and denominator can be attributed to any unit of same dimension, for example, to the unit of heat transfer surface (thermal index), to the unit of mass (mass index) or to the unit of volume (volume index).

Regarding to the probe operation experience, the changes in flow velocity have different influence on the performance indicators under other equal conditions [16]. The heat transfer coefficient correlates with the flow velocity v_f in proportion to the degree of 0.6–0.8, the flow resistance is proportional to v_f with the degree of 1.7–1.8, the power for pumping the fluid is proportional to v_f with the degree of 2.75.

As the flow velocity increases, the pumping power increases much faster than the amount of energy recovered and transferred, i. e. the value of the E decreases with increasing fluid velocity for a certain probe with a certain surface. For this reason, the value of E cannot be an absolute measure of the thermal and hydrodynamic efficiency of a closed loop design; it should be analyzed in comparison of two or more systems only.

In addition to the coefficient E, the geothermal system performance can be evaluated by the efficiency coefficient η defined as the relation of the actual amount of heat transferred to its theoretical maximum. Sometimes this ratio may exceed 0.9 [16]. The maximum amount of thermal energy can be expressed as the product of flow rate and its volumetric heat capacity by the difference between the fluid inlet temperature and the ambient temperature. Despite a certain universality this criterion does not refer to the energy efficiency and quantifies just the share of recovered heat.

The authors proposed a more universal indicator to assess the effectiveness of both open and closed loop designs [1, 2]. It deals with the parameter ξ_E quantifying the energy balance in the geothermal system; ξ_E relates the thermal energy recovered to the thermal equivalent of electricity consumed by heat pumps and spent for fluid transportation and flow in tubes. It was suggested that the electricity required for operation is generated from fossil fuels (coal or gas), and the output of geothermal systems is compared with the thermal capacity of the fuel being burned in power facilities. Based on the physical essence of this relation, we formulated a criterion of geothermal system efficiency as $\xi_E > 1$. According to our calculations and assessments, the ratio ξ_E may vary from 0.8 to 4.2.

Despite some kind of universality, ξ_E does not quantify the economic and environmental aspects of mine water heat recovery. Therefore, we need to involve other indicators in the analysis also including the profit P and the reduction of carbon dioxide emission E_{CO_2}. The profit P in the first approximation can be defined as the difference between the cost of produced energy and the cost of electricity consumed in operation. The value of E_{CO_2} is calculated as the reduction in CO_2 emission into the atmosphere reached owing to the replacement of conventional power facilities burning fossil fuels with the heat exchangers recovering low-grade energy from mine water.

Unsolved aspects of the problem. Despite the existing variety of single parameters applicable to assess the effectiveness of mine water thermal use, till now there is still no well-grounded criteria set that would enable integrally analyzing relevant technology features, energy balance, as well as economic and environmental aspects. In addition, most of the indicators discussed above do not refer to the costs of generating power for running heat pumps and circulating fluids in geothermal systems.

The above review of parameters and criteria revealed that evaluations to identify most promising mining sites for industrial installation should include the conversion factor *COP*, the energy ratio ξ_E, thermal capacity P_{th}, CO_2 emission reduction E_{CO_2} together with the profit *P*. The set of these indicators would allow comprehensively analize recovery costs, required spends, expected environmental effect, which is necessary to rationally select the sites for detailed feasibility studies before equipment installation.

In this regard, **the purpose of this study** is to develop an approach to rank abandoned mines in terms of their priority of installing open and closed loop geothermal systems by applying the set of basic criteria that allow to consider in first approximation technical, geological, mining conditions and preliminary assess the performance efficiency. The top of the priority list can be interpreted as the most promising sites for further explorations.

Methods. Among the parameters quantifying the efficiency of heat recovery in abandoned mines, the heat flux, rock thermal conductivity, withdrawal depth (or probe length), flow rate, and geothermal system designs (Table 1) have been identified as the most influencing. The method outlined below aims to integrate all these indicators for ranking the potential sites. Such an approach allows to study the patterns of heat recovery efficiency depending on local conditions. The approach was validated for the Donetsk coal basin, where most of abandoned mines in Ukraine are located.

To evaluate the deep geothermal flux, the previously generated map [17] has been combined with mine locations as shown in [1]. According to the statistical treatment, the geothermal gradient within this area varies from 0.0278 to 0.0389 °C/m (Fig. 1), with the specific geothermal flux *q* varying from 50 to 70 mW/m^2.

In addition to the geothermal flux, we estimated the distance L_{min} to potential local consumers of thermal energy and expected heat losses during transportation in the supply network. The parameter L_{min} is defined as the distance between the water hoisting location to the nearest residential area in a nearby settlement with the heat demand comparable to the estimated thermal capacity of the geothermal system [1, 3].

To properly calculate the heat loss P_{wt} in supplying pipelines to potential consumers we followed the recommendations [18] that evaluate its specific normative value per pipe running meter at 15–20 W/m assuming the open-air insulated pipes with a diameter of 100–150 mm and the average fluid temperature of 55 °C. Thus, P_{wt} was calculated by multiplying the maximum specific loss (20 W/m) by the minimum distance L_{min} to heat consumers.

The initial mine water temperature T_0 was evaluated as the mean value of temperatures at the upper and lower bounds of the flooded interval (Fig. 2) considering the thickness of overlaying and carboniferous rocks, the geothermal gradient as well as water cooling at 1 °C in the shaft when pumping up mine water to the ground. Similar to the assumption in [19], the volume of workings is assumed to be evenly distributed within the mined-out space; mine water from different horizons is mixed in the withdrawal point. These assumptions are in line with the modeling of hydraulic flow and heat transport in an open loop geothermal system. In the study (Rudakov and Inkin, 2021), it was proved that the mixed water temperature under a steady regime depends primarily on flow resistance in workings rather than on the withdrawal point position. Therefore, if workings are evenly distributed, we can average the rock temperature in the flooded interval for preliminary calculations. In the case of uneven distribution of workings in this interval, the estimated values may deviate by a few degrees Celsius from the average temperature.

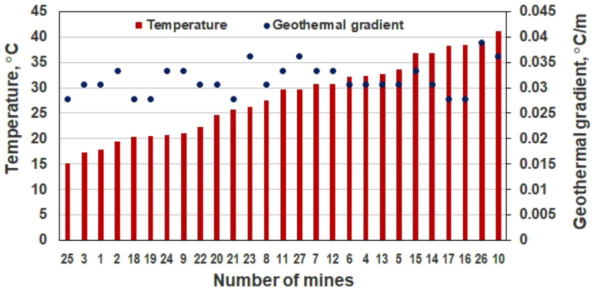

Fig. 1. The estimated values of mine water temperature in the flooded interval combined with the geothermal gradient in the mines:

1 – Selidivska; 2 – Novohrodivska 2; 3 –D.S. Korotchenko; 4 – Izotov; 5 – Oleksandr Zakhid; 6 – Kondratyevka; 7 – Vuhlehirska; 8 – Bulavinska; 9 – Olkhovatska; 10 – Rumiantsev; 11 – Artyom; 12 – Gagarin; 13 – Komsomolets Donbasu; 14 – Lenin; 15 – Kocheharka; 16 – Karl Marx; 17 – Chervonyi Profintern; 18 – Poltavska; 19 – Yenakiievska; 20 – Rodina; 21 – Pervomaiska, 22 – Kirov; 23 – Sokolohorovka; 24 – Holubovska; 25 – Bezhanivska; 26 – Haievoy; 27 – 60 years of Soviet Ukraine

It should be noted that the mine water levels identified by [20] and latest reports in Fig. 2 were valid in 2019 and now may differ; besides, the local tariffs for heat and electricity may have changed. However, these circumstances do not reduce the relevance of this approach because it focuses on a methodology for ranking sites in terms of geothermal system feasibility rather than exact calculation of priority indexes for mining sites.

Statistical treatment of the geothermal gradient distribution over 27 mines with available data (Fig. 1) enabled revealing the higher variability in the mine water temperature compared to the geothermal gradient and specific geothermal flux due to the influence of geotechnical conditions – primarily, depth of workings – against more stable natural conditions. The correlation coefficient between temperature and specific geothermal flux of 0.46 was found to be statistically significant at a confidence level of 98 %. Despite the higher variability of geotechnical conditions, a larger geothermal gradient looks preliminary as a favorable factor for installation.

Most of the mines selected for comparison are located across the area of mining cities of Ukraine (Novohrodivka, Horlivka, Yenakiieve) or nearby. Here the heat consumers are often in the proximity of potential locations of geothermal systems able to produce thermal energy. According to measurements using the Google Map tools, the distance to local heat consumers $L_{\max}$ with a significant energy demand often does not exceed 1.6 km, which may cause heat loss when transportation is below 32 kW. This value looks acceptable for open systems with a thermal capacity P_{th} over 500 kW intended for heat supply of residential and commercial buildings in settlements in the close vicinity of water hoisting points. However, the same distances would be unacceptable for the systems of low thermal capacity P_{th} below 200 kW, mostly of closed loop systems like the probes; they should be installed as close as possible to consumers located directly within the post-mining areas.

Among all parameters in Table 1, the energy ratio ξ_E looks quite universal, as it evaluates the energy balance within the geothermal system involving both geotechnical (flood zone, drainage, etc.) and geothermal parameters; at the same time, it can also be used for estimating economic and environmental effects. However, the other parameters due to their prevalence should also be included in estimations of energy recovery. For this reason, all five previously discussed indicators (COP, P_{th}, ξ_E, P, E_{CO_2}) are proposed to include in evaluations and ranking the potential sites.

The basic indicators for ranking are the COP and thermal capacity P_{th}, these are included in the ratio ξ_E to calculate the energy balance in a geothermal system. The economic parameter P and the reduction of CO_2 emission E_{CO_2} are calculated based on P_{th} and ξ_E with the inclusion of tariffs and fossil fuel combustion indicators. Thus, the profit P and emission reduction E_{CO_2} depend on the previous three parameters; alongside with this they depend on additional factors that have to be considered as well.

Therefore, the ranking of mines in terms of heat recovery effectiveness is performed with five aforementioned indicators separately plus the complex indicator K_Σ defined as follows

$$K_\Sigma = \frac{K_{COP} + K_{Pth} + K_\xi + K_P + K_{ECO_2}}{5K_{\Sigma,\max}} \cdot 100\,\%,$$

where K_{COP}, K_{Pth}, K_ξ, K_P, K_{ECO_2} are the ranks of an evaluated site (mine) in ascending order in the general list sorted by the relevant parameter value; $K_{\Sigma,\max}$ is the maximum value of the rank that coincides with the number of list items (here is the number of mines selected for analysis). In the studied case $K_{\Sigma,\max} = 27$.

Introducing a relative scale and using the ranks of individual parameters allows, in combination with the overall ranking, to highlight the individual benefits and features of sites in various aspects of geothermal system performance.

The following assumptions were made when performing the assessments:

- mine water is withdrawn 10 m below its level in the shaft;
- technological and design parameters of pumps for raising water up to the ground are the same for all selected sites and open geothermal systems;
- in non-circulation open geothermal systems, electricity costs for pumping mine water are not included in consideration because they are already accounted in the water management costs needed to maintain a hydrodynamically safe mine water level;
- geothermal probes are installed through the whole thickness of the flooded interval;
- the thermal potential of mine water is fully used on the ground with cooling water to the temperature of 6 °C;
- heat losses during transportation to local consumers are included in calculations of the thermal capacity of open systems but ignored for closed loop systems because the latter are reasonable to install near to the water hoisting points only;
- the profit of thermal energy and reduction of CO_2 emission are calculated for the heating season that lasts 3600 hours (150 days);
- capital costs are not considered as they mostly depend on equipment features.

Results. At first, ranking the mines was performed for open loop systems with the discharge of thermally used water into surface watercourses (non-circulation systems) at the existing flow rates Q [20] (Table 2, Fig. 3).

The estimated maximum thermal capacity of these systems ranges from 1.56 to 24.41 MW (mean value 11.09 MW), COP

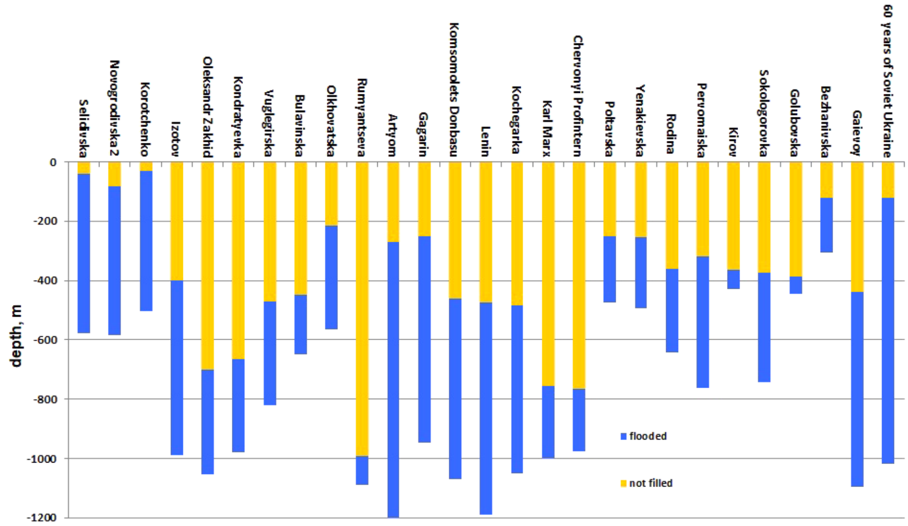

Fig. 2. The water level in the selected mines of Donbas

Table 2

Initial data for ranking potential open non-circulation geothermal systems in Donbas

No.	Mine	Q, $10^6\ m^3/a$	P_{th}, MW	COP	ξ_E	P, thousand UAH*	E_{CO_2}, kt
1	Novohrodivska 1-3	3.74	14.04	7.88	3.50	62.46	9.91
2	Artyom	4.20	13.23	6.47	2.88	56.91	8.52
3	Holubovska	2.93	5,76	4.79	2.13	23.12	3.02
4	Kirov	0.96	2.09	5.03	2.23	8.50	1.14
5	Lenin	1.65	6.78	9.05	4.02	30.77	5.03
6	Vuhlehirska	6.35	20.87	6.74	3.00	90.46	13.73
7	Poltavska	0.82	1.56	4.73	2.10	6.25	0.81
8	Chervonyi Profintern	5.70	24.41	9.74	4.33	111.74	18.53

* per season, calculated for the end of 2021

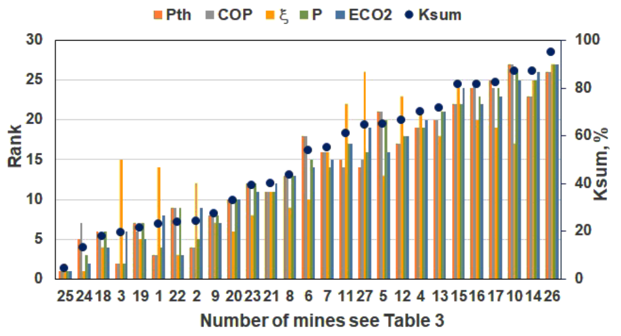

Fig. 3. Results of ranking the open non-circulation geothermal systems that can be installed in abandoned mines

from 4.73 to 9.74 (mean value 6.08); the energy ratio ξ_E from 2.1 to 4.33 (mean value 3.02). Using gas instead of coal as a fuel to generate electricity should enhances the energy efficiency of heat recovery by about 20 % due to the higher caloric capacity of gas.

The highest efficiency is expected for the mines Chervonyi Profintern ($\xi_E = 4.33$) and Lenin ($\xi_E = 4.02$) due to the intensive drainage and higher water temperature compared to other sites; these mines also have the highest *COP*. The expected thermal capacity of the system at the mine Vuhlehirska is ranked the second in the list (20.87 MW) due to the large amount of drainage water (6.35 million m^3/year). However, the relatively low mine water temperature (mean value 20.87 °C) positions this site only at 5*th* position. The highest values of the complex indicator K_Σ have been calculated for the mines Chervonyi Profintern (K_Σ = 100 %), Vuhlehirska ($K_\Sigma = 77.5$ %), and Novohrodivska 1-3 ($K_\Sigma = 75$ %).

The selected mines have been also ranked for the case of open circulation systems with the discharge of thermally used water back to the mine. The same assumptions as for non-circulation systems above have been made; we assumed a pumping rate of 250 m^3/d in calculations.

The open circulation systems look less efficient as compared to non-circulation ones due to a significantly lower thermal capacity and additional electricity costs to maintain the mine water circulation (Table 3, Fig. 4).

The coefficient *COP* of open circulation systems varies in a wider range 4.12 to 11.76, with the mean value 6.66 close to its value for non-circulation systems of 6.08. The thermal capac-

Table 3

Initial data for ranking potential geothermal systems in abandoned mines of Donbas (H_{dr} is depth of water withdrawal, H_w the thickness of the flooded interval)

No.	Open loop circulation systems						Closed loop systems					
	H_{dr}, m	P_{th}, kW	*COP*	ξ_E	*P*, thousand UAH per season	E_{CO_2}, tons	H_w, m	P_{th}, kW	*COP*	ξ_E	*P*, thousand UAH per season	E_{CO_2}, tons
1	51.5	133.6	4.41	1.79	507.5	58.1	536	33.8	3.66	1.47	73.0	10.71
2	93.6	139.1	4.61	1.75	524.0	58.7	501	35.7	3.68	1.48	76.7	11.49
3	40	124.3	4.36	1.79	472.5	54.3	475	29.0	3.61	1.45	63.5	8.93
4	410	295.7	7.23	2.07	1177.0	151.0	590	80,1	4.19	1.70	150.1	32.58
5	712	320.0	7.68	1.76	1208.8	136.5	353	50.2	3.83	1.52	104.9	17.05
6	675	287.0	7.16	1.65	1059.2	112.0	315	42.3	3.74	1.48	90.8	13.65
7	482	273.9	6.74	1.81	1045.6	121.4	348	44.4	3.77	1.51	93.7	14.83
8	457	244.5	5.95	1.64	899.4	94.3	203	22.6	3.55	1.39	51.8	6.29
9	224	161.7	4.84	1.57	584.1	57.9	351	28.0	3.60	1.44	61.9	8.44
10	1002	401.9	11.76	2.00	1584.1	198.8	98	17.6	3.50	1.28	43.9	3.76
11	280	269.5	6.47	2.10	1076.4	139.3	930	113.7	4.68	1.90	190.3	53.26
12	261	275.2	6.77	2.22	1116.5	149.4	697	89.4	4.31	1.76	162.0	38.09
13	472	309.7	7.33	2.02	1223.2	154.3	608	83.5	4.23	1.72	155.0	34.37
14	484	359.2	9.05	2.41	1487.1	207.4	716	113.6	4.68	1.90	190.2	53.20
15	493	344.4	9.02	2.34	1416.8	195.0	567	89.8	4.32	1.76	163.1	38.17
16	766	361.8	9.88	2.04	1434.5	182.5	244	40.6	3.73	1.47	87.8	12.85
17	776	368,8	9.74	2,04	1460.5	185.4	209	34.5	3.66	1.44	76.5	10.35
18	262	158.0	4.73	1.47	554.2	49.7	223	16.9	3.50	1.37	39.1	4.54
19	263	159.5	4.77	1.48	561.5	51.0	240	18.5	3.51	1.38	42.6	5.08
20	371	201.5	5.39	1.55	724.0	70.5	282	27.3	3.59	1.43	61.0	8.06
21	328	210.0	5.61	1.68	779.9	84.0	446	45.9	3.78	1.52	95.9	15.57
22	375	172.9	5.03	1.40	592.4	48.5	63	5.4	3.39	1.20	14.5	0.88
23	384	218.3	5.71	1.63	801.9	83.7	368	38.8	3.71	1.49	83.2	12.53
24	397	149.5	4.79	1.25	483.1	29.8	57	4.4	3.39	1.14	12.4	0.55
25	130	95.3	4.12	1.39	326.2	26.6	187	9.3	3.43	1.33	22.2	2.29
26	449	378.4	10.22	2.72	1610.1	236.5	656	111.0	4.64	1.89	187.2	51.64
27	130	257.8	6.48	2.44	1070.2	150.1	898	110.3	4.62	1.89	186.0	51.25

[*] See the names of the mines in the caption of Fig. 1

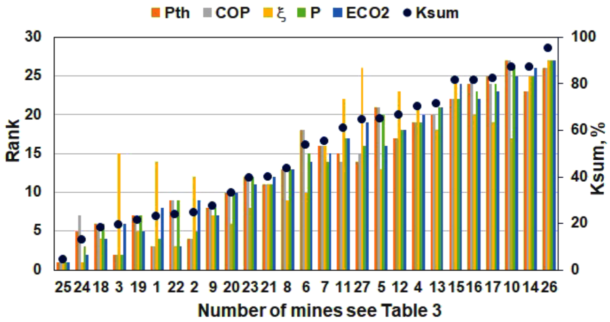

Fig. 4. Ranking open circulation systems that can be installed in abandoned mines

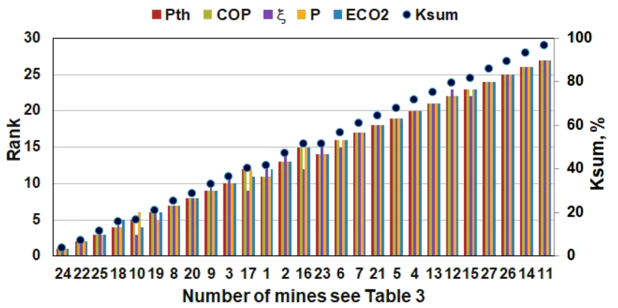

Fig. 5. Results of ranking closed loop systems that can be installed in abandoned mines

ity of circulation systems was found to depend primarily on the flow rate.

The mean value of ξ_E for circulation systems 1.85 is noticeably lower than 3.02 for non-circulation ones for the same sites due to ignoring energy expenses for mine drainage. In total, ξ_E varies from 1.25 to 2.72 through all 27 mines. The highest value of ξ_E for circulation systems 2.72 is calculated for the mine Haievoi; and the highest $COP = 11.76$ is expected for the mine Rumiantsev. The lower energy parameter for this mine is due to the need for deepening the pump for water withdrawal and the associated additional energy costs with regard to a slight increase in the mine water temperature by only 2.1 °C.

Five most promising sites to install circulation systems include the mines of Haievoi ($K_\Sigma = 95$ %), Rumiantsev ($K_\Sigma =$ $= 87.1$ %), Lenin ($K_\Sigma = 87.1$ %), Chervonyi Profintern ($K_\Sigma =$ $= 82.1$ %), and Karl Marx ($K_\Sigma = 81.4$ %). The higher the geothermal gradient for a site is, the higher are the ranks of all the indexes. In contrast, the withdrawal depth H_{dr} has a dual effect on the index K_Σ. On the one hand, deepening the pump leads to an increase in the temperature of pumped mine water, thus, increasing the rank of P_{th} and COP; on the other hand, a deeper pump position increases electricity costs for pumping, and hence, reduces the ranks of ξ_E, P, and E_{CO_2}. The maximum thermal capacity over 350 kW can be reached at the mines Rumiantsev, Haievoi, Chervonyi Profintern, Karl Marx, and Lenin, owing to high mine water temperature.

The mine Haievoi was identified on the priority list top with the highest rank for ξ_E, P, and E_{CO_2} although its geothermal gradient of 0.036 °C/m is lower than at the mine Rumiantsev of 0.039 °C/m (Fig. 1). Along with this, the ranks of the mine Rumiantsev for P_{th} and COP are the second due to a deeper position of water withdrawal $H_{dr} = 1002$ m as compared to the mine Haievoi with $H_{dr} = 449$ m (Table 3) that has the ranks in these parameters equal to 27. Thus, even though the geothermal gradient at the mine Rumiantsev reaches the maximum among the selected mines, this mine was ranked the second due to the adverse impact of pumping depth on P_{th} and COP.

The mines Rumiantsev and Lenin were ranked with the same K_Σ at the second and third positions in the priority list for open circulation systems. The Lenin mine with an estimated geothermal gradient of 0.033 °C/m and $H_{dr} = 484$ m was ranked *23rd* for P_{th} and COP, and *25th, 25th*, and *26th* for ξ_E, P and E_{CO_2} respectively.

In addition to open circulation systems, we performed the same analysis to closed loop systems based on geothermal probes (Table 3, Fig. 5). We performed calculations for coaxial probes of average thermal resistance $R_{th,cx,av}$ 0.2 m·°C/W and specific pressure loss of 1 mbar per 1 m of probe plus 30 mbar in the heat exchanger tubes on the surface. The maximum temperature in the heating circuit was taken 55 °C, heat pump efficiency 0.5; the duration of the heating period is 3600 hours. Besides, coal was assumed to be a fuel used for power generation when evaluating CO_2 reduction potential.

The assumed value of $R_{th,cx,av}$ falls in the range of the thermal resistance for coaxial probes but do not reach the minimum, hence, the estimates of thermal capacity P_{th} and energy efficiency ξ_E should be regarded as conservative. Changing $R_{th,cx,av}$, if applied to all mining sites, leads to changing the absolute values of thermal capacity but does not affect the order of potential sites in the priority list; this order depends solely on the relations of calculated parameters for different sites.

The specific heat extraction rate of coaxial probes varies from 49.8 to 179.4 W/m at a mean value of 115 W/m, which exceeds several times the values of this parameter for near-surface geothermal probes. This is due to the deeper positioning of potential probe locations and the higher temperatures around the probes. The COP of heat pumps for geothermal probes varies in the range from 3.39 to 4.68 with an average value of 3.86, which is below the same values for open non-circulation (5.07) and circulation (4.88) systems.

Five top promising sites from the priority list for closed loop geothermal systems with the highest K_Σ include the mine Artyom ($K_\Sigma = 96.4$ %), Lenin ($K_\Sigma = 92.9$ %), Haievoi ($K_\Sigma =$ $= 89.3$ %), 60 years of Soviet Ukraine ($K_\Sigma = 85.7$ %), and Kocheharka ($K_\Sigma = 81.4$ %). In contrast to open circulation systems, mainly three factors (geothermal gradient, flooded zone interval and depth to the mine water level) influence P_{th}, COP, ξ_E, P, and E_{CO_2}; this changed the top of the generated priority list. The same as for open non-circulation systems, the geothermal gradient heightens the ranks, whereas the flooded interval and the pumping depth have a dual effect. On the one hand, increasing H_w and H_{dr} leads to an increase in pumped water temperature, thus increasing ξ_E, P and E_{CO_2}; on the other hand, this raises electricity costs for pumping, thus reducing these parameters.

The partial ranks for P_{th}, COP, ξ_E, P, and E_{CO_2} strongly correlate with each other for closed loop systems with the correlation coefficients over 0.98; four top sites in the priority list have the same partial ranks equal to the common rank of K_Σ. For example, the mine Artyom on the top has all ranks equal to 27, the item in the list mine Lenin has all ranks of 26 and so on till the *5th* position. In contrast, the priority list of open circulation systems demonstrates a noticeable deviation for the correlation coefficients between ξ_E and other parameters of 0.7–0.76, whereas these coefficients among other parameters exceed 0.98. Lower correlations between the energy ratio ξ_E and other parameters are due to a higher impact of geotechnical and mining factors (power generation, pumping depth, flooded interval, etc.).

Generally, the results of ranking the potential sites for coaxial probe installation are similar to those for open loop circulation systems except ξ_E. In contrast, ranking of open non-circulation systems leads to other priorities due to a more significant impact of the pumping rate, whereas the performance of all circulation systems depends more on relatively stable geothermal conditions, particularly, the temperature field in depth.

Conclusions. Ranking and identification of most promising sites for geothermal system installation in terms of heat recovery efficiency is proposed to perform with the heat pump conversion factor *COP*, thermal capacity, the energy balance of the system, profit of system operation, and CO_2 emission reduction. The energy balance is evaluated by the relation of produced thermal energy to the thermal equivalent of electricity required for maintaining the operation. These five parameters allow one to integrate the performance indicators of geothermal systems, thus, quantify relevant technological, energy, economic and environmental aspects using basic available parameters.

Ranking abandoned mines has been performed for 27 sites in Donbas with available data with five parameters separately and with the complex parameter K_{Σ} defined through the contributions of partial indexes. As a result of calculations, we identified the ranks of the sites in terms of heat recovery efficiency with open non-circulation and circulation system and closed loop geothermal systems as well.

Three top priority sites for open non-circulation systems are the mines Chervonyi Profintern, Vuhlehirska, and Novohrodivska 1-3; three top priority sites for open circulation systems include the mines Haievoi, Rumiantsev, and Lenin; the top promising sites for closed loop systems are the mines Artyom, Lenin, and Haievoi. These sites refer mostly to deep mines in the central part of Donbas with enhanced geothermal gradient over 0.03 °C/m.

The results of ranking the mines by efficiency of heat recovery enable prioritizing the sites considering technical, economic, and environmental aspects, thus, drawing preliminary conclusions on the technical and economic feasibility of geothermal installations and quantifying the potential of post-mining areas. Although mining and hydrodynamic conditions in the studied area might have changed since the data were received, the proposed approach of ranking the mines remains valid and applicable with refined data.

The proposed technique with appropriate modifications can be applied also to active coal mines and other sites, including non-coal mines and ground source heat pumps. The proposed approach is therefore regarded as the first step to a comprehensive assessment using rough data for all sites. On the one side, in case of adding more information it can be supplemented by evaluations of the flows between adjacent mines, capital costs, refining the heat demand of local consumers, payback period etc. On the other side, a more detailed evaluation technique may run across the lack or the uncertainty of data; in this regard the proposed approach looks balanced for the initial level of information on mining sites and can be of interest for potential investors. The next step of this approach may be feasibility studies on identified priority sites.

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Підхід до ранжування закритих шахт відносно ефективності використання їх геотермального потенціалу

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Мета. Розробка підходу до ранжування закритих шахт стосовно ефективності вилучення тепла із шахтних вод геотермальними системами, заснованого на застосуванні набору основних критеріїв, що дозволяютьураховувати в першому наближенні геологічні й гірничі умови, а також попередньо оцінювати ефективність експлуатації розташованих на них систем.

Методика. Запропонований підхід включає ранжування закритих шахт за п’ятьма основними показниками, що зазвичай доступні або легко розраховуються: коефіцієнт перетворення теплових насосів *COP*, енергетичний баланс, теплова потужність, прибуток від експлуатації та скорочення викидів CO_2. Енергетичний баланс, уведений авторами раніше, визначається як відношення виробленої теплової енергії до теплового еквіваленту електроенергії, необхідної для роботи системи. Ці показники інтегровані в комплексний показник, що використовується для порівняння очікуваної ефективності та створення списків пріоритетності встановлення промислових систем на шахтах.

Результати. Ранжування 27 закритих вугільних шахт Донбасу виконано за наявними даними з використанням п'яти зазначених параметрів окремо й комплексного показника, визначеного через осереднення значень усіх параметрів. Визначені найбільш перспективні ділянки для розміщення закритих, відкритих безповоротних і циркуляційних геотермальних систем із точки зору ефективності вилучення тепла. Це, переважно, стосується глибоких шахт у центральній частині Донбасу з підвищеним геотермальним градієнтом понад 0.03 °С/м.

Наукова новизна. Уперше для групи шахт було обґрунтований і протестований підхід до оцінки їх геотермального потенціалу й ранжування з точки зору ефективності використання теплової енергії на основі існуючих і уведених параметрів експлуатації. Розроблена методика дозволяє аналізувати й попередньо кількісно оцінювати доцільність роботи геотермальних установок різної конструкції.

Практична значимість. Запропонований підхід до ранжування колишніх ділянок із видобутку вугілля дозволяє сформувати списки пріоритетності вилучення низькопотенційної енергії із шахтної води, таким чином визначити геотермальний потенціал і найбільш перспективні ділянки для подальших детальних техніко-економічних обгрунтувань і експлуатації геотермальних систем різних типів.

Ключові слова: *закриті шахти, шахтні води, геотермальні системи, вилучення тепла, ефективність експлуатації, ранжування*

The manuscript was submitted 24.03.22.