Model investigations into assessing optimal power consumption modes for major pump stations of iron ore underground mines

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Abstract. The article investigates into the level of energy efficiency of main water pump stations of iron ore underground mines in case of time-of-day electricity rate. There are developed and suggested methods of analyzing the influence of pump electric capacity on electricity cost based on multifactor regressive models. The data on power consumption of iron ore mines indicates a complex character of analyzing the results obtained. However, application of information technologies enables using static materials in a new way including indices of power consumption, costs, water intake, mining depth, the number of pumps and their capacity by synthesizing mathematical models as complicated objects through in-depth procession of static materials and substantiation of the obtained results. For the first time, there are used multifactor regressive models considering multicollinearity and non-linearity of pump capacity in order to study its influence on power costs by using the elasticity factor. Analysis of mathematical simulation results relevant to static materials and applying the algorithm of studying dependency of the consumed power costs on pumps' capacity reveals some critical values resulting in corresponding effects. The authors recommend to apply the elaborated algorithm to conducting corresponding calculations by for mining enterprises to monitor formation of the strategy of providing energy efficiency under time-of-day electricity rates.

1 Introduction

Mining enterprises are considered energy-intensive or, to be exact, electric power-intensive [1-4]. The fact that power makes about 90% of the whole energy consumption and over 30% of the cost forms the basic component of the current level and constantly increasing power-intensity of mineral mining, thus negatively affecting mining enterprises' economy and their competitive character on the international market of raw materials [3-5].

The characteristic of the research object. The problem of controlling power supply and consumption in terms of some technological factors is challenging and real-life among other issues of reducing energy-intensity of mineral mining [6-7]. To do this, there are some positive steps taken at mining enterprises including ore underground mines. Among those, are a limited number of energy-intensive consumers consuming about 90% of the total power (Fig. 1) [8, 9]. Facts like these a priori are highlighting the vector-related character of developing the strategy of researching into control over power-supply/consumption of such enterprises by transforming energy-intensive consumers into power regulators [8-10]. Besides, this process is stimulated by the *Law on power in Ukraine* which has actually intensified the 'power load' on mining enterprises, thus enhancing this process [8].

2 Research materials

Analysis of distributing power consumption levels among energy-intensive consumers of iron ore underground mines enables or rather testifies to the individual character of each enterprise (Fig. 1).

Without generalizing solutions to the energy-efficiency problem of all energy-intensive consumers of iron ore underground mines, from all the mentioned issues (Fig. 1), we focus on investigating into power consumption and control levels of major pump stations.

According to Fig. 1, Batkivshchina mine has the highest power consumption level, while Hvardiiska – the lowest. It should be noted that besides typical conditions of pump stations, unlike other power consumers, they are noted for functioning not only in periods of enterprises' active operation, but also after their full or partial conservation (closure) [3-5].

It is essential to accentuate that power consumption of pump stations at non-operating underground mines is actually higher than that of operating ones (Fig. 2-3) [9-

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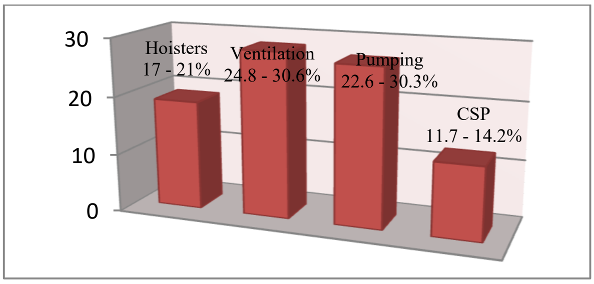
12]. At some underground mines, systems of underground water pumping are often combined into a single power complex. This causes some additional aspects affecting the choice of a pumping scheme design and operation modes of corresponding equipment.



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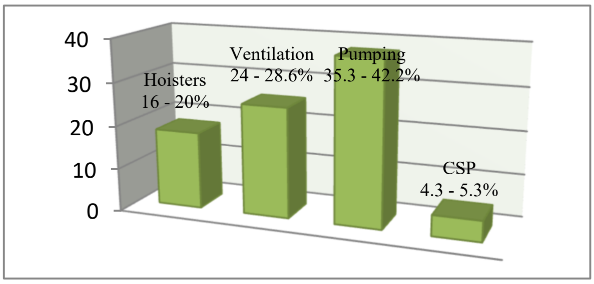

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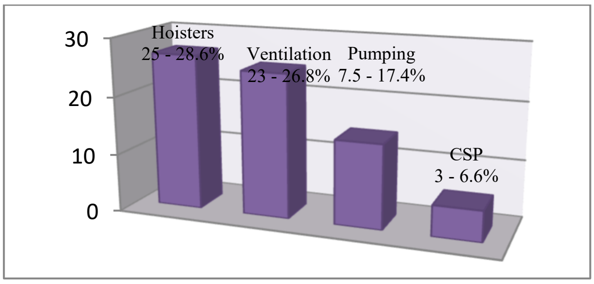

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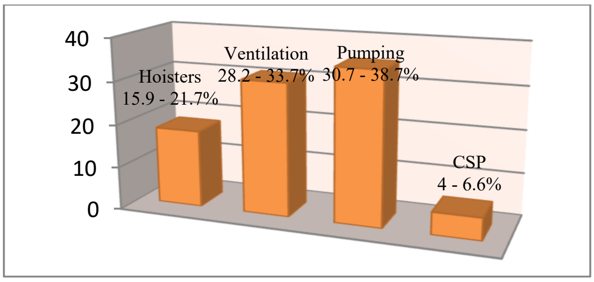

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Fig. 1. Variations of power consumption levels by types of mine consumers: a – Zhovtneva, b – Batkivshchina, c – Hvardiiska, d – Ternivska.

Yet, the basic component forms the foundation for the pumping structure of an individual underground mine and remains as given in Table 1.

According to Fig. 2-3, power consumption levels do not change greatly form year to year and tend to be stable.

Energy efficiency of underground mining enterprises' pump stations can be enhanced by:

- improving the technology of their 24-hour functioning and transferring them from the maximum pumping to a more economical mode of power consumption;
- creating return-water pump stations.

The latter will allow mining enterprises to generate their own electric power. The algorithm of major pump stations functioning is as follows: during 'economical time periods' water is pumped from the mine into the surface to corresponding water storage ponds, while during 'non-economical' ones, part of water from those ponds is pumped to the mine and pump motors start generating power [11-14].

Table 1. Established capacity of motors at Kryvyi Rih underground mines.

Mine	Motors		
	Capacity, kW	Number	Total capacity, kW
Ternivska	800	9	7200
	315	4	1260
	250	4	1000
			Total 9460
Hvardiiska	800	9	7200
	630	3	1890
	500	1	500
	315	3	945
			Total 10535
Zhovtneva	800	8	6400
	400	8	3200
			Total 9600
Batkivshchina	800	20	16000
	560	6	3360
			Total 19360

In other words, the power supply complex structure is transformed into the distributed power generation pattern [8].

With that, it is also necessary to develop (elaborate) the structure of pump stations' functioning under the power generation mode and upgrade the pump stations themselves both under the pumping mode and the power generation one.

To analyze the given process, one should develop mathematical models to analyze and elaborate trends of implementing theoretical results.

It is possible by introducing modern system-based approaches and mathematical and statistical methods.

By analyzing power consumption of pump stations, we can identify basic impact factors for individual iron ore underground mines (Table 2) [15-19].

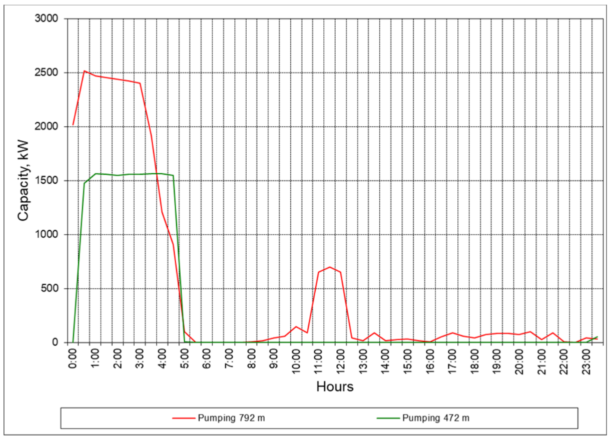
While treating a power-consuming object (an underground mine) as a structural scheme, we can single out some input changes with controlling and disturbing actions of a corresponding energy-intensive unit, while the total electricity load of a mine is an output value.

In its general form, the mathematical model of the iron ore underground mine's consumption can be set by the function of input variables [6]:

$$P_{\Sigma} = F(\nu, n_i, Q_j, Q_{\omega}, q_j, R_j) \quad (1)$$

where P_{Σ} is the total electric load of a mine, kW/year; ν is intensity of the skip hoister functioning, t/year; n_i is the number of operating pumps at the j-th pumping stage, units; Q_j is efficiency of the j-th mine fan, (m^3/sec); Q_{ω} is total efficiency of underground mining sites, (t/year); q_j is water inflow for the *j-th* pumping stage, (m^3/sec); R_j is resistance of the fan network of the j-th main mine fan. For model (1) variables v, n_j, Q_j are controlling, while Q_w, q_j, R_j are disturbing.

a)



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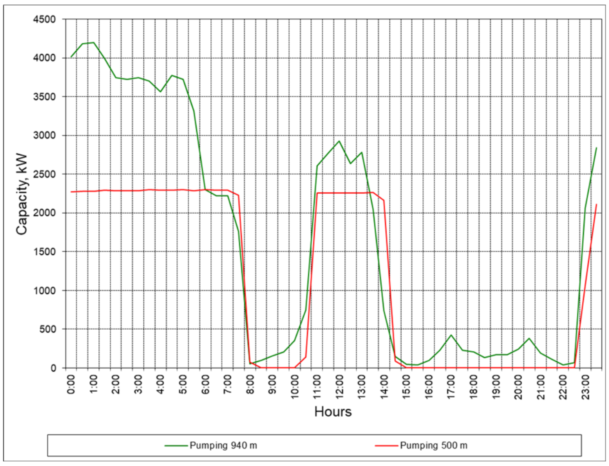

c)

d)

Fig. 2. Power consumption levels at major pump stations of some Kryvyi Rih iron ore mines in May 7, 2012: a – Ternivska, b – Hvardiiska, c – Batkivshchina, d – Zhovtneva.

Table 2. Basic factors impacting Kryvyi Rih iron ore mines' power consumption.

Power consumption of pump stations, kW/year			**Mining depth, m**	**Water inflow, m^3**			**Number of pumps, units**	**Capacity, kW**
2014	2015	2016		2014	2015	2016		
Ternivska								
11307677	10742330	8984057	1350	1585407	1494432	1211279	4	315
Hvardiiska								
9888508	8258434	6556150	1350	1310352	1136586	844396	3	315
Zhovtneva								
1037486	9293986	8482342	1265	1466460	1273886	1167783	1	400
Batkivshchina								
25801367	26878130	25583364	1465	4416601	4619121	4394257	4	800

According to established formalization, power consumption of pump stations can be set as:

$$P_\Sigma = F(v_1, n_i, q_j, R_j) \qquad (2)$$

where P_Σ is total power load of corresponding pump stations, kW/year; v_1 is a level, m; n_i is the number of operating pumps at the j-th pumping stage, units; q_j is water inflow for the j-th pumping stage, (m^3/sec); R_j is capacity, kW.

For (2), variables v_1, n_i, Q_i are controlling, while R_j is disturbing.

After considering the diagram of total power load realization of various combinations of input variables and recognizing dependency of power consumption of corresponding pump stations on controlling and disturbing actions, we can control functioning of the energy-intensive station according to the set criterion.

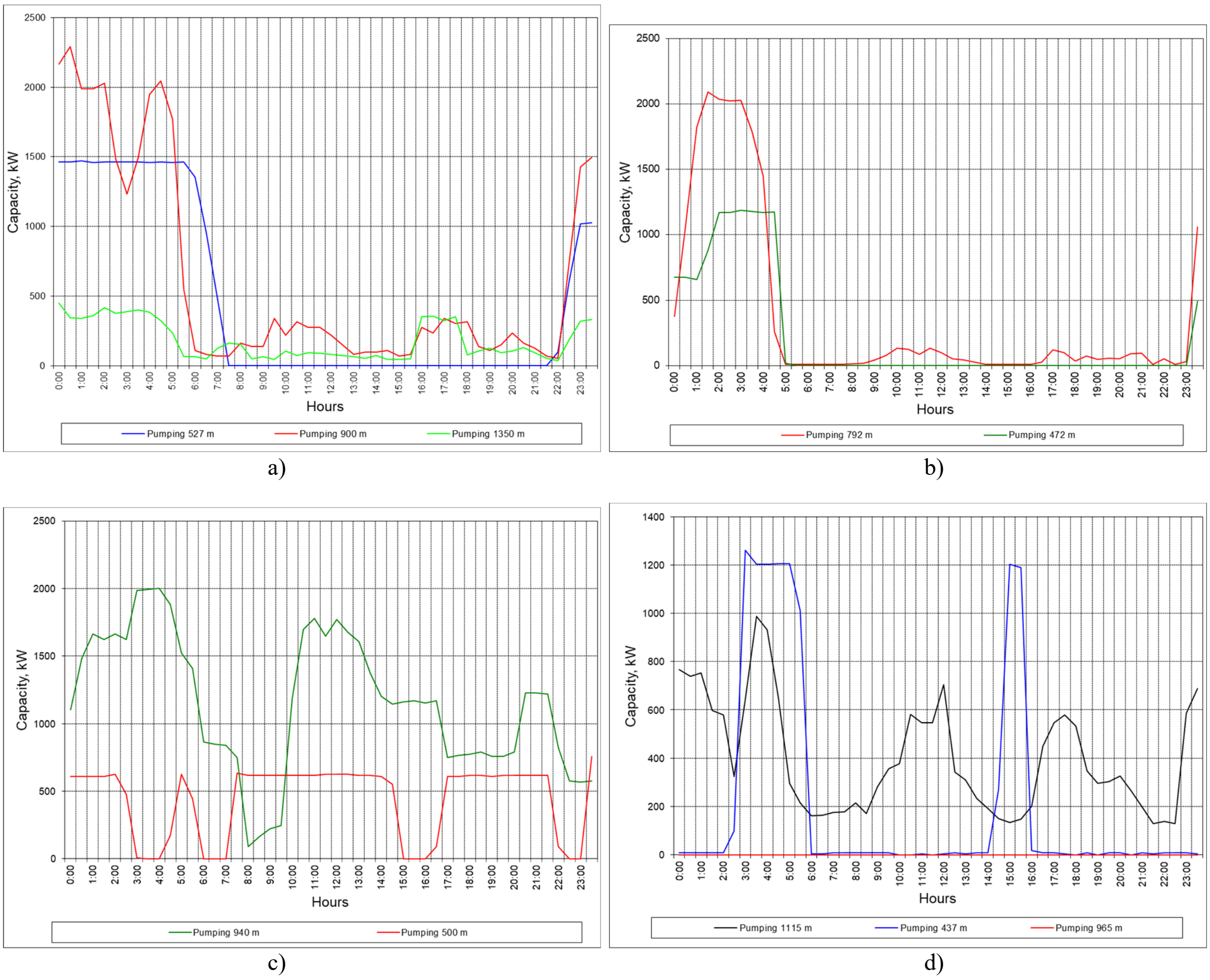

Fig. 3. Power consumption levels at major pump stations of some Kryvyi Rih iron ore mines in February 15, 2019: a – Ternivska, b – Hvardiiska, c –Batkivshchina, d – Zhovtneva.

The simplified two-area time-of-day rate can be written as:

$$C_\Sigma = C_\partial + C_н \qquad (3)$$

where C_∂, $C_н$ are expenditures considering two-area (day, night) rates, *UAH*.

Besides, we can write:

$$C_\Sigma = C_1 \cdot W_\Sigma, C_н + C_2 \cdot W_\Sigma,$$

where C_1, C_2 are area rates, *UAH/kW*.

According to [9], the maximum effect of controlling consumption is achieved by reducing loads in peak hours of the power system. In this case, the formula for expenditures required to minimize loads for pump stations can be set as the criterion:

$$C = \frac{C_1}{T_1}\int_0^{T_1} P_\Sigma\,(t)dt + \frac{C_2}{T_2}\int_0^{T_2} P_\Sigma\,(t)dt \rightarrow min \qquad (4)$$

where T_1, T_2 are selected intervals of day and night hours, *hours*.

Thus, the problem involves finding values controlling variables$v_1(t); n_i(t); g_i(t)$ which, with set values of disturbing actions R_j will form the diagram of power consumption $P_\Sigma(t)$ that will have the criterion at least (4). The choice of values of controlling actions should consider some technological constraints associated with continuity of the process and provision of standard working conditions at an underground mine. The conditions include:

- keeping the accumulating underground bunker unfilled:

$$\int_0^T Q_ш(t)dt = \int_0^T v(t)dt, \qquad (5)$$

- keeping the water level in water storage ponds stable:

$$\sum_{j=1}^{n}\int_0^T q_j(t)dt = \sum_{j=1}^{n}\int_0^T Q_{nj}\cdot n_j(t)dt, \qquad (6)$$

where Q_{nj} is efficiency of a pump of the *j*-th pumping rate, m^3/sec; n is the number of pumping stages.

Real-time solution to the given problem with constraints (5) and (6) calls for application of calculation controlling devices and industrial programming controllers. On the first stage, they should forecast power consumption of an underground mine and provide a controller with recommendations for taking relevant controlling actions.

Meanwhile, reduction of criterion (4) in a general form is quite a complicated task even when applying computers. To simplify this problem, it is expedient to divide total target function (4) into local target functions.

The solution provides for in-depth preliminary analysis of the factor research.

For comparative analysis, we use Z-scaling to obtain a single interpretation system for indices equaling from 0 to N.

By way of illustration, we accentuate the research conducted at Batkivshchina mine with the largest water inflow among underground mines of Kryvyi Rih iron ore basin. Thus, we obtain the following diagram:

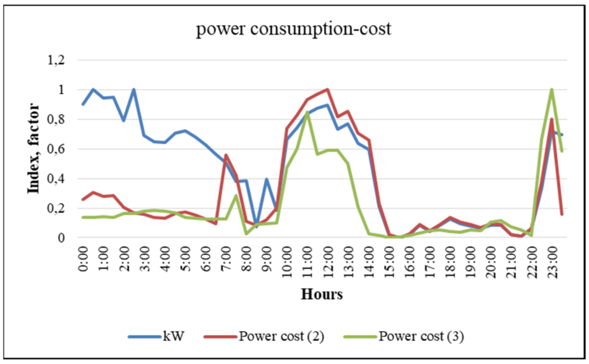

Fig. 4. Dependency of power consumption and its cost on the time of the day.

Visual analysis of the diagram enables stating some correlation of power costs and time-of-day power rates (Fig. 4). Yet, after totaling the output data, we observe excessive power costs for area power rates in comparison with the two-area one. In other words, it is expedient to conduct a multifactor research into power consumption. In a general case, the form of the multifactor regressive model is indefinite. Yet, while investigating into efficiency of power consumption, it is reasonable to use a linear form of a model structure representing it in an additive manner. On the basis of Batkivshchina mine data, $\hat{Y}$ is the consumed power cost (UAH), x_1 is water inflow (m^3/year), x_2 is mining depth (m), x_3 is the number of pumps (units), x_4 is motor capacity (kW) [9-12],

$$\hat{Y} = a + a_1x_1 + a_2x_2 + a_3x_3 + bx_4^2 + \varepsilon , \qquad (7)$$

where a, a_1, a_2, a_3, b are parameters; ε is uncontrolled disturbance.

The next step of building the model involves identification of parameters through determining their values that are included into (7).

Processing output data in MS Excel enables identifying these parameters by the least-square method.

The multifactor regressive model results in the following (7).

To identify multicollinearity, according to the output data, we build a correlation matrix of input variables.

$$R = \begin{pmatrix} 1 & 0,886 & 0,702 & 0,572 \\ 0,886 & 1 & 0,665 & 0,611 \\ 0,702 & 0,665 & 1 & 0,420 \\ 0,572 & 0,611 & 0,420 & 1 \end{pmatrix} \qquad (8)$$

Analysis of correlation table (8) reveals that there is a close correlation between variables x_1 and x_2 which indicates multicollinearity. As the variable x_1 can be expressed by x_2, the variable x_1 can be excluded from input variables. The correlation matrix of input variables results in the following:

$$R_1 = \begin{pmatrix} 1 & 0,665 & 0,611 \\ 0,665 & 1 & 0,420 \\ 0,611 & 0,420 & 1 \end{pmatrix} \qquad (9)$$

Analysis of correlation matrix (9) indicates no close correlation between input variables, i.e. there is no multicollinearity.

In the given research, it is reasonable to apply a linear model representing it in an additive form.

Identification of model parameters by processing the corresponding statistic materials enables finding these parameters by means of the least-square method. Multifactor regressive model (9) results in:

$$Y = -0,391x_2 + 2,728x_3 + 33,23x_4 \qquad (10)$$

With that, the determination factor makes R^2 = 0.824, while the Fischer criterion is F = 14.1. The table value of the Fischer criterion is $F_T(0,05;3;8) = 4,07$. As $F = 14,1 > F_T(0,05;3;8) = 4,07$, equation (10) is statistically significant.

Absence of the nonlinear member for pump capacity indicates a monotonous character of dependency of power costs on pump capacity.

Thus, on the basis of the simulation results for Batkivshchina mine, it is expedient to conclude that the influence of pump capacity on power costs is positive, i.e. it increases this value. With that, elasticity of power costs in compliance with pump capacity is calculated by:

$$E_{Y/x_4} = \frac{33,23x_4}{-0,391\overline{x}_2 + 2,728\overline{x}_3 + 33,23\overline{x}_4}, \qquad (11)$$

Fig. 5 shows the diagram of function (11).

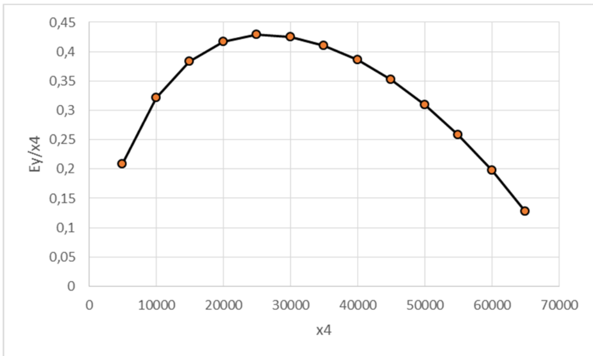

Fig. 5. Elasticity of power costs by pump capacity at Batkivshchina underground mine.

Analysis of Fig. 4 reveals that elasticity depends on power costs in compliance with motor capacity of Batkivshchina mine being positive and increases monotonously. Thus, there are developed methods of economic and statistical analysis that enable obtaining high-quality evaluation by using critical power costs depending on motor capacity as well as assessing its influence on power costs.

3 Conclusions

1. The suggested methods involve innovative approaches to evaluating power costs for operating pump stations of iron ore underground mines.
2. Application of modern IT enables digital methods of processing statistic data of power consumption indices including consumed electricity costs, the water inflow

level, the mining depth, the number of pumps and capacity of motors.

3. After synthesizing mathematical models as complex objects, the authors assess the influence of pump capacity on power consumption and conduct numerical analysis by using the elasticity factor to determine dependency of power costs on the capacity index of pump motors. This approach is worth applying in practice to forming the strategy of providing energy efficiency with time-of-date electricity rates.

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