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Economic aspects relating to machine operations on a mine main drainage system

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Abstract

This article presents an economic analysis of the exploitation of the main mine drainage according to the condition of machines. The study is based on actual operating data obtained during the operation of an underground hard coal mine. Through the selection of state estimators, appropriate sensory systems, as well as a long-term economic approach, operating procedures were developed that allowed for the introduction of significant financial savings. Operating costs are reduced by lowering energy consumption and reducing the costs of current repairs and spare parts. In addition to the classic approach to monitoring the state of a machine, based on the observation of residual processes, a global coefficient, referred to as unit energy consumption, has been proposed. Thanks to this, the operation of the machine occurs not only on the basis of its current dynamic state, but also due to the control processes of the machine's operation. Moreover, the article refers to the area related to water safety and the reliability of the pumping station.

Introduction

In underground mines, there is a seepage of groundwater, which poses a risk of flooding the mine (d'Obyrn, 2013). Drainage systems are built to protect against the effects of water inflow. Its main element is the primary drainage station, usually installed on the lowest level of the mining plant. Its task is to drain the water flowing into the mine, which is collected in water galleries. Depending on the amount of incoming water and the depth of the foundation of the main drainage station, the operating costs vary within a vast range. In Polish mines, there is usually a moderate or high inflow of water and, in combination with considerable depths up to 1000 m, the operating costs of the main drainage are dominant (Bukowski, 2007). An important element influencing costs is the safety of the system, which has a direct impact on the safety of the mining plant. The main costs of the drainage system are:

- Purchase of pumps, motors, pipelines, and other fittings;
- Installation of machinery, construction of waterways, construction of pipelines in the shaft, and construction of power lines;
- Consumables;
- Periodic inspections, service, and cleaning of sedimentation tanks;
- Running and major repairs;
- Renovation and main course;
- Direct service;
- Environmental fees;
- Technological security;
- Electricity.

The only utility product of the pumping station's operation is the safety of the underground mine and, moreover, the ability to excavate coal and other minerals. Thus, it is difficult to enter a cost-benefit-based account directly. Bearing in mind the main goal, which is water safety, it is possible to analyze the method of operating the drainage system together with its design and reliability calculations (Brzychczy, 2019). The presentation of possibilities for optimizing the operation of the main drainage system will be presented, based on the example of an operating underground coal mine in Poland.

Description of the research object

The main drainage system located at the shaft, at a level of 500 m in the analyzed underground coal mine, consists of ten pumping units installed in the pump chamber. The pump units are high-pressure pumps of the OW250/8 and WPWE-250/7LH types. Each pump unit is connected to two discharge pipelines with a diameter of 500 mm, which pump water to the surface. The pump units given in Table 1 were identified.

Table 1. Pumping station of the main drainage system of the primary mining plant

Assembly No.	Motor type	Pump type	Remarks
1	SCDdm 134 u	OW 250B/8	Technological considerations
2	SCDdm 134 u	OW 250AM/8	
3	S1 500X-4D	WPWE-250/7LH	
4	SCDdm 134 u	OW 250AM/8	
5	S1 500X-4D	WPWE-250/7LH	
6	SCDdm 134 u	OW 250AM/8	
7	Sh500 H4D	OW 250F/8	
8	S1 500X-4D	WPWE-250/7LH	Warranty repair
9	Sh500 H4D	OW 250AM/8	Renovation
10	Sh500 H4D	OW 250AM/8	Out of order

The water flow in the area of the main shaft pumping station is 20.22 m^3/min, and the daily flow is 21,117 m^3. The capacity of the waterways is 21,020 m^3. In the case of stopping the pump station due to, for instance, power shortage or other failures, the time to fill the waterways is approximately 17.3 hours. A "2+1" (two are working, one is waiting) pump work program for a period of three months should be implemented in the pumping station. The "2+1" system means a continuous operation of two pumps and periodic connection of a third pump.

In the shaft there are 2 collectors, which transport water to the surface and the sedimentation tank. The outer diameter of the collectors is 500 mm. The collectors are run in parallel, close to each other. The suction pipelines supplying water from the well to the pumps have a diameter of 300 mm, while the diameter of the discharge-side pipelines connecting the pumps with the collectors is 250 mm. The pumped water is very salty; therefore, it should be expected that the inner of the pipeline and/or collector is heavily corroded, which increases the flow resistance.

The main design assumptions were based on mining regulations and accounted for, among others, the following assumptions:

- The devices, together with the main drainage systems, should enable the discharge of the highest daily water inflow in a time not longer than 20 hours.
- If the pump chamber is equipped with pump units, the number of pumps in these units is at least:
  - 5 pumps – with 2 pumps working in a group,
  - 7 pumps – with 3 pumps working in a group.
- Main drainage devices should have at least two discharge pipelines, with a total capacity not less than the total rated capacity of the required number of installed pumps, at a flow velocity of not more than 3 m/s.

In the main drainage pumping stations, measurements were carried out that were necessary to perform the flow characteristics of the pumps (Zimroz et al., 2014; Korbiel, Biały & Czerwiński, 2016; Pawlik, 2020). The following were measured: volumetric in the manifold, pressure in the suction, and discharge nozzles, as well as the engine's electrical power. An ultrasonic flowmeter FlowKat 200 was used to measure the flux. Pressures were measured with dial gauges: vacuum with a vacuum gauge using a range of 0.1–0 MPa and discharge pressure via pressure gauges with a measuring range of 0–8 MPa. Electric power consumption was determined with a SENTRON PAC3200 analyzer. The pumps were throttled by means of valves installed in the pipelines connecting the pumps with the main collector. In some pumps, it is possible to close the valves with actuators controlled from the supply cabinet; in the remaining pumps, the valves were closed manually. The valve opening degree was not known, but it was controlled by manual operation. Measurements were performed after establishing the flow conditions. After changing the degree of opening of the gate valve, the system worked for a few minutes and, after that time, the operating parameters were read. Measurements of pumping units no. 2, 3, 4, 5, 6, and 7 were carried out in the pumping station. The remaining units were under renovation or, for operational and technological reasons, were not active. The exemplary measurement results of pump 2 are presented in Table 2, while the collective results for the highest flow for all tested pumps are presented in Table 3. The measurement results were used to determine the total pressure (the pump head), power output, and pump efficiency.

On the basis of the measured values, the operating parameters were calculated (Skotniczny et al., 2010), which are presented in the tables. The pump head height, H_u, is determined from the relationship:

$$H_u = \frac{p_t - p_s}{\rho g} + \frac{c_t^2 - c_s^2}{\rho g} + \Delta h_m \tag{1}$$

where p_s and p_t represent the pressure in the suction and discharge ports, respectively, c_s and c_t are the water velocity in the suction and discharge ports, respectively, and Δh_m is the height of the excess of the discharge pressure gauge in relation to the suction pressure gauge, $\Delta h_m = 0.6–0.7$ m.

The velocities in the suction and discharge nozzles are calculated using the volume flow of water and the cross-sectional area of the nozzles, i.e.:

$$c = \frac{Q}{A} \tag{2}$$

where c denotes the average water velocity in the nozzles, Q is the water volume flow, and A is the cross-sectional area, in which the diameter of the suction port D_s = 300 mm and the diameter of the discharge port D_t = 250 mm.

Table 2. Operation parameters of the pump unit no. 2

No.	Suction pressure	Discharge pressure	Stream	Electrical power	Speed at the suction port	Speed at the discharge port	Pump head	Power output	Efficiency of the pump unit	Pump shaft power	Pump efficiency
	p_s	p_t	Q	P_{el}	c_s	c_t	H_u	P_u	η_{zp}	P_m	η_p
	bar	bar	m^3/min	kW	m/s	m/s	m	kW	[–]	kW	[–]
1	–0.47	50	8.4	1138	1.98	2.85	515.2	707.6	0.622	1081.1	0.654
2	–0.47	51	8.2	1132	1.93	2.78	525.4	704.4	0.622	1075.4	0.655
3	–0.47	52	8.1	1130	1.91	2.75	535.5	709.2	0.627	1073.5	0.661
4	–0.47	53	8	1128	1.89	2.71	545.6	713.6	0.633	1071.6	0.666
5	–0.46	54	7.9	1118	1.86	2.68	555.7	717.7	0.642	1062.1	0.676
6	–0.45	55	7.6	1117	1.79	2.58	561.4	697.5	0.624	1061.1	0.657
7	–0.44	56	7.3	1104	1.72	2.48	571.6	682.2	0.618	1048.8	0.650

Table 3. Cumulative operating parameters of the pump units

No.	Suction pressure	Discharge pressure	Stream	Electrical power	Speed at the suction port	Speed at the discharge port	Pump head	Power output	Efficiency of the pump unit	Pump shaft power	Pump efficiency
	p_s	p_t	Q	P_{el}	c_s	c_t	H_u	P_u	η_z	P_m	η_p
	bar	bar	m^3/min	kW	m/s	m/s	m	kW	[–]	kW	[–]
2	–0.47	50	8.4	1138	1.98	2.85	515.2	707.6	0.622	1081.1	0.654
3	–0.48	48.4	9.8	1150	2.31	3.33	489.7	784.68	0.682	1092.5	0.718
4	–0.48	48.0	6.9	988	1.63	2.34	494.9	558.3	0.565	938.6	0.595
5	–0.48	46.4	10.2	1145	2.38	3.43	478.5	790.19	0.690	1087.8	0.726
6	–0.48	49	8.6	1185	2.03	2.92	505.1	710.23	0.599	1125.8	0.631
7	–0.48	48	8.9	1108	2.10	3.02	494.9	720.17	0.650	1052.6	0.684

Effective power, i.e., power transferred to the stream of pumped water, is determined from the relationship:

$$P_u = \rho g H_u Q \tag{3}$$

The efficiency of the pump unit is related to the power supplied to the electric motors, i.e.:

$$\eta_{zp} = \frac{P_u}{P_{el}} = \frac{\rho g H_u Q}{P_{el}} \tag{4}$$

The power on the pump shaft was found by accounting for the efficiency of the electric motor. A constant value of motor efficiency was assumed ($\eta_{sel} = 0.95$ for newer motors and $\eta_{sel} = 0.93$ for older ones). Pump shaft power is determined from:

$$P_m = \eta_{sel} P_{el} \tag{5}$$

and pump efficiency from:

$$\eta_p = \frac{P_u}{P_m} = \frac{\eta_{zp}}{\eta_{sel}} \tag{6}$$

Dependencies (1)–(6) were used to calculate the pump flow characteristics (Figures 1 and 2).

The pump regulation range is small; it is a natural consequence of the purpose of the pumps and their primary role in the mine drainage. The pumps operate with full openings of the valves in order to minimize energy losses resulting from flow resistance, which shortens the operation time. The highest value of the water volumetric corresponds to the normal operation of the pump, i.e., when the valves are fully open (Michlowicz & Wojciechowski, 2021).

Table 4 presents the results of measurements and calculations of the pump operation parameters at full opening of the valves. This state corresponds to the highest efficiency of the pumps and a lack of throttling of the flow. The energy losses occurring in the transport of water under these conditions correspond to the flow resistance that results from the configuration and geometry of the pipeline system. The tables also include the relative pump head, defined as the ratio of the effective head in real conditions, H_u, to the catalog head of the pump, H_{uk}, at the same flow. The values of this fraction can be interpreted as a measure of the correctness of the pump selection for the task of lifting water to the required height. Calculating the ratio value H_u/H_{uk} allows us to determine whether the pumps are correctly matched to the requirements of the pumping system. The H_u/H_{uk}

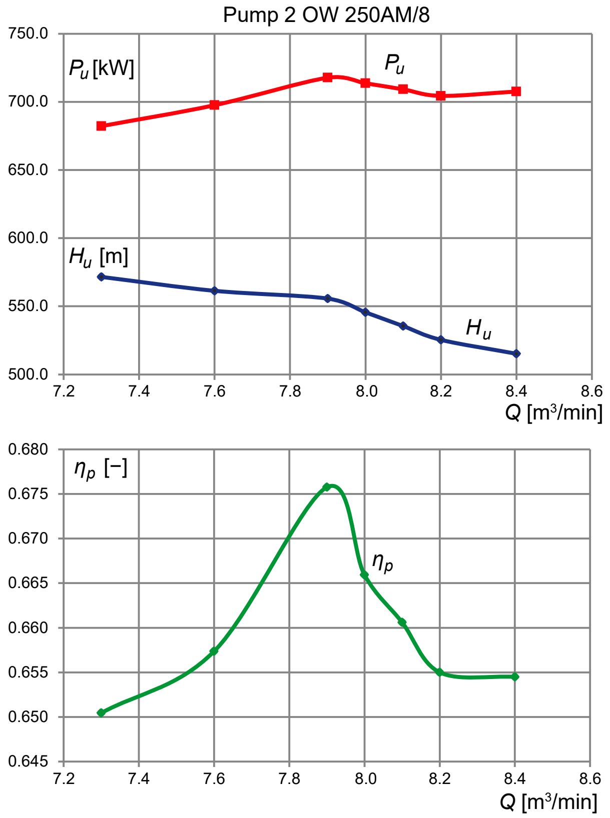

Figure 1. Flow characteristics of pump 2 – OW250AM/8: effective head $H_u = H_u(Q)$, useful power $P_u = P_u(Q)$, and pump efficiency $\eta_p = \eta_p(Q)$

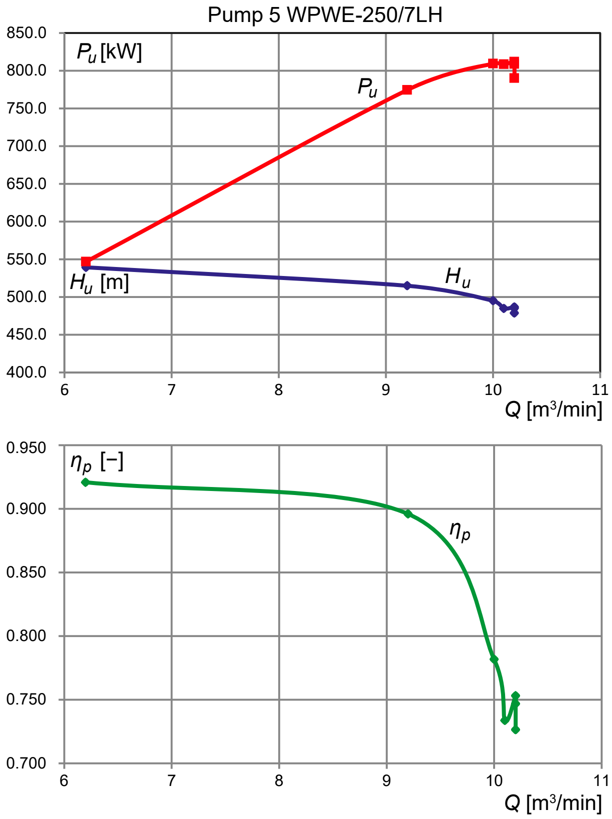

Figure 2. Flow characteristics of pump 5 – WPWE-250/7LH: effective head $H_u = H_u(Q)$, useful power $P_u = P_u(Q)$, and pump efficiency $\eta_p = \eta_p(Q)$

value at the level of 0.93 for the pumping station indicates a slight degree of oversizing of the pumping system (Tajduś et al., 2017).

The value of the fraction of the efficiency factor, η_p, to the catalog efficiency, η_{pk}, of the pump at a steady stream of water can be taken as a measure of the quality of the pump condition. The lower the value of this ratio, the worse condition of the pump in its operation. The pumps operating in the pumping station have a value of this ratio above 0.82, while the average value for all pumps is 0.85, which means that the pump quality can be interpreted as good (Janus, Skotniczny & Richert, 2019).

Table 4 also shows the coefficients determining the energy consumption of the pumps, q_P, and the costs of water pumping, q_E. The q_P factor indicates the amount of electricity in kWh required to pump out 1 m^3 of water. On the other hand, the q_E coefficient determines the cost of pumping 1000 m^3 of water at a price of PLN 280/MWh.

For pumps operating in the pumping station, the energy consumption of the process is q_P = 1.873–2.387 kWh/m^3; the average value is q_P = 2.155 kWh/m^3. The costs of pumping out 1000 m^3 of water in the pumping station are q_E = 524–668 PLN/1000 m^3, while the average value is q_E = 600 PLN/1000 m^3. The costs of pumping water are also shown in Figure 3; here, the red line is the average value for the main drainage pumping station in the shaft. In Table 4, the yellow highlighting indicates the estimated values of the energy consumption coefficient and unit costs in the situation of pump operation with catalog head and pump efficiency at measured water streams (Korbiel & Wojciechowski, 2019).

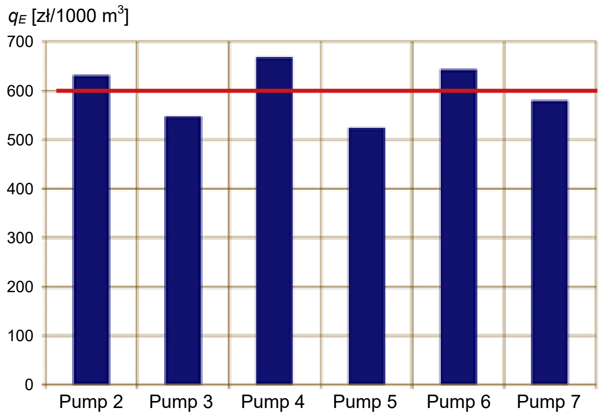

Figure 3. Cost of pumping 1000 m^3 of water in the pumping station

Analysis of the work of pumping units

Ten pump sets are used for the main drainage (engine – multi-rotor pump). The sets work with 100% redundancy – in a parallel system (Białecka & Prażak, 2019). The diagram of Figure 4 shows a list of ten pumps marked from P1 to P10.

The capacity of the water galleries is 22,020 m^3 (i.e., after about 18 hours, when the pumps are not working, flooding of the underground galleries occurs). Water seepage to the mine is 20.22 m^3/min; i.e., 1213.2 m^3/h on average approximately 873,500 m^3/month. The pump capacity determined in the tests is on average 8.6 m^3/min, i.e., 516 m^3/hour. Thus, there is a need for 2.35 pumps, i.e., approximately 1690 hours of pump operation/month (Table 5 – column SUM). The operating times of individual pumps during the year are summarized in Figure 5.

Determination of the efficiency of pumping sets

A diagram of the relationships that determines the efficiency is shown in Figure 6, while the results of the calculations are presented in Table 6 (Zgrzebski, Laskowski & Danis, 2022).

Table 4. List of pump operation parameters at maximum efficiency

		Pump 2	Pump 3	Pump 4	Pump 5	Pump 6	Pump 7	Mean
Volume flow, Q	m^3/min	8.4	9.8	6.9	10.2	8.6	8.9	8.8
Useful lifting height, H_u	m	515.2	489.7	494.9	478.5	505.1	494.9	496.7
Relative lift height, H_u/H_{uk}	–	0.93	0.99	0.82	0.98	0.92	0.92	0.93
Electric power, P_{el}	kW	1138	1150	988	1145	1185	1108	1119
Pump efficiency, η_p	–	0.654	0.718	0.595	0.726	0.631	0.684	0.668
Relative pump efficiency, η_p/η_{pk}	–	0.87	0.86	0.82	0.87	0.84	0.92	0.85
Electricity consumption, q_P	kWh/m^3	2.257	1.957	2.387	1.873	2.299	2.075	2.155
Cost of pumping water, q_E	zł/1000 m^3	632	548	668	524	644	581	600
Electricity consumption, q_{Pk}	kWh/m^3	2.119	1.690	2.642	1.675	2.090	2.048	2.005
Cost of pumping water, q_{Ek}	zł/1000 m^3	593	473	740	469	585	574	561

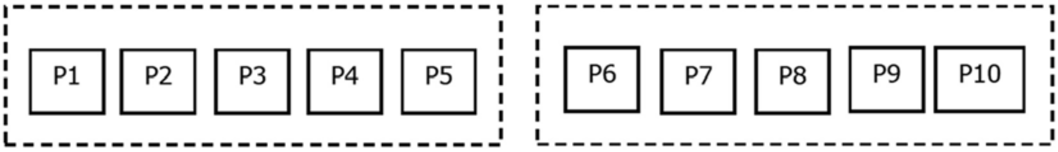

Figure 4. Scheme of parallel redundancy of the main pumping station

Table 5. Example of an annual summary of the use of pumps

Month	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	SUM
	Working time [hours]										[hours]
I	bd	bd	bd	bd	bd	bd	bd	bd	bd	bd	
II	233	0	65	0	0	508	45	0	725	7	**1583**
III	5	1	8	0	153	50	5	621	50	662	**1555**
IV	0	0	0	0	169	0	42	734	0	727	**1672**
V	0	0	72	35	611	49	44	85	610	125	**1631**
VI	0	355	108	0	344	0	37	0	551	98	**1493**
VII	0	714	742	0	0	35	43	0	0	95	**1629**
VIII	0	695	578	0	9	3	40	62	0	160	**1547**
IX	0	696	94	0	74	0	13	744	0	350	**1971**
X	0	647	0	0	173	1	8	603	0	178	**1610**
XI	0	34	0	710	134	0	22	34	0	713	**1647**
XII	0	0	0	725	190	0	0	0	0	722	**1637**
SUM	**238**	**3142**	**1667**	**1470**	**1857**	**646**	**299**	**2 883**	**1936**	**3837**	**17,975**
Average/month	**21.6**	**285.6**	**151.4**	**133.6**	**168.8**	**58.7**	**27.2**	**262.1**	**176.0**	**349**	**1634.1**

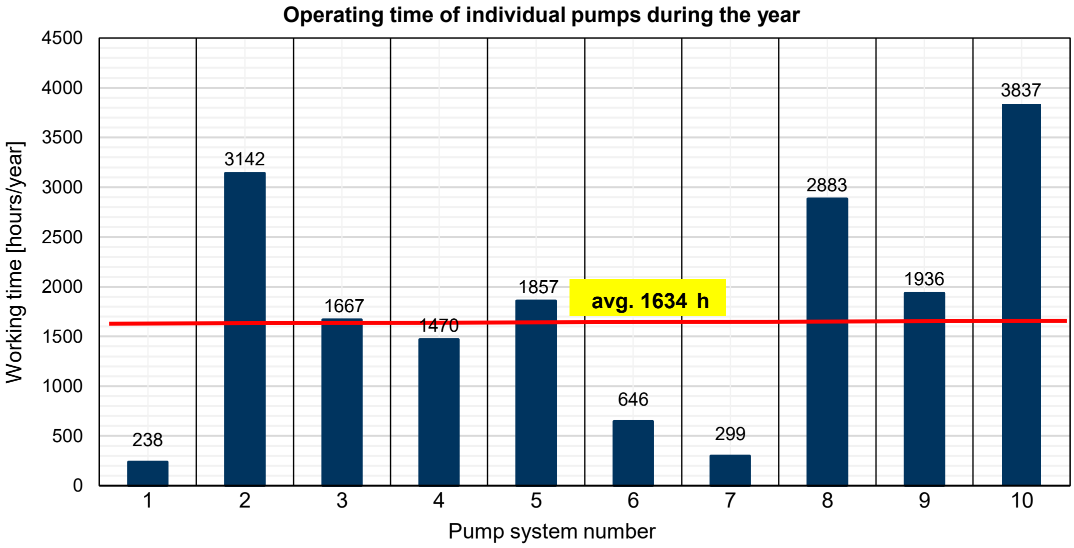

Figure 5. Diagram of the operation times of the P1 – P10 pump units

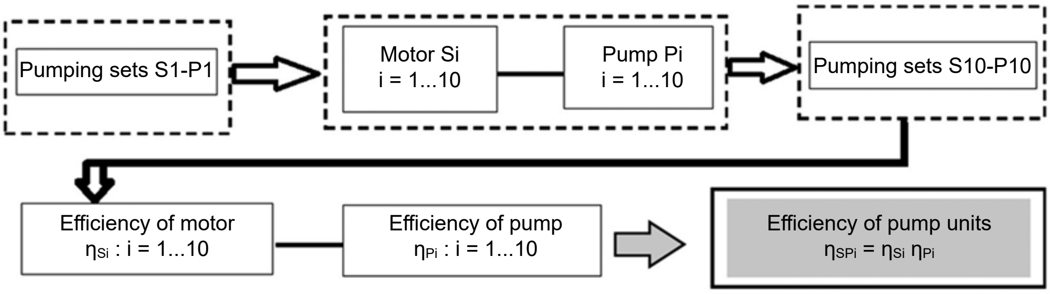

Figure 6. Scheme for determining the efficiency of pump units

Table 6. Efficiency of the pumping units in the pumping station

No.	Set	Pump efficiency	Set efficiency [%]
1	Pump No. 1	0.65	62
2	Pump No. 2	0.52	49
3	Pump No. 3	0.69	65
4	Pump No. 4	0.59	56
5	Pump No. 5	0.73	69
6	Pump No. 6	0.63	59
7	Pump No. 7	0.68	65
8	Pump No. 8	0.59	56
9	Pump No. 9	0.66	63
10	Pump No. 10	0.68	65

Economic evaluation of the operation of main drainage pumps

The operating costs, K_{exp}, are the sum of all costs related to the operation of the pump units, i.e.:

$$K_{\mathrm{exp}} = K_{\mathrm{zak}} + K_E + K_{ob} + K_{\mathrm{deg}} \tag{8}$$

where K_{zak}, K_E, K_{ob}, and K_{deg} are the purchase, energy, service, and degradation/repair costs, respectively.

The purchase costs constitute the cost of installing a complete set consisting of an engine with elements of electrical equipment for pumps, foundation system, and installation. The purchase value depends on the selection of the system, manufacturer, method of operation, etc. For further analysis, the value of K_{zak} = PLN 1,000,000 was adopted, which is an indicative value. The full-service life of the set was also assumed, amounting to 15 years of operation. This value is mainly related to the operating parameters of the engine. The pledge efficiency of 8 m^3/min was also assumed; the requirement is 2.5 pumps.

The cost of electricity was assumed to be the full load of the system. Considering the engine power of 1250 kW and the assumed electricity price of PLN 380/MWh, the energy cost is PLN 475/h, i.e., PLN 4,161,000 per year. It should be noted that due to the dynamically changing environment, the price of electricity fluctuates significantly, especially at the turn of 2021 and 2022 (d'Obyrn, 2013).

The cost of service was assumed to be the average remuneration amounting to PLN 6,000 per month (the employer's cost, i.e., including tax, for which all contributions are paid to the Social Insurance Institution and contributions to PPK or PPE). The worker operates all the pumps in the pumping station. The calculations ignored the increase in the minimum wage in the analyzed period.

The cost of degradation includes all the expenses related to the reconstruction of the technical condition of the pump unit. The most dynamic degradation process is observed at the pump. Its elements are subject to wear, which can be regenerated or replaced. Based on the analysis of the available materials, the cost of pump renovation was assumed to be PLN 300,000. Also supposed is an average time between renovation of 10,000 h (i.e., approximately 14 months). The operating costs should include the costs of engine degradation (replacement of bearings), the cost of lubricants, the replacement of seals, etc. These costs were assumed to be the amount of PLN 5000 per year.

Scenario I

The total cost of operating one pump is shown in Table 7. It has been assumed that the pump will operate continuously throughout its lifetime, i.e., 15 years.

It should be noted that the total cost of operation is mainly determined by the cost of electricity (92.09%). For the purposes of this analysis, a pledge expenditure at 8 m^3/min for one pump was assumed. Assuming full efficiency, the pump will pump

Table 7. Pump operating costs in scenario I

Operating cost component	Cost	Share in total cost	Remarks
K_{zak}	1,000,000 zł	1.47%	–
K_E	62,415,000 zł	92.09%	Annual energy cost – PLN 4,161,000.
K_{ob}	432,000 zł	0.64%	Annual cost of servicing 2.5 pumps – PLN 1,080,000. An employee operates 2.5 pumps.
K_{deg}	3,932,145 zł	5.80%	14 months – time between subsequent renovations. Renovation cost for 1 year: PLN 257,143. Annual other degradation costs – PLN 5000.
Total	67,779,145 zł	100.00%	–

Table 8. Pump operating costs in scenario II

Operating cost component	Cost	Share in total cost	Remarks
K_{zak}	1,000,000 zł	2.89%	–
K_E	31,207,500 zł	90.08%	Annual energy cost – PLN 4,161,000.
K_{ob}	432,000 zł	1.25%	Annual cost of servicing 2.5 pumps – PLN 1,080,000. An employee operates 2.5 pumps.
K_{deg}	2,003,571 zł	5.78%	14 months – time between subsequent renovations. Renovation cost for 1 year: PLN 257,143. Annual other degradation costs – PLN 5000.
Total	34,643,071 zł	100.00%	–

4,204,800 m^3 per year, i.e., 63,072,000 m^3 during 15 years of operation. Considering the adopted assumptions and the costs included in Table 7, the cost of pumping out 1 m^3 is PLN 1.07.

Scenario II

The total cost of operating one pump is shown in Table 8. It has been assumed that the pump will operate continuously throughout its service life, i.e., 15 years, and the pump load will be 50%.

Assuming a pledge expenditure of 8 m^3/min for one pump with 50% efficiency, the pump will pump 2,102,400 m^3 per year, i.e., 31,536,000 m^3 during 15 years of operation. Taking into account the adopted assumptions and the costs included in Table 8, the cost of pumping out 1 m^3 is PLN 1.10.

Assuming the required total flow rate of 20 m^3/min, a load of 2.5 for the pump is necessary. Accounting for the costs of operating the pumps presented in scenarios I and II, the total cost of the pumping station's operation over a period of 15 years will amount to PLN 170,201,361. In turn, the annual cost of the pumping station, consisting of 3 units, will amount to PLN 11,346,757.43.

The conducted analyzes show that the cost of operation is mainly determined by the cost of electricity – it accounts for over 90% of the total cost. The cost of electricity depends on the price and the efficiency of the pump unit. Therefore, actions aimed at improving efficiency should result in a significant improvement in the financial results.

Table 9. Energy consumption and the annual cost of electricity for the process

Efficiency	Energy consumption in PLN/m^3	Annual cost of electricity (20 m^3/min)
100%	0.52	5 466 000
80%	0.65	6 833 000
75%	0.69	7 253 000
70%	0.74	7 779 000
65%	0.80	8 410 000
60%	0.87	9 145 000
55%	0.95	9 986 000
50%	1.04	10 933 000

The energy needed to pump out 1 m^3 is 1000 kg × 9.81 m/s^2 × 500 = 4.9 MJ = 1.36 kWh. Therefore, for different efficiencies, the energy consumption of the process has the values presented in Table 9.

Conclusions

The conducted research and analyzes have shown that the dominant cost of operating the drainage of the main underground coal mine is the cost of electricity. The amount of energy in relation to the amount of water pumped out depends on the efficiency of the pumping machines. The introduction of energy indicators made it possible to determine the unit operating costs of the pumping station. Considering the electricity prices, a 10% efficiency improvement can reduce costs equivalent to buying new equipment. Thus, the continuous analysis of the efficiency of machines, in conjunction with the optimal scenarios of the system operation, can significantly reduce the overall operating costs. The recommendations presented in the article were implemented in one of the mines. Preliminary economic data show the effectiveness of the proposed solutions.

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