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To cite this article: Anatolii Kolienko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **970** 012007

View the article online for updates and enhancements.

Efficiency of mine water use in the centralized heat supply system of city district

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Abstract. Technological solutions for the use of mine waters energy potential in district heating system of settlements in the coal-mining regions using heat pumps have been substantiated. Using the example of mines in the Central Donbas, an analysis of composition and quantity of mine waters has been carried out, an assessment of the energy potential of mine waters and an assessment of the sufficiency of such a potential to meet the needs of buildings of cities for heating and hot water supply have been carried out. A schematic diagram has been developed for the implementation of a project for the use of mine water in district heating systems in cities while maintaining the function of existing boiler heating systems as peak sources of heat. Thermodynamic calculations of the heat pump cycle in real conditions of using mine water have been carried out. A quantitative assessment of the main technical, economic and environmental indices of the project is presented. The selection of equipment has been carried out and the efficiency assessment of its work has been made. It is recommended to use heat pumps using the thermal potential of mine water in district heating systems for both operating and closed mines.

1. Introduction

Mine waters are waters in mine, underground water entering the underground working and removed by drainage systems – i.e. water-removing from the existing and abandoned mines.

The relevance of the topic on the beneficial use of mine (mine water) is confirmed by the development of the Concept of reforming the coal industry in Ukraine, designed for 2020-2024 [1]. A distinctive feature of such a document is its goal of reducing the use of fossil fuels and the intention to join the European Green Deal, which is based on the achievement of the Sustainable Development Goals until 2030 and the implementation of the Paris Climate Agreement [2].

One of the objectives of the EU Directive on the development of renewable energy 2018/2001/EU [3] in the field of district heating systems is to increase the energy efficiency of such systems, generate heat from renewable energy sources, create systems that are characterized by mutual redundancy, the ability to meet daily and seasonal consumption peaks. Such systems are referred to as "fourth generation heat supply systems" [4, 5].

Implementation of the Concept for Ukraine should become a compromise between ambitious goals and realities, in which about 28 million tons of mined coal provide up to 29 % of the primary energy in the energy balance.

An additional challenge is the introduction of the Carbon Border Adjustment mechanism, the introduction of which will lead to the establishment of a duty on goods produced using fossil fuels

with large emissions of carbon dioxide [6].

The main task of the Reform Concept is to ensure a fair transformation of mining regions and the protection of miners, including meeting the needs of mining monotowns for heat and hot water supply [7]. A significant part of the centralized heat supply systems (CHST) in such cities have heat sources in the form of coal-fired boiler houses. There are no medium pressure gas supply systems in many regions. Thus, the abandonment of coal will mean the collapse of the central heating system in monotowns of coal-mining regions.

Under such conditions, mine waters, which are pumped out during coal mining in working mines, as well as to prevent flooding of neighboring enterprises and flooding of the surface – in abandoned mines, represents a stable source of alternative energy [8]. In accordance with the Law of Ukraine On Alternative Energy Sources [9], the thermal energy of mine water refers to alternative energy sources, which means it is subject to such a Law.

The purpose of the work is to identify possible economically and technically feasible ways of using the thermal energy of mine water from drainage systems of the existing and abandoned mines to maintain the operability and high efficiency of the central heating system in residential areas of coal-mining regions in the context of the Concept implementation for reforming the coal industry in Ukraine.

2. Methods

Studying of the possibility to use mine water as a source of heat for centralized heat supply systems for cities and towns in coal-mining regions was carried out in the following sequence:

- studying the issue of environmental safety of using mine water, analysis of the of mine water composition;
- determining the volume of mine water flow in some mines of Donbas - (statistical data, results of real measurements);
- assessment of the of water content water-inflow coefficient in mines;
- assessment of the mine water composition and the possibility of its use as an energy carrier;
- assessment of the energy potential of mine water's energy potential;
- an overview of the of the centralized heat supply system state in some cities of coal-mining regions, assessment of the central heating system operation possibility under the conditions of using the thermal potential of mine water;
- development of a schematic diagram of using mine water as an energy carrier for heat pumps of the "water-to-water" type as part of the central heating system;
- assessment of the heat pumps using efficiency in the central heating system of cities;
- assessment of the practical feasibility of implementing a scheme for using mine water to generate heat in the centralized heating system;
- study of the energy return index on investment (EROI) for heat pumps using the potential of mine water;
- environmental assessment of the project for the use of mine water in the centralized heating system of the city.

To assess the water-inflow coefficient and the volume of mine water inflow, we used data on the actual performance of pump station units of operating and abandoned mines (full-scale measurements with subsequent averaging over the year); analysis of literary sources was carried out with a description of the operating experience of mines in the central Donbas.

Assessment of the energy potential was carried out by means of thermodynamic calculations using data on the mine waters characteristics. Other stages of work are the results of the elaborations of this article's authors, which were carried out based on calculating the cycle of the heat pump and assessing its thermodynamic efficiency.

3. Results and discussion

As a rule, mine waters are characterized by mechanical, bacterial, chemical, radiation and bacterial pollution and high salinity (up to 70 g/l and more). In the development of sulfide ores and coal beds,

they have a high content of sulfate ions, metals and have an acid reaction. Such mine waters intensively corrode drainage systems.

After purification and demineralization, mine water can be used as a technical water supply for mines (for example, for dust suppression) instead of drinking water. According to statistics, the technological demand for the mines' own needs is up to 15 % of the water volume that is taken in the drainage process. The rest of the mine water is discharged into clarification ponds and into the hydrographic network, enters the Donbas river basins, and is accumulated in water reservoirs. In figure 1 a photo of a clarifier pond is presented.

Figure 1. Pond clarifier for mine water.

The photo shows the formation of water vapor on the surface of the pond in connection with the discharge of water with the temperature of about 25 °C. Outside air temperature is + 2 °C. The temperature of the reservoir in the area of the drainage pipeline of the drainage system is +19 °C.

Now the situation with water use in mines is developing in such a way that city water pipelines with scarce drinking water, as well as artesian water, are used for own economic needs. The possibility of using mine water for the needs of domestic drinking and industrial water supply is determined by their belonging to the classification group in terms of quality indices, as well as the sources of water supply. According to the existing regulatory documents (State sanitary norms and rules: "Hygienic requirements for drinking water intended for human consumption") [10] the use of mine water as a source of drinking water supply is not provided. For this purpose, only drinking water obtained from surface or underground sources of drinking water supply can be used.

In addition, for sources of drinking water supply, a necessary requirement is the creation of sanitary protection zones (SPZ), which cannot be performed for operating mines. This can only be done in closed mines.

For other purposes (for example, to use the thermal potential) mine water can be taken from any mine, including the working one. It is also possible to take water from open sources such as retention ponds, or clarifying ponds

But in this case, the thermal potential of water is lost due to heat loss from the surface of reservoirs to the environment and a decrease in water temperature.

Thus, for example, the temperature measurement of mine water from the drainage unit of the Tsentralna mine in Myrnoghad, which performed at an outside air temperature of + 10 °C, indicates that the water temperature in the settling pond near the discharge pipe is about + 19 °C, and at a distance from it – about 90 °C. Depending on the concentration of mineral salts (S), alkalinity (A) and hardness (H), mine waters are classified (Ukrainskyi naukovyi tsentr tekhnichnoi ekolohii) into the following groups:

Group 1. C = 1.5-1.8 g/l; S = 8-12 mg-eq/l; H up to10-12 mg-eq/l.

Group 2. C = 3-3.5 g/l; A up to 10-12 mg-eq/l.

Group 3. C = over 3.5 g/l; H up to 12 mg-eq/l.

For the use of mine water, both as a source of water supply and as an alternative source of energy, it is extremely important to perform an accurate analysis of mine water at each mine where the project is planned to be implemented. The most common mine water pollutants are suspended solids and hardness salts. Table 1 shows the averaged characteristics of mine waters in the region of central Donbas.

Table 1. Averaged results of mine water analytical control.

Magnitude	Units of measurement	Results of the analysis	
		Before clarifying pond	After clarifying pond
hydrogen index	pH units	7.3	7.2
water hardness	mg-eq /dm^3	28.5	27.5
dry residual	g/dm^3	5.762	5.320
celerity	degr.	10.7	10.1
calcium	mg/dm^3	290	282
magnesium	mg/dm^3	171	166
sulfates	mg/dm^3	406	358
chlorides	g/dm^3	3.075	2.950
nitrates	mg/dm^3	0.5	0.5
nitrites	mg/dm^3	0.04	0.04
phosphates	mg/dm^3	0.08	0.08

Chemical analysis of mine water indicates the presence up to 4 g/l of mineral salts (chlorides - up to 3 g/l), pH 7.3, hardness 28 mg-eq/dm^3, dry residue - up to 6 g/l before the clarifying pond.

According to the given composition, mine water at the sampling points belongs to the category of saline natural waters, or the third group of the above classification. To be used as a working medium of industrial refrigeration machines, the carbonate hardness of mine water should not exceed 6 mg-eq/l, and the total mineralization should not exceed 2000 mg/l [11,12].

An important document regulating the rules for the use of mine water is the sanitary rules and norms "Hygienic requirements for coal industry enterprises" [13]. But this document was canceled on 01.01.2017. The State Sanitary Rules and Norms "Coal Industry Enterprises" are in force, the provisions of which are also valid for coal preparation and briquette factories [14].

According to this document, mine water used for household needs is subject to purification, neutralization, demineralization, disinfection and must comply with the requirements of DerzhSanPiN "Drinking water. Hygienic requirements for the quality of centralized drinking water supply" [10].

The number of closed mines in Donbas is constantly increasing. In this regard, the issue of using mine water is of great importance. In addition, the pumping of mine water is important primarily from the point of view of emergency recovery in mines and stabilization of drainage.

Analysis of the quantity and temperature of mine water shows that it can serve as a source of energy for the central heating system. Such energy sources are classified as renewable and alternative energy sources [15].

Thus, for example, cooling every 180 m^3/h of mine water by 50 °C permits to obtain up to 1400 kW, of thermal energy, which is enough to provide heat for heating up to 10-11 apartment buildings per 60 apartments each.

Utilization of low-potential heat of mine water and an increase in the thermal potential of the coolant is possible through the use of heat pumps of the "water-to-water" type.

Water with the temperature of up to 15 ... 20 °C can be considered as an efficient low-potential source of heat for a "water-to-water" heat pump for use in their own needs in mines - in heating

systems, hot water supply or cooling air ventilation, as well as in central heating systems of Donbas cities. Already at an average annual water temperature of +10 ... +12 °C, the use of water as a low-potential source of heat in a heat pump can be economically feasible.

Due to the implementation of the reverse thermodynamic cycle in the heat pump, it is possible to increase the thermal potential of the energy carrier in the required quantities.

table 2 shows the values obtained by the authors of the average annual consumption and the thermal potential of drainage systems in some mines (the amount of heat that can be obtained when using mine water in heat pumps).

Table 2. Characteristics of mine water.

Mine name	Average annual consumption of mine water, m^3/hour	Average annual temperature of mine water, ^{o}C	Thermal potential, kW
Tsentralna Mine, Myrnohrad	767	18-20	6800
Novodonetska Mine, Novodonetsk	250	13	2200
Bilozerska Mine	420	12	3700
Almazna Mine	420	14	3600
Mine Dobropilska	320	15	2800
Mine "Novohrodivska" 1- 3	446	12	3750
D.S.Korotchenko Mine	1138	14.5	9300
Kotlyarevska Mine	552	13	4100
Kyrakhivska Mine	718	13	6400

The data in the table indicates a sufficiently powerful thermal potential of mine water. Provided that the heat pump operates year-round, the amount of heat that can only be obtained from the Tsentralna mine in Myrnohrad may be about 54 thousand MW/h.

This amount of heat is equivalent to the combustion of 12.4 thousand tons of coal with a heating value of 5.8 kWh/kg and the efficiency of boiler plants is 75 %. Replacing such an amount of coal when using mine water from the drainage system of only one mine permits to reduce the annual amount of CO_2 emissions into the atmosphere by 32 thousand tons (the CO_2 emission factor for coal is 2.6 tons of CO_2/ton of coal) [16].

The volume of discharged mine water depends on the water abundance coefficient. And it, in its turn, is determined by the hydrological conditions of coal deposits, technological characteristics and other conditions. For mines in the central region of Donbas, the water abundance coefficient is up to 15-20 m^3/t of coal. Mine water salinity varies from 2 to 10 g/dm^3.

Calculations of the project's profitability for using the thermal potential of mine water in the central heating plants of cities can be performed based on the specific index of mine water consumption of 150 m^3/h, which permits, when using a "water-to-water" heat pump, to provide a heat output of the unit of about 1.4 MW, which is equivalent to annual heat production from the energy of mine water of about 6000 MWh for the heating period. This amount of heat is enough to meet the heating needs of 5 multi-storey buildings with 60 apartments each.

The increase in heat production is limited by the performance of the drainage units.

Economically feasible temperature of hot water (heat carrier) at the outlet of the heat pump is about 55 °C. Such parameters of the heat carrier are insufficient to meet the heating needs of residential buildings and public buildings in the entire range of outdoor temperatures.

When the heat carrier is dispensed in the central heating station according to the temperature schedule of 80/60 °C, the heat carrier's temperature of 550 °C is only sufficient to meet the heating needs from the beginning of the heating period to the average daily outside air temperature of – 1.5 °C. Along with this, it should be noted that the frequency of temperatures from +80 heating period to a temperature of -1.5 ^{o}C is about 3127 hours from 4224 hours of the heating season duration. And this,

in its turn, accounts for 74 % of the entire heating period duration [17].

Thus, the base load for heating needs (74% of the duration of the heating period) is provided by supplying heat from the heat pump. The rest of the heating period – 26 % of the total duration - heat generation is carried out from district boiler houses, built into the general thermal circuit of the system by additional heating of the network water.

The indices of the technical and economic efficiency of the project implementation significantly depend on the amount of unproductive heat losses in the system, including in heating networks at the site from the source of mine water (mine or sediment pond) to the boiler house, which will provide additional heating of water for district heating. For some cities this distance is hundreds of meters, while for others it is 2-3 km. The possibility of using the potential of mine water for the hot water supply system, as well as for cooling the ventilation air supplied to the mine, is also important for technical and economic calculations. The presence of such consumers significantly improves the economic performance of the project.

Provided that the potential of mine water is simultaneously used to heat the heat carrier in the district heating system, hot water supply and cooling ventilation air, the main efficiency factor of the heat pump increases significantly. In addition, mining administrations are interested in supplying mine water for use in the heating system of cities.

The general schematic thermal diagram for implementation of the system to use the heat of mine water for the purposes of centralized heat supply to production facilities of mines and residential buildings in the adjacent residential area of cities are shown in figure 2. Calculations of the heat demand for heating and hot water supply of the Myrnohrad city were performed, the routing of communications was performed, the selection of equipment for the implementation of the given schematic diagram was performed.

Due to the contamination of mine water, the scheme provides for additional heat exchangers, which protects the thermal mechanical equipment of the heat pump and boiler room.

At the same time, it must be stated that the thermal potential of the mine water will be somewhat lost. The selection of equipment for the scheme and the calculation of the technical and economic indices of the project were carried out for an average annual temperature of mine water of about + 15^0C, taking into account heat losses in the intermediate heat exchanger.

The use of mine water as an alternative source of energy provides for preliminary water purification from mechanical impurities. Switching on peak boilers on fossil fuels for heating the network water during the period when the outdoor temperature drops below - 1.5 °C will be carried out automatically.

The construction of the heat pump's thermodynamic cycle and the calculations of the cycle on the basis of a vapor compression refrigeration machine for the initial data obtained above have been performed (figure 3).

R717 Refrigerant consumption is 1.115 kg/s. Mine water consumption is 85 m^3/h, central heating water consumption is 93 m^3/h. Thermal productivity of one heat pump unit at the heat carrier temperature of 55°C is 1330.5 kW. Electricity consumption is 282.6 kW.

For the conditions of real mines and specific central heating plants of cities, the required thermal efficiency of the installation can be achieved by increasing the number of modular heat pump units with the above characteristics. For example, to provide heat to the consumers of the boiler houses "Naberezhna", "Olymp", "Horna", the central heating station in Myrnohrad with a total connected heat load of 4.5 MW needs 4 units. The distance from the source of mine water to the boiler houses does not exceed 300m.

Transportation of the heat carrier to consumers is performed using the existing heating networks. The total thermal potential of mine water from the Tsentralna mine in Myrnohrad permits to generate up to 8 MW of thermal energy, which can provide up to 40 % of the annual heat demand for heating residential and civil buildings in the city.

Table 3 shows the parameters of the characteristic points in the cycle shown in the diagram in figure 3.
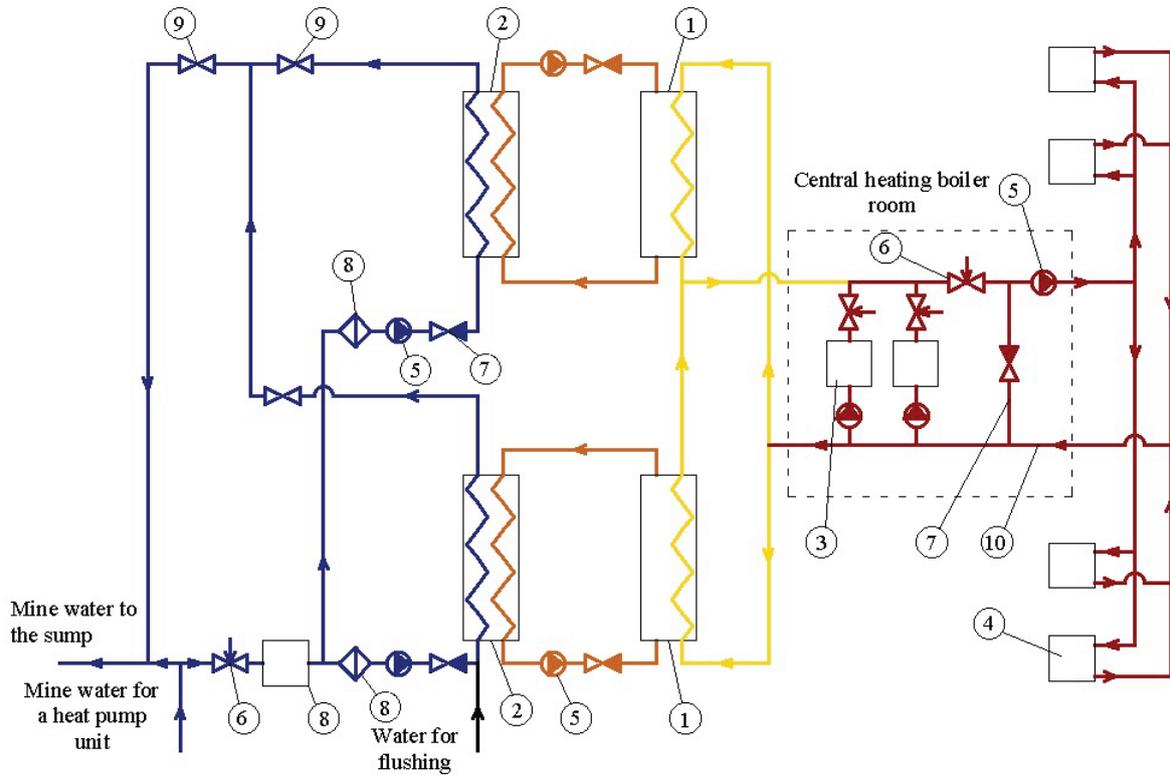
Figure 2. Schematic diagram of the mine water use in the central heating system of the city: 1-heat pump units; 2- intermediate heat exchanger of mine water; 3- hot water boilers for boiler houses; 4- communal and household heat consumers; 5-circulation pumps; 6- adjusting fittings; 7- unit for regulating heat supply from the boiler room; 8- mine water reserve tank; 9- shutoff valves; 10-pipelines of the heating network.
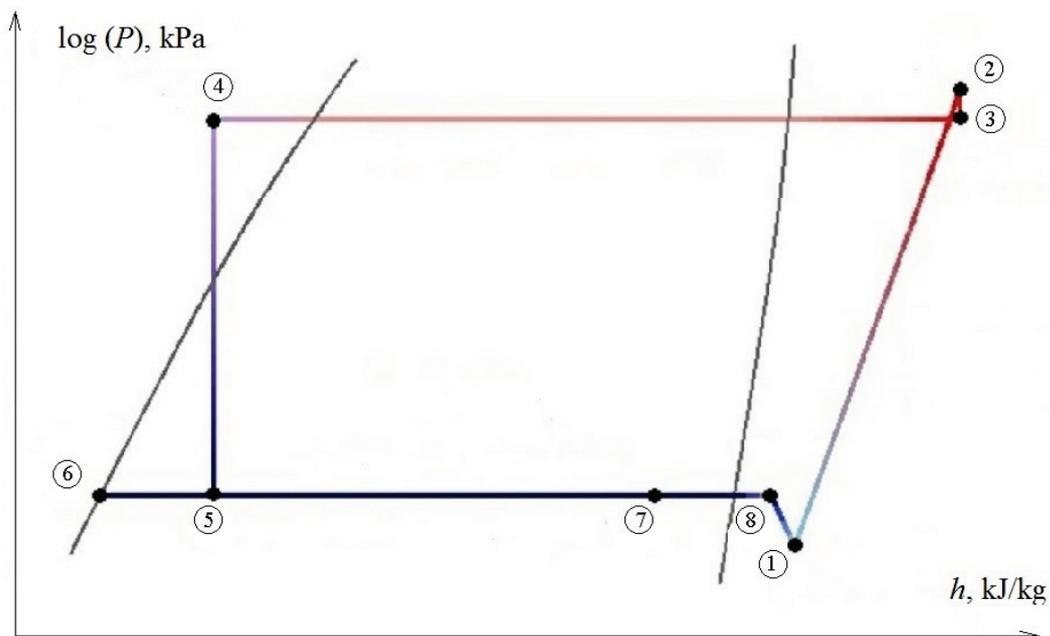

Figure 3. Actual cycle of a vapor compression heat pump in the log (P) -h state diagram of the working fluid R717.

Table 3. Parameters of the heat pump cycle.

Point number on the heat pump cycle diagram	Pressure kPa	Temperature, °C	Enthalpy kJ/kg	Density kg/m^3
1	718.4	16.0	1463.4	5.6
2	2341.5	126.8	1697.4	13.1
3	2312.4	126.8	1698.2	12.9
4	2312.4	54.0	446.4	555.7
5	730.5	15.0	446.4	-
6	730.5	15.0	251.8	617.5
7	730.5	15.0	1218.1	-
8	730.5	15.0	1459.7	5.7

Heat loss in the compressor is assumed to be 12 %, isentropic efficiency is 0.65.

The thermodynamic efficiency of using heat pumps was assessed by the value of the conversion factor (*COP*), which shows the amount of energy received q_1 in relation to the cost of external energy in cycle l (electrical energy for the drive of the compressor and pumps was considered as external energy supplied). $COP = q_1/l = 3.8$. The values of q_1 and l were determined from the difference in the working fluid enthalpies according to the construction of the cycle in the log (P)-h axes (figure 3).

For the initial conditions given above, the *COP* value is 3.8 kW, which means the useful consumption of 3.8 kW of mine water energy for every 1 kW of the electrical energy consumed.

For the conditions of Myrnohrad, the use of 4 "water-to-water" heat pump units with a thermal capacity of 1332 kW each based on mine water from the Tsentralna mine means an annual reduction in heat generation at boiler houses by 11267 MW/h, or a reduction in the annual consumption of natural gas in the central heating system by the value of about 1.25 million m^3.

Reducing CO_2 emissions into the atmosphere make 2,450 tons per year.

The economic effect of reducing natural gas consumption is about UAH 14 million per year. The net economic effect, taking into account the operational additional costs associated with the implementation, will amount to about UAH 10 million.

The investment cost of the project is about € 4.0 million (about 120 million UAH). The simple payback period is about 12 years. Technical life of the equipment - 25 years.

However, it should be borne in mind that for many single-industry towns of Donbas, the policy of the economy decarbonization and the refusal to use coal in central heating plants may mean the complete impossibility of supplying heat to central heating stations and the need for heat consumers to switch to autonomous heating systems. Therefore, the use of heat from mine water in central heating systems has considerable social significance.

In addition, a technical and economic analysis of the project's implementation efficiency for the use of heat pumps applying the method of energy profitability *Energy Return on Investment (EROI)* is of considerable interest [19].

The essence of this method is to assess the value of the *EROI* coefficient, which is the ratio of the energy that will be obtained during the operation of the energy source for the entire period of operation, E_0 in (MJ) to the amount of energy that is spent on the device, organization and process of energy generation, E_s in MJ:

$$EROI = \frac{E_0}{E_S}.$$ (1)

The value of E_S is determined by the sum of energy consumption, which is equivalent to the consumption of energy spent on the manufacture of equipment for the heat pump itself, piping, shut-off and control valves, thermal mechanical equipment, pumps and drives to them - E_{S1}; energy spent on the production of building materials, mortars, metal structures, concrete, energy costs equivalent to the whole process of construction buildings and infrastructure during the construction of an energy facility - E_{S2}; the energy required to ensure the current operation of the complex for the construction of

an energy source - E_{S3}; and the energy that will be required to accompany the process of the facility liquidation - E_{S4}:

$$E_S = E_{S1} + E_{S2} + E_{S3} + E_{S4} . \qquad (2)$$

In the case of *EROI* > 1, the amount of energy that is generated during operation is greater than the amount of energy that is spent on the device and operation of the energy source. Thus, the introduction of such an energy source has a technical and economic feasibility in terms of ensuring a sustainable energy cycle, and vice versa, if the *EROI* coefficient is <1, then the introduction of an energy source is impractical, since the energy consumption for its creation and maintenance exceeds the amount of generated energy during the life cycle of the source.

To assess the technical and economic feasibility of implementing heat pumps using mine water in the central heating system of settlements in mining regions, it remains to assess the corresponding energy costs and energy generation. The planning horizon for the assessment is taken equal to 25 years [20]. The calculation results are shown in table 4.

Table 4. Assessment of the technical and economic efficiency of the heat pumps use applying the method of energy efficiency Energy Return on Investment.

The name of a resource or item of material or other costs that require energy consumption, or its generation	Per unit energy consumption MJ/unit of measure	Amount of obtained or expended energy, MJ·10^6
Amount of energy that will be obtained during the operation of a heat source using heat pumps (E_0, MJ)	-	+490.95
Consumption of energy that must be expended to generate electrical energy used during the operation of heat pumps (N, MJ)	-	-88.19
Ferrous metal used in the manufacture of heat pump units (M_1, kg)	Tube- 19.8; Leaf- 25.1; Mean-22.6	- 0.91
Non-ferrous metal spent for manufacture of heat pump units, shut-off and control valves, pumps and electric motors, other heat and electro-mechanical equipment (M_2, kg)	Aluminium - 155; Brass - 44; Titanium -745; Bronze -69; Copper - 42	- 1.56
The mass of ferrous metal consumed in the construction of pipelines, shut-off and control valves and other thermal and mechanical equipment (M_3, kg)	Tube- 19.8; Leaf- 25.1; Mean- 22.6 per 1 t	- 1.13
Concrete used in the facility construction (V_1, m^2)	Concrete– 886; Sand-0.081	-0.886
Mass of ceramic, silicate and other building materials (M_4, t)	Brick- 3; Ceramics - 10; Bitumen - 51	-0.8
Mass of metal structures during the facility construction (M_5, t)	Rolled iron – 28	-1.68
Energy costs required for the current operation of the facility (except for electrical energy) (E_{S3}, MJ)	-	- 1.5
Energy costs required for the facility abandonment (E_{S4}, MJ)	-	- 2.5
Other resources (MJ/m^2)	Asphaltic roads-2800; Translucent road guards -320; Polyvinyl chloride plates-80; MDF panels – 11	-3.2
Total energy consumption for the project (E_S)		- 102.3
Total, energy balance		+ 388.65
EROI Coefficient		4.8

Assessment of technical and economic efficiency using the Energy Return on Investment method indicates a sufficiently high energy feasibility of implementing heat pumps as a source of alternative energy in the district heating system using the energy potential of mine water.

4. Conclusions

In connection with the policy of the economy decarbonization and the reduction of greenhouse gas emissions, there are risks associated with a possible shortage of coal, as the only possible type of fuel, in boiler houses of centralized heat supply systems in single-industry towns of mining regions. Thus, the existing heat supply systems of such cities are under the threat of incapacity. The analysis on the possibility of using new energy sources in the form of low-grade heat contained in mine water with the use of "water-to-water" heat pumps has been carried out. The composition, parameters and quantity of mine water were studied, the coefficient of water abundance in mines and the thermal potential of mine water were determined. The calculation of the thermodynamic cycle of the heat pump has been carried out, a schematic diagram of its use in the district heating system has been developed. According to the proposed scheme, the basic load on heating and hot water supply of the city is covered by the heat output of the heat pump, and the peak load is covered by the existing boilers of the district boiler houses. Thus, the safety of the existing centralized heat supply systems of cities is ensured. It is shown that the efficiency factor of using heat pumps in the proposed scheme is not less than 3.8, which provides significant savings in fossil fuels and a decrease in greenhouse gas emissions into the atmosphere. The temperature modes of heat sources operation are recommended for the case of alternative energy sources adaptation in the heat supply system. The selection of equipment for implementation of the developed concept of using the low-grade heat of mine water has been carried out. Technical and economic calculations were performed for using the energy profitability criterion indicating the high energy feasibility of implementing the energy potential of mine water in the heat supply systems of cities in mining regions.

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