

Actualization of prospects of thermal usage of groundwater of mines during liquidation

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Abstract. The aim of the paper is justification of the economically efficient technological scheme for development of a thermal resource of “Stashkov” mine after its closure, ensuring the maintenance of a favorable energy and ecological-hydrogeological regime in the region. A geotechnological scheme of environmentally safe usage of mine water was justified, involving water pumping up to the surface, heat removal and water reverse pumping into the seams. The suggested circulation system is characterized by an increased energy balance, since it is used to extract almost all the groundwater heat, as well as part of the heat of host rocks. In order to estimate the effectiveness of usage of this technology, calculations of usage of mine water as a source of low-potential energy in heat pumps in comparison with other alternatives (groundwater and surface water streams) using Mathcad software were performed, and it was established that this gives great conversion coefficients of mine water. A geotechnological scheme of usage of mine water was developed, which considers heat transfer, filtration direction, velocity and temperature of groundwater during pumping and removal of heat-transfer fluid from an aquifer for heating and cooling of buildings. The mechanism of heat removal in a flooded rock massif of amine during liquidation was studied with justification of environmentally safe usage of mine water.

1 Introduction

According to different programs of restructuring the coal industry, the number of mines planned for liquidation in Ukraine is constantly increasing. In accordance with estimates, a significant number of closed mines will appear in its territory in the near future, that constitute a significant threat to the environment and require substantial expenses to maintain their hydrodynamic safety, as well as to eliminate involuntary unemployment [1, 2]. Thus, for example, the closure of the M.I. Stashkova Mine in the Western Donbas in 2021 will lead to flooding of a developed space and a threat of rapid rise of mine water level to the daylight surface [3]. In addition, many nearby settlements will experience an acute shortage of heat in the conditions of constantly growing prices of energy carriers. At the same time, a considerable resource of mine water with temperature of up to 20 °C will be concentrated in the flooded mine workings, which are currently practically not used.

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Foreign scientific and practical experience in the utilization of mine water heat from flooded mine workings [4, 5] shows the applicability and profitability of this technology. Currently, there are a lot of local projects in which the heat of water from closed mines is used to heat one- or two-storey buildings (Germany, France, and England). The most large-scale is a Dutch project, which is called MinewaterProject. In the city of Heerlen, the water of a mine, which had been flooded for almost 30 years, now heats the area with 350 buildings, over 200 of which are residential buildings. At the same time, pumping out of mine water is accompanied by technical difficulties associated primarily with high mineralization of water and the presence of various substances in it, which requires usage of special equipment and the organization of an environmentally safe water usage cycle.

Profitability of usage of warm mine water for heating and hot water supply increases dramatically when using heat pumps. Thus, at “Blahodatna” mine of “Pavlohradvuhillia DTEK” PJSC, pumping out of mine water in an amount of 200 m³/h with a conversion coefficient of heat of 3.5 provided annual savings of about \$60 thousand [6]. At the same time, heat pump operation does not create harmful emissions into the environment, which is especially important for coal mining regions. However, the usage of heat pumps in mines is not widespread due to large capital expenses on their installation and maintenance. In connection with this, the purpose of this paper is to justify a cost-effective technological scheme for development of a thermal resource of “Stashkova” mine after its closure ensuring the maintenance of a favorable energy and ecological-hydrogeological regime in the region.

2 Presentation of main research material

When developing a technological scheme for usage of mine water heat, it must be kept in mind that after a mine is closed and flooded, filtration flows in a rock massif are characterized by an increase in velocity and flattening of levels near natural channels due to a multiple increase in permeability of disturbed rocks. This leads to underflooding and subsidence of the day surface. Flows of low-potential heat from a technogenic aquifer are drained through natural channels containing environmentally harmful components. In this connection, it is expedient to produce heat from mine water in combination with technologies for its treatment, which are more economically efficient exactly in the presence of waste low-potential heat.

The main elements of the suggested technological scheme are presented in Fig. 1, on the basis of which, a systematic pumping out of water from flooded mine workings of different horizons using water wells is required to prevent flooding of the area around the mine. At the same time, the maximum operating efficiency of wells is achieved by combining their shafts with main workings. The rise of water to the day surface is performed using electrical centrifugal pumps (General Electric, Centrilift, Novomet, etc.), the usage of which is caused by their trouble-free operation in corrosive liquids with dissolved salts, gases and mechanical impurities. In addition, pumps of this type are characterized by simplicity of ground equipment, a long operation period between repairs (2 – 3 years), a large pumping out depth (up to 4 km) and a significant flow rate (up to 10 000 m³/day).

After the water enters the day surface, it is sent to the inter-pipe space of a heat pump evaporator, where it is used as a low-potential source of thermal energy and is cooled by boiling the refrigerant (working medium, which is low-boiling fluorochlorine-containing hydrocarbons) in the evaporator pipe space. Refrigerant constantly circulates in a closed contour of the pump, undergoing changes in its aggregate state in its devices and transferring heat from a renewable source of mine water to the consumer of average-potential heat due to the expenditure of high-potential energy in the compressor. At the same time centrifugal and heat pumps consume electricity for operation, the amount of

which is proportional to the power of a heat flow going to heat buildings. Mine water, cooled as a result of emission of thermal energy to the pump evaporator, enters the storage ponds located in Kosminna, Svidovok and Taranova gullies, from where it is discharged into the r. Samara. It should be noted that in order to reduce the influence of mine water on a quality of water in the river, they should be discharged in portions depending on the hydrogeological regime of the river.

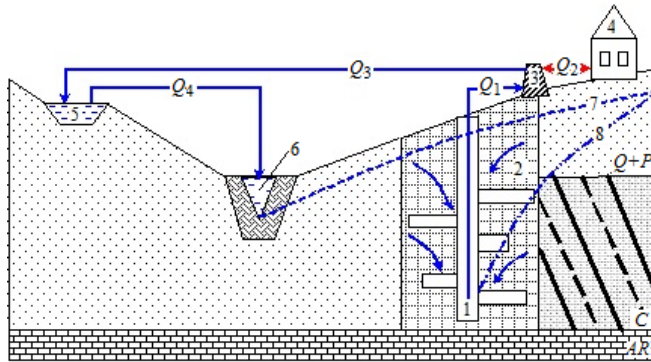


Fig. 1. Technological scheme of a geomodule for development of mine water heat: 1 – mine workings; 2 – developed coal massif; 3 – heat pump; 4 – building; 5 – storage pond; 6 – surface water flow; 7, 8 – level of mine water before and after their pumping to the surface; $Q_1 - Q_4$ – flow rate of mine water from workings, coolant from the pump, wastewater into a storage pond and settled water into a river, respectively.

The suggested technological scheme of mine water usage has a number of obvious environmental (prevention of territory underflooding, reduction of environmental impact) and energy (heating of buildings) advantages. However, it is necessary to carry out a feasibility study of scheme operation effectiveness for its implementation, the tasks of which are as follows:

- assess the maximum possible heat flow occurring from pumping out of groundwater from different horizons of a mine;
- determine the conversion coefficient of heat pumps, depending on the temperature of mine water;
- perform a comparative analysis of usage of mine water in heat pumps with other types of natural low-potential sources of thermal energy;
- establish the profit obtained from the operation of the suggested geomodule by determining the cost of electricity for operation of centrifugal and heat pump, as well as the cost of heat generated by them;
- quantify the prevention of CO₂ emissions due to the usage of heat pumps.

To solve the set tasks, it is necessary to determine the water temperature of various horizons of “Stashkova” mine concentrated in mine workings. In this case, in the first approximation, it can be assumed that hydrodynamic parameters of seams do not depend on a heat transfer processes [7], and the water temperature and temperature of a rock skeleton coincide at every point. Assume that mine water movement within the mine field occurs along the flooded workings, heat exchange in the computed plane is absent [8], the H axis is directed down. The heat flow q caused by heat of earth interior enters flooded mine workings from the bottom (from the depths). A neutral stratum of rocks, the temperature of which is constant and equal to the average annual temperature in the region (about +9 °C) lies above, 10 m below the day surface. Under these conditions, a differential equation of heat conduction about H axis considering convection is:

$$\frac{\partial^2 T}{\partial H^2} - \frac{V}{a} \cdot \frac{\partial T}{\partial H} = 0, \quad (1)$$

under the following boundary conditions:

$$T = T_1 \text{ when } H = H_1;$$

$$q = -\lambda \partial T / \partial H \text{ when } H = H_2.$$

The general solution of equation (1) with given boundary conditions is [9]:

$$T = T_1 + \frac{q}{\lambda B} [\exp B(H - H_2) - \exp B(H_1 - H_2)]; B = \frac{V}{a}. \quad (2)$$

In this case, the thermal flow of mine water contained in the flooded workings is determined from the expression

$$Q = CQ_1(T - T_{dev}), \quad (3)$$

where T_1, H_1 are temperature and distance to the neutral stratum; H is depth of location; a, λ are thermal diffusivity and thermal conductivity of water-saturated rocks; V is vertical velocity of filtration; q is heat flow from the depth; C, T, T_{dev} are volumetric heat capacity and temperature of mine water before and after usage respectively.

The Table 1 shows the temperature and the natural thermal potential of mine water contained in mine workings calculated by formulas (2) and (3). According to the obtained data, the heat flow increases with an increase of the depth of location of seams and the amount of pumped out water. At the same time, the total thermal potential of “Stashkova” mine is 1.72 TJ/day. It should be noted that in order to maintain hydrodynamic equilibrium, the flow of mine water was assumed equal to the predicted inflow of water into each coal seam, previously determined using mathematical modeling [10, 13]. The depth of seam location was assumed as the average value of an interval of its development. Thermophysical properties of rocks were set as characteristic of the conditions of Western Donbas: $q = 54 \text{ J/day} \cdot \text{m}^2$; $C_w = 4187 \text{ kJ/m}^3$; $\lambda_{av} = 245 \text{ kJ/m} \cdot \text{day} \cdot \text{°C}$; $a_{av} = 0.05 \text{ m}^2/\text{day}$; $T_1 = 9 \text{ °C}$; $T_{dev} = 5 \text{ °C}$; $H_1 = 10 \text{ m}$.

Table 1. Temperature and thermal potential of water, located in mine workings of “Stashkova” mine.

Seam	Average depth of location, m	Water inflow, m ³ /day	Temperature of mine water, °C	Heat flow, TJ/day
C_{10}^u	125	9600	12.45	0.30
C_8^u	175	4800	13.95	0.18
C_6^l	240	3240	15.90	0.15
C_5	270	22000	16.80	1.09

In assessing the operational efficiency of the suggested geomodule, it is necessary to calculate the conversion coefficient of the heat pump when using mine water. This indicator is the ratio of its heating capacity to the electricity consumed by it and is determined from the following expression:

$$K_T = h \cdot \frac{T_2}{T_2 - T_3}, \quad (4)$$

where h is coefficient of pump thermodynamic perfection; T_2, T_3 are condensation point (of heat consumer) and refrigerant boiling point (of low-potential energy source), K.

To determine K_T of the heat pump using formula (4), which uses mine water from a specific seam as a low-potential source of thermal energy, it is necessary to set its temperature (table), the coefficient of pump thermodynamic perfection (assumed to be 0.6) and the temperature of a heat consumer (temperature of hot water entering the heating system, from 50 to 70 °C, depending on the outside air). Scientific and practical interest is also in the performance of a comparative analysis of usage of mine water in heat pumps with other types of low-potential sources of thermal energy (groundwater and natural water flows). In order to do this, graphs (Fig. 2) of K_T changes depending on a type of source and temperature of a heat consumer were built in Mathcad software package. In the performed calculations, the following parameters were assumed: during the heating period, the temperature of soil and water bodies is 9 and 5 °C, respectively.

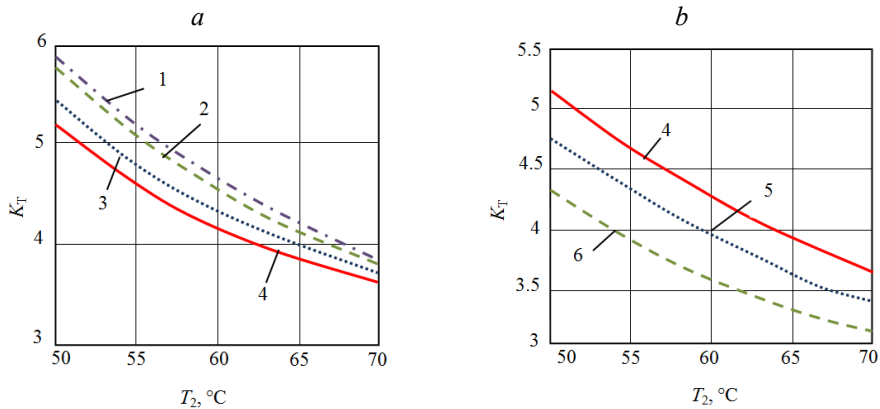


Fig. 2. Comparison of a conversion coefficient of a heat pump when using as a source of low-potential energy: 1 – 6 mine water of seams C_5 , C_6^1 , C_8^u , C_{10}^u , soil and surface water bodies, respectively.

Analysis of the obtained data indicates an increase of a conversion coefficient of the heat pump with increasing depth of pumping out of mine water, as well as its decrease with increasing temperature of the heat carrier supplied to the consumer. This indicates an increase of K_T with a decrease of the temperature difference between the source and the consumer of heat ($T_2 - T_3$), and, accordingly, its decrease with an increase in this difference. This circumstance unambiguously confirms the advantage of usage of mine water in heat pumps in comparison with other natural sources of low-potential energy.

In order to establish the operational efficiency of a heat pump for heating buildings, in addition to determining the conversion coefficient, it is necessary to calculate the consumption of electricity consumed by them, as well as its cost. The following expressions can be used for this:

$$N_{h.p.} = \frac{Q_2}{K_T}; \quad (5)$$

$$S_{h.p.} = N_{h.p.} \cdot T_E. \quad (6)$$

where $N_{h.p.}$, $S_{h.p.}$ are electric energy, consumed by the drive of a heat pump and its cost, T_E is current electricity tariff for enterprises (1 kW·hr = 1.76 UAH).

Fig. 3 indicates the results of calculations by formulas (5) and (6). Their analysis shows that the amount of electricity consumed by the heat pump increases with increasing temperature difference between the source and the consumer of heat, as well as with the amount of mine water used.

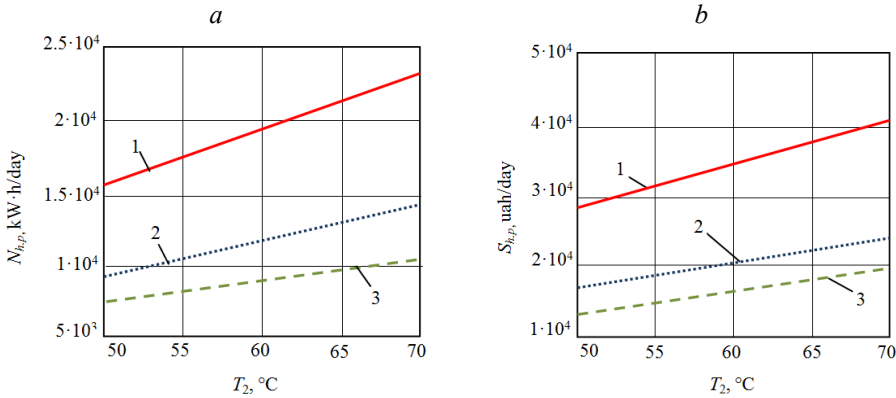


Fig. 3. Consumption (a) and cost (b) of electric energy consumed by a heat pump when using: 1 – 3 mine water of seams C_{10}^u , C_8^u and C_6^1 respectively.

The cost part of a geomodule should also include electricity consumed by a centrifugal pump for pumping out the mine water from mine workings. The following expression can be used to determine its quantity [11]:

$$N = k_z \frac{g Q_1 H \rho_v}{\eta_n \eta_p}, \quad (7)$$

where k_z is reserve coefficient, assumed depending on a pump drive; g is free fall acceleration; Q_1 is well inflow; H is depth of a seam location; ρ_v is water density; η_n , η_p are pump and heat transfer efficiency.

It should be noted that the operational cost of the geomodule (Z) is defined as a sum of a cost of electricity that supplies the centrifugal and heat pumps, and the profit (P) is defined as the difference between the cost of thermal energy produced by the geomodule and the electrical energy consumed by the pumps. Fig. 4 shows the values of these indicators. When performing the calculations, the tariffs for heat energy currently in Ukraine were assumed ($4.18 \text{ GJ} \approx 1416 \text{ UAH}$).

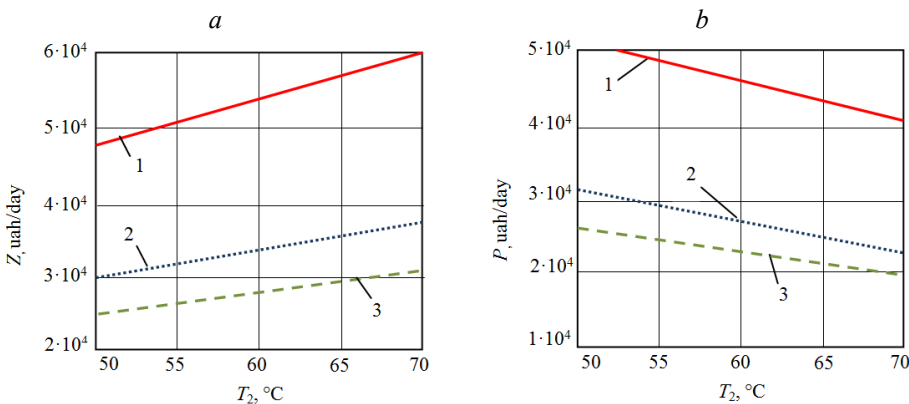


Fig. 4. Total expenses for electricity (a) that supplies a geomodule operation and a profit (b) gained from its operation. See designations in Fig. 3.

As can be seen from the obtained results, the profit from operation of the geomodule is estimated to be tens of thousands of UAH per day, which is very effective in the conditions

of modern Ukraine. However, it must be kept in mind that the obtained results are indicative and do not consider the initial capital costs for drilling wells (in the condition of their absence in the mine field) and industrial equipment (centrifugal and heat pumps, heat supply systems, etc.). However, they can be used in preparation of investment projects and business plans aimed at alternative heat supply systems for buildings.

Scientific, practical, and economic interest is the construction of complex graphs of a magnitude of the predicted profit, when the suggested geomodule is in operation. For this, Fig. 5 shows the changes in this parameter depending on the amount of mine water pumped out from a depth of 200 m and the temperature of a heat consumer, and Fig. 6 shows the value of the same indicator depending on a depth of pumping out and the temperature of a consumer with a well inflow rate of 5000 m³/day.

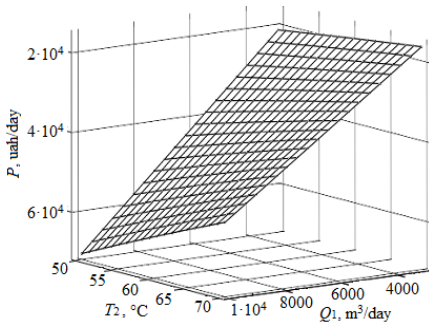


Fig. 5. Predicted profit from geomodule operation depending on the amount of mine water pumped out and a temperature of a heat consumer.

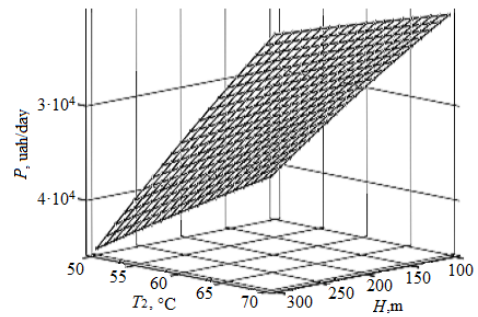


Fig. 6. Predicted profit from geomodule operation depending on a depth of pumping out of mine water and the temperature of a heat consumer.

According to the tasks formulated in this paper, in addition to the economic indicators of the suggested geomodule, it is necessary to determine the environmental expediency of its usage. This can be performed by establishing the prevention of CO₂ emissions when using heat pumps for heating buildings instead of traditional energy sources (coal, oil products and natural gas).

To solve the problem, use the method of calculating emissions of greenhouse gases [12, 14 – 16], according to which the calculation of CO₂ emissions (tonnes/day) for each type of fuel is performed by the formula:

$$E = Q \cdot K_1 \cdot K_2 \cdot K_3, \quad (8)$$

where K_1 is coefficient of oxidation of carbon in a fuel (coal – 0.98, oil products – 0.99, gas – 0.995); K_2 is coefficient of carbon emissions (coal – 25.58 tonnes/J, oil products – 20.84 tonnes/J, gas – 15.04 tonnes/J); K_3 is coefficient of conversion of carbon into carbon dioxide (3.66).

Fig. 7 shows the results of calculations performed by the formula (8). At the same time, the reduction of CO₂ emissions was determined both for the daily period of time (a) and for the entire heating season (b, November – March \approx 150 days). An analysis of the obtained data shows that the amount of reduction of CO₂ emissions largely depends on the consumption of mine water and taken as an alternative source of heat supply. On average, when the geomodule is working at Stashkova mine at full capacity (when using mine water from all 4 layers for heating), this value is 120 tonnes/day, which corresponds to preventing 18,000 tonnes of CO₂ from entering the atmosphere during the heating season and clearly indicates the environmental expediency of the suggested geotechnology.

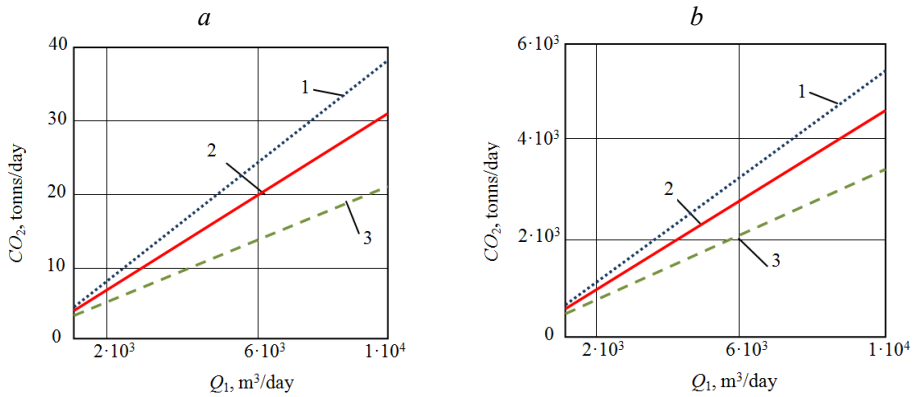


Fig. 7. Prevention of CO₂ emissions per day (a) and season (b) during geomodule operation compared to other alternative options of heat supply: 1 – 3 – coal, oil products and natural gas.

3 Conclusions

Analysis of operation of energy industry and the current ecological situation in coal mining regions of Ukraine indicates the need to preserve non-operational and unprofitable mines. The main problems arising from this are related to regulation of groundwater level, both in liquidated and neighboring operational mines. In addition, after the closure of mines in areas of coal enterprises, limited reserves of other types of natural energy carriers lead to a cessation of heating of buildings and a need to find alternative sources of thermal energy. At the same time, closed mines possess its considerable technogenic resource concentrated in mine water.

For the purpose of a complex usage of a thermal resource of water from flooded mine workings, a geotechnical scheme is justified, which makes it possible to economically expediently stabilize energy consumption and ecological situation in coal mining regions by combining technologies for heat generation, mine drainage, water regime control and mine water treatment in a single module. In accordance with calculations performed in Mathcad software package, the usage of mine water as a source of low-potential energy in heat pumps in comparison with other alternatives (groundwater and surface watercourses) gives their greater heat conversion coefficients (5.2 – 5.8 at $T_2 = 50$ °C and 3.2 – 3.9 at $T_2 = 70$ °C).

Evaluation of economic efficiency of the suggested geotechnological scheme was performed by determining the profits from its operation. This indicator was calculated as the difference between the cost of thermal energy generated by the geomodule and the electric power consumed (centrifugal and heat pump). It was established that the profit from operation of the geomodule, depending on a horizon of mine water pumping out and the temperature of a heat consumer, varies from 20 to 55 thousand UAH per day. In addition, the usage of this geomodule for heating buildings instead of traditional energy carriers (coal, oil products and natural gas) significantly reduces emissions of CO₂ into the atmosphere (up to 120 tonnes/day when using mine water from all horizons for heating).

Further development of this work is expedient by increasing the accuracy of the used calculation scheme by considering changes in water temperature during the movement and the impact of operation of several wells at once. In addition, a more detailed economic assessment of the suggested geotechnological scheme, based on the establishment of capital expenses for its creation and modern investment criteria, is needed.

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