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VALIDATION OF THE OPERATION EFFICIENCY CRITERIA FOR GEOTHERMAL PROBES IN FLOODED MINE WORKINGS

Purpose. To develop and test the energy and cost criteria for evaluating the operation efficiency of a closed geothermal system using coaxial or U-shaped probes that can be installed in flooded workings of mines.

Methodology. To justify the energy and cost criteria, we applied thermodynamic, hydraulic and cost-efficiency relationships, conducted the engineering analysis of closed geothermal systems, studied hydrogeological settings and geothermal conditions of the mines of the Selidovo group in Donbas. The developed criteria were examined within the ranges of key parameters such as the flow rate of the heat transfer fluid and the probe submerged length.

Findings. We quantified the influence of the probe submerged length and the heat transfer fluid flow rate on the energy balance and the net present value NPV and identified the parameter combinations that allow achieving efficient heat recovery in terms of energy balance and cost-efficiency. The produced/spent energy ratio may reach $1.5-2.2$ and the $NPV -$ a few dozen thousand € when increasing the submerged depth to 500 m at the flow rate of 20 m^3/d. A higher flow rate may lead to a negative energy balance but the NPV remains positive within some ranges of the probe submerged length, thus, indicating the system profitability. The payback period can be shortened to a few years.

Originality. The proposed energy criterion balances the thermal energy produced and the thermal equivalent of electric energy generated using fossil fuel and spent on system operation. This ratio as distinct from the usually applied COP parameter allows comparing the energies of the same nature and drawing more adequate conclusions on environmental acceptability of a geothermal system.

Practical value. The proposed criteria can be used for prioritization of geothermal system installation and the operation efficiency evaluation among the number of potential sites in post mining areas.

Keywords: *mine water; geothermal probes, energy criteria, thermal energy, net discount value*

Introduction. In accordance with the provisions of the UN International Convention (Paris Charter, 2015), the renewable energy sources including geothermal energy have been recognized as one of the priorities and an effective tool in combating global climate change [1, 2]. Along with this, geothermal systems like the other facilities generating "green energy" have both the advantages and downsides in terms of practical application [3]. For this reason, geothermal system installation at any specific site should be justified by a comprehensive analysis with comparing the efficiencies of alternative and conventional facilities taking into account the energy balance and economic dimension.

Such an analysis is especially important when studying the feasibility to explore a huge thermal resource of closed mines. The annual discharge of pumped mine water with a temperature of $16-20$ °C after shutdown of many coal mines in Donbas is estimated at hundreds of millions of m^3. According to the data of Production Association "Ukrheolohiia" [4], the estimated thermal potential of low-mineralized mine water (below 3 g/dm^3) in Ukraine for an annual discharge of 467.3 million m^3 exceeds 834.5 Gcal/h, which is equivalent to a capacity of 970.5 MW. Geothermal applications in post-mining areas, in contrast to deep-borehole geothermal systems, do not require large capital costs for drilling and provide a possibility of relatively cheap pumping of warm water at a temperature of $30-35$ °C from depths of up to 1 km. It should be noted that a large amount of water should be pumped in any case to maintain a safe mine water level in terms of keeping quality of ground water in overlying aquifers.

Literature review. With the regard to these advantages mine water heat recovery is becoming more widespread in the post-mining areas of Europe and the United States, which reduces fossil fuel consumption and facilitates "green energy" development [5]. Currently almost 30 geothermal systems installed at closed mines with thermal capacity of 0.35 to 4.6 MW are under operation in different countries, most of them are situated in the Ruhr coalmining area of Germany [6].

The experience of geothermal system operation at closed mines revealed a few challenges [7, 8]. The first one is to ensure environmentally safe and sustainable long-term heat recovery with maintaining a safe mine water level to avoid trapping mine water to the overlying aquifers used for water supply; secondly, it is necessary to maintain the system efficiency that reduces in time due to discharge of cooled water back to the mine after thermal use. This requires a detailed feasibility study on hydrogeological and geothermal conditions, based on the predictive modeling of flow and temperature changes underground, balancing the created thermal capacities with the local demands of existing and prospective consumers of thermal energy, and taking into account seasonal fluctuations in temperature and energy consumption.

In addition, existing designs do not fully take into considerations the consequences of using mineralized water as a coolant with a high salt content. The lack of appropriate engineering solutions to these challenging issues leads to the fact that currently the available geothermal potential of closed mines in Ukraine with the exception of the mine "Blahodatna" in Western Donbas is hardly used.

In the case of moderate mine water temperature slightly below 20 °C heat pumps can be used not only for producing thermal energy in the heating season but also for cooling and air conditioning in the summer as it is done at the Barredo mine in Spain. Such a way of using mine water looks promising under climatic conditions of Donbas with warm summers and rising summer temperatures in recent decades due to climate change.

Generally, geothermal systems for heat recovery at the mines can be divided into two groups:
- open systems with pumping mine water to the ground surface and discharge of thermally used water to surface watercourses or back to mines at a certain distance from the pumping point;
- closed systems based on geothermal probes with the heat transfer fluid circulating isolated from surrounding rocks or mine water; the probes can be installed both in the upper part of the backfilled mine shaft or degassing boreholes or submerged in mine water in flooded underground workings.

On the one hand, open systems provide much higher thermal output owing to more intensive pumping. On the other hand, these systems use the mine water with suspended particles, salts and the substances chemically aggressive to metals as the heat transfer fluid. Thus, open system operation under strict environmental and technical requirements needs installation of an additional heat exchange circuit with another fluid, which reduces the profitability of energy production. In addition, open systems become profitable in case of high demand on thermal energy near the mine, which is often unachievable.

In contrast, closed geothermal systems are less powerful [9], but the probes can be installed in almost all suited vertical mine workings and wells within the mine, thereby increasing the total thermal capacity. Besides, close systems do not disturb hydrochemical fields; they are much less expensive than open ones and can be used to heat local low-capacity facilities such as individual buildings, greenhouses, single storages located near the unused workings. Despite these advantages there are only a few examples of operating closed geothermal systems in post-mining areas [10], which, however, have not become widespread yet.

Purpose. In this regard, the purpose of the study is to develop and test the criteria for evaluating the efficiency of geothermal probe operation of different design that can be installed in watered parts of flooded mines for heat recovery.

Materials and methods. The generalized design of the most common closed systems with geothermal probes is depicted in Fig. 1; the values of key thermodynamic and technical parameters are brought together in Table.

The parameters H_{mw} and H_w meet the conditions of the Selidovo group of mines in Donbas; the specific heat output of a probe is taken according [11].

The distances between geothermal system elements depend on locations of mine workings, facilities, and infrastructure at specific mines; the efficiency of system operation are to be evaluated by thermodynamic and hydrodynamic modeling.

Commonly, a closed geothermal system includes coaxial or U-shaped probes installed in flooded vertical workings of the mine; the heat transfer fluid (25—38 % aqueous solution of ethylene glycol) circulates in the probes. At the heat pump outlet on the ground the fluid has a temperature T_1 lower than the temperature of mine water around the probe. Heat flux q from completely or partially flooded disturbed rocks warms the heat transfer fluid to a temperature T_2. Thermal energy gained underground is recovered in the heat pump evaporator and the cooled fluid is then injected into the probe with the initial tem-
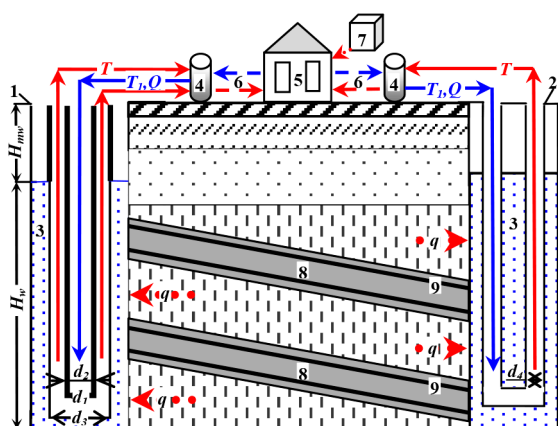
Table

Thermodynamic and technical parameters for evaluations of closed geothermal systems

Parameter	Notation	Range	Unit
Temperature of the heat transfer fluid after cooling	T_1	6	°C
Flow rate of the heat transfer fluid in the probe	Q	20—40	m³/d
Depth to the mine water level	H_{mw}	20—80	m
Flooded zone thickness of the mine	H_w	100—500	m
The inner diameter of the inner tube (coaxial probe)	d_1	0.03—0.05	m
The outer diameter of the inner tube (coaxial probe)	d_2	0.07	m
The inner diameter of the outer tube (coaxial probe)	d_3	0.1—0.14	m
The inner diameter of the tube of the U-shaped probe	d_4	0.03—0.07	m
Specific heat output per running meter of a probe	q_p	45—60	W/m
Temperature in the heating system of buildings	T_{hs}	40—60	°C

perature T_1. The heat recovered is supplied to consumers through the heating circuit and the hot water supply system. To cover the peaks of thermal energy consumption by buildings in the cold season, a backup boiler house running with traditional energy sources (coal, gas) is put into operation in winter.

In practice, to assess the efficiency of heat pump operation the conversion factor of energy (Coefficient of Performance *COP*) defined as the ratio of the heat output produced to the electrical energy consumed is used [12]. Despite the common use of *COP* it does not take into account the cost of electricity required for fluid circulation with regard to pressure losses due to hydrodynamic resistance in the probe, which is especially important for the probes submerged to the depths of hundreds of meters. With account for electric energy consumption required for heat pump operation the efficiency of geothermal systems may prove to be somehow overestimated in comparison to conventional power facilities [13, 14].

In view of the above remarks, the energy criterion to evaluate the efficiency of a geothermal probe is proposed to define as the ratio ξ_E of the thermal energy produced by the heat pumps $P_{hp,th}$ taking into account its losses during transportation U_{tr} to the thermal equivalent of electrical energy required for operation

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

where ω is the thermal equivalent of electricity; $P_{p,el}$ is the electrical power needed to pump the coolant through the geothermal probe; $P_{hp,el}$ is the power consumed by heat pumps; $P_{tr,el}$ is electrical power consumed for heat transportation to consumers, Δt_{op} is the operating time.

In terms of energy balancing the operation of geothermal systems makes sense if $\xi_E > 1$.

To estimate the thermal equivalent of the electric power required to provide fluid circulation in the geothermal probe and heat pump operation, it is assumed that electricity is generated by thermal power plants using coal or gas as fuel. Then the thermal equivalent ω can be calculated as

$$\omega = \frac{\eta_h}{\eta_{TPP}},$$

Fig. 1. Generalized design of a closed geothermal system with coaxial (1) and U-shaped (2) probes within the flooded zone (3) of the mine:

4 — heat pump; 5 — heat consumers; 6 — direct and reverse movement of the heat transfer fluid from the pump to consumers; 7 — reserve boiler house; 8 — coal-bearing rocks; 9 — coal seams

where η_{TPP} is thermal power plant efficiency (commonly 0.4 for coal and 0.6 for gas); η_h is the heating system efficiency.

Introducing a thermal equivalent allows more adequate evaluating the energy balance and profitability for geothermal system operation instead of usually applied parameter *COP*.

The maximum heat capacity that can be achieved using a heat pump with a geothermal probe submerged in mine water is calculated by the formula

$$P_{hp,th} = q_p H_w,$$

notations in Table 1.

With the estimated or given thermal capacity $P_{hp,th}$ we can evaluate the temperature of the circulating fluid at the outlet of the geothermal probe as follows [15]

$$T_2 = \left(\frac{P_{hp,th}}{Q C_f} \right) + T_1,$$

where Q, C_f are the flow rate and volumetric heat capacity of the heat transfer fluid, respectively.

The electric power required to maintain fluid circulation in the geothermal probe can be calculated by the formula [16]

$$P_{p,el} = \kappa_s \frac{g Q H_p \rho_f}{\eta_p \eta_{ht}},$$

where κ_s is the assurance factor taken depending on the pump motor; g is the gravity acceleration; ρ_f is the density of the heat transfer fluid; η_p, η_{ht} the efficiency of the pump and heat transfer; H_p is the pump head defined as

$$H_p = H_g + H_f; \quad H_g = 2(H_{mw} + H_w),$$

where H_g is the difference of absolute marks in the probe; H_f is the pressure loss on friction resistance. These parameters are different for coaxial and U-shaped probes.

For the case of a coaxial probe

$$H_{f,c} = H_{f,c1} + H_{f,c2};$$

$$H_{f,c1} = \frac{\lambda \left(H_{mw} + H_w \right)}{d_1} \cdot \frac{v_{c1}^2}{2g}; \quad H_{f,c2} = \frac{\lambda \left(H_{mw} + H_w \right)}{\Delta d} \cdot \frac{v_{c2}^2}{2g};$$

$$v_{\tilde{n}1} = \frac{Q}{S_{\tilde{n}1}}; \quad S_{c1} = \frac{\pi d_1^2}{4}; \quad \Delta d = d_3 - d_2;$$

$$v_{c2} = \frac{Q}{S_{\tilde{n}2}}; \quad S_{\tilde{n}2} = \frac{\pi \Delta d^2}{4}.$$

For the case of a U-shaped probe

$$H_{f,z} = \frac{2 \lambda \left(H_{mw} + H_w \right)}{d_4} \cdot \frac{v_z^2}{2g}; \quad v_z = \frac{Q}{S_z}; \quad S_z = \frac{\pi d_4^2}{4}.$$

Here $H_{f,c1}$, $H_{f,c2}$, $H_{f,z}$ are pressure losses due to friction resistance in the inner tube of the coaxial probe, its intertube space and the tube of the U-shaped probe; S_{c1}, S_{c2}, S_z are, respectively, the cross-sectional area of these pipes; λ the friction coefficient.

The electric power consumed by the heat pump is evaluated by the relation

$$P_{hp,el} = \frac{P_{hp,th}}{COP},$$

where a theoretically achievable *COP* is calculated as

$$COP = h \frac{T_{pot}}{T_{pot} - T_2},$$

where h is the heat pump efficiency.

An additional criterion for technical and economic efficiency of a closed geothermal system is a positive energy cost balance defined as the ratio of the produced thermal energy cost $C_{hp,th}$ taking into account the transportation loss cost $C_{th,tr}$ to the total cost of electricity spent on fluid circulation in the probe $C_{p,el}$, heat pump operation $C_{hp,el}$, heat transportation to consumers $C_{tr,el}$ and maintenance of a geothermal system C_{mnt}

$$\xi_C = \frac{C_{hp,th} - C_{th,tr}}{C_{p,el} + C_{hp,el} + C_{tr,el} + C_{mnt}}. \quad (2)$$

The cost of heat produced and consumed by the system is

$$C_{hp,th} = P_{hp,th} a_{th}; \quad C_{p,el} = P_{p,el} a_{el}; \quad C_{hp,el} = P_{hp,el} a_{el},$$

where a_{th} is the tariff for thermal energy; a_{el} is the electricity tariff.

In this paper we neglect the terms related to transportation in (1, 2) (U_{tr}, $P_{tr,el}$, $C_{tr,el}$, C_{tr}, $C_{th,tr}$) assuming that the heat consumer is located next to the geothermal module. Then the additional value obtained as a result geothermal system operation can be estimated by the expression

$$P_{add} = C_{hp,th} - C_{p,el} - C_{hp,el}. \quad (3)$$

The profitability of a geothermal system installed at closed mines can be assessed using the criterion of net discount value (*NPV*) internationally applied in investment analysis. This criterion quantifies the amount that the investor expects to get back from the project upon the capital and operation costs covered by the profit. The *NPV* is defined as follows

$$NPV = -C_{in} + \sum_{t=0}^{N} \frac{P_t}{\left(1 + R\right)^t},$$

where C_{in} is the initial cost of creating a geothermal module; N is the expected number of years for the project; R is the annual percentage of income from alternative investment options, such as deposits or bonds according to the current average deposit rate in Ukraine.

The initial costs of creating a closed geothermal system in a flooded mine C_{cp} and C_{Up} for a coaxial and U-shaped probe, respectively, can be evaluated by the following expressions

$$C_{c,in} = C_{pump} + C_{cp}(H_{mw} + H_w);$$

$$C_{U,in} = C_{pump} + 2 C_{Up}(H_{mw} + H_w),$$

where C_{pump}, is the cost to install heat pumps with auxiliary equipment; C_{cp} and C_{Up} are the costs to install coaxial and U-shaped probes per a running meter.

Another criterion to be taken into account in evaluation of efficiency operation for closed geothermal systems is the payback period T_{pb} defined as

$$T_{pb} = C_{in} / P_{add},$$

where P_{add} is calculated by (3).

One more criterion applicable in evaluations of geothermal applications is the net present value (*NPV*) that quantifies the investor's net return. This parameter is very common in international investment practice and, as distinct to the more detailed criterion (2) allows giving a preliminary assessment of profitability for the expected operation period. If $NPV > 0$, the anticipated return will exceed the investment costs and the geothermal installation is considered profitable.

Results. We performed the calculations for geological and mining conditions of three mines of the Selidovo group in Donbas including the mine named after D. S. Korotchenko, "Selidivska" and "Novohrodivska" [17, 18]. The part of parameters required for calculations was set according to Table 1; the others were assigned as follows [19]: $C_w = 4.2$ MJ/(m$^3 \cdot$ °C); $\kappa_s = 1.1$; $\rho_f = 1000$ kg/m^3; $h = 0.6$; $\eta_p = 0.7$; $\eta_{ht} = 0.95$; $\lambda = 0.02$; $\eta_{TPP} = 0.4$ for coal; $\eta_{TPP} = 0.6$ for gas; $a_{th} = 50$ €/Gcal; $a_{el} = 0.05$ €/kW·h; $C_{pump} = 18\,000$ € (up to 30 kW); $C_{cp} = 10$ €/m; $C_{Up} = 3$ €/m; $R = 0.05$. The values in € are indicated as the equivalents in UAH.

The plots in Figs. 2, 3 show how the energy criterion ξ_E for a geothermal system with coaxial and U-shaped probe changes versus the submerged length of the probe below the
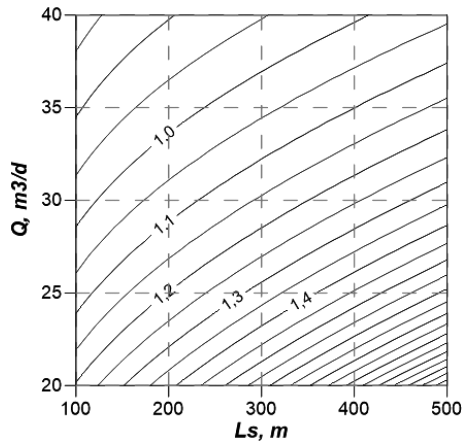
Fig. 2. Change in the energy criterion ξ_E for a geothermal system with a coaxial probe depending on the submerged length L_s and the heat transfer fluid flow rate Q at $\eta_{TPP} = 0.4$; $H_{mw} = 20$ m; $T_{hs} = 50$ °C, probe diameters $d_1 = 0.04$ m; $d_3 = 0.11$ m

mine water level denoted as L_s and the flow rate of the heat transfer fluid Q.

The obtained data clearly indicate an increase in the criterion ξ_E from 0.9 to 2.1 (Fig. 2) with increasing the submerged length and decreasing flow rate. The values ξ_E increase when replacing the thermal equivalent of electric power generated using coal with that of natural gas due to the lower efficiency of coal as a fuel. The geothermal system operation becomes energetically unfavorable ($\xi_E < 1$ i. e. the energy spent exceeds the energy produced) at high flow rates and small submerged lengths, which is to see at the top left corner of the plots.

The pattern of changing the energy criterion for a system based on a coaxial probe is similar to a U-shaped probe (Fig. 3) but with lower values of ξ_E from 0.7 to 1.5 due to the lower specific heat output per running meter of a U-shaped probe compared to the coaxial one.

Fig. 4 shows that the payback period of a geothermal system T_{pb} with a coaxial and U-shaped probe sharply decreases with increasing the submerged length. For the submerged length of 100−200 m the payback period lasts tens of years; with deepening the probe to a depth of 400−500 m T_{pb} shortens to 4−6 years, which looks quite acceptable with regard to the international practice of investment projects of geothermal industry [20]. Increasing the flow rate gets the payback period longer although with a higher thermal output; along with this
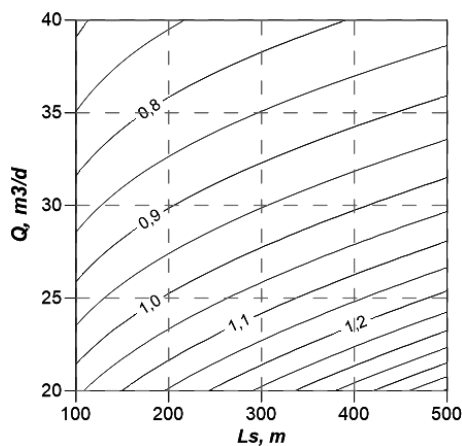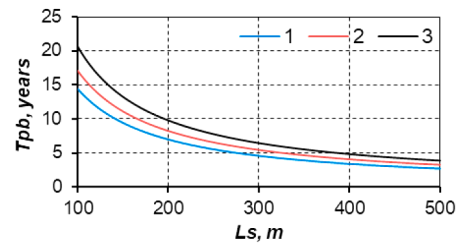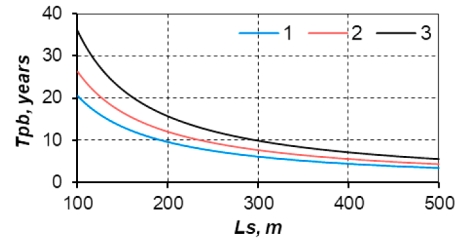

a

b

Fig. 4. Change in the payback period for a geothermal system with a coaxial (a) and U-shaped (b) probe depending on the submerged length L_s and the heat transfer fluid flow rate Q of 20 m³/d (1), 30 m³/d (2), 40 m³/d (3), at $\eta_{TPP} = 0.4$; $H_{mw} = 20$ m; $T_{hs} = 50$ °C, probe diameters $d_1 = 0.04$ m; $d_3 = 0.11$ m

the flow rate is more influential parameter to the payback period than to the energy criterion.

We evaluated the *NPV* parameter for a geothermal system with the coaxial probe regarding its higher efficiency compared to the U-shaped probe. The plots in Fig. 5 show the

a

b

Fig. 3. Change in the energy criterion ξ_E for a geothermal system with a U-shaped probe depending on the submerged length L_s and the heat transfer fluid flow rate Q at $\eta_{TPP} = 0.4$; $H_{mw} = 20$ m; $T_{hs} = 50$ °C; $d_4 = 0.04$ m
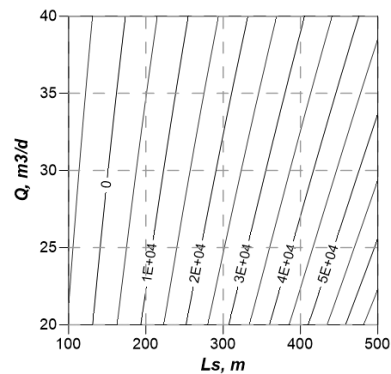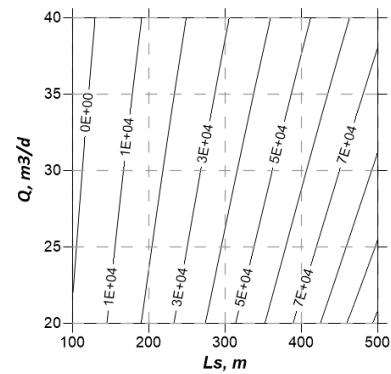
Fig. 5. The change in the NPV (€) of a geothermal system with a coaxial probe depending on the depth of the submerged length L_s and fluid flow rate Q for the period of 15 years (a) and 25 years (b); $H_{mw} = 20$ m; $T_{hs} = 50$ °C; $d_1 = 0.04$ m; $d_3 = 0.11$ m

growing *NPV* with the increasing submerged length. The system operation is expected to become profitable ($NPV > 0$) when the submerged length exceeds $100-170$ m depending on the flow rate and the operation time [21, 22]. The *NPV* may reach 60 thousand € in 15 years and 100 thousand € in 25 with increasing L_s and low flow rate.

It should be noted that for high flow rates and the submerged lengths from $100-170$ m to $400-500$ m the *NPV* becomes positive (Fig. 5) even if the thermal equivalent of the energy spent on operation exceeds the produced thermal energy. For example, $\xi_E < 1$ for $Q > 33$ m^3/d (Fig. 3) and *NPV* still remains positive. This is due to the higher thermal energy cost compared to electricity currently in Ukraine and may by different in other countries with other ratios between thermal and electric energy tariffs.

Conclusion. In this study, we proposed the energy and cost criteria to evaluate the operation efficiency of a closed geothermal system using a coaxial and U-shaped probe that can be installed in flooded mine workings. The energy criterion balances the thermal energy produced and the thermal equivalent of electric energy generated using fossil fuel and spent on system operation including consumption by heat pumps, fluid circulation and overcoming hydrodynamic resistance in the probe. This ratio as distinct from the *COP* parameter allows comparing the energies of the same nature and drawing more adequate conclusions on environmental acceptability of a geothermal system. The cost criterion refers to the operation period and balances the costs of the thermal energy produced, its losses, and the electric energy spent on system operation. The additional criteria are the parameters of net present value *NPV* and payback period used in investment analysis.

The efficiency criteria were tested assuming the conditions of the mines of the Selidovo group in Donbas potentially suitable for geothermal installations. We examined the change in energy criterion and *NPV* parameter for the submerged length of the probe from 100 to 500 m and the fluid flow rate from 20 to 40 m^3/d and identified the areas with positive values of the energy criterion and *NPV*. The produced/spent energy ratio may reach $1.5-2.2$ and the *NPV* a few dozen thousand € when increasing the submerged depth to 500 m at the flow rate of 20 m^3/d.

It was shown that the energy spends with increasing the flow rate may exceed the thermal energy produced but the *NPV* simultaneously remains positive, which indicates the system profitability. Such a disparity emerges due to the lower cost of electrical energy with respect to the thermal energy cost and may differ in other countries with different energy tariffs. The payback period can be shortened to a few years with the increasing submerged length of the probe at a relatively low flow rate.

The proposed criteria can be used for prioritization of geothermal system installation and the operation efficiency evaluation among the number of potential sites in post-mining areas.

Further studies may include refining the key geothermal system parameters such as specific heat output and heat transfer fluid temperature by thermodynamic and flow modeling as well as site-specific feasibility assessments with the comprehensive analysis of different efficiency criteria.

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Обґрунтування критеріїв ефективності експлуатації геотермальних зондів у затоплених гірничих виробках

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Мета. Розробка й тестування енергетичного та вартісного критеріїв для оцінки ефективності роботи закритої геотермальної системи, що використовує коаксіальні або U-подібні зонди, які можна встановлювати в затоплених виробках шахт.

Методика. Для обґрунтування енергетичного й вартісного критеріїв застосовано співвідношення термодинаміки, гідравліки та оцінювання економічної ефективності, проведено інженерний аналіз закритих геотермальних систем, досліджено гідрогеологічні параметри й геотермальні умови шахт Селідівської групи на Донбасі. Розроблені критерії були перевірені в діапазонах таких важливих параметрів, як витрата теплоносія й довжина занурення зонда.

Результати. Кількісно оцінено вплив довжини занурення зонда й витрати теплоносія на енергетичний баланс і чисту дисконтну вартість *NPV* і визначено комбінації параметрів, що дозволяють досягти ефективного відбору тепла з точки зору теплового балансу та економічної ефективності. Відношення виробленої енергії до витраченої може досягати 1.5–2.2, а параметр *NPV* — кількох десятків тисяч євро при збільшенні глибини занурення до 500 м при витраті 20 м³/добу. Більш високі витрати можуть призвести до негативного енергетичного балансу, але *NPV* залишається позитивним у деяких діапазонах довжини занурення зонда, що вказує на прибутковість системи. Термін окупності може бути скорочений до кількох років.

Наукова новизна. Запропонований енергетичний критерій визначає баланс між виробленою тепловою енергією й тепловим еквівалентом електричної енергії, виробленої з використанням викопного палива та витраченої на роботу системи. Цей коефіцієнт, на відміну від зазвичай застосовуваного параметра *COP*, дозволяє порівнювати енергії однакової природи й робити більш адекватні висновки щодо екологічної прийнятності геотермальної системи.

Практична значимість. Запропоновані критерії можуть бути використані для пріоритезації встановлення геотермальних систем і оцінювання ефективності експлуатації серед числа потенційних ділянок у гірничопромислових районах після припинення видобутку.

Ключові слова: *шахтні води, геотермальні зонди, енергетичний критерій, теплова енергія, чиста дисконтна вартість*