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Assessment of energy efficiency improvement strategies for ventilation and hoisting systems during the reconstruction of the Molibden mine

R.V. Klyuev
Moscow Polytechnic University, Moscow, Russian Federation
✉ *kluev-roman@rambler.ru*

Abstract
The economic efficiency of high-performance mining enterprises largely depends on the parameters and operating modes of energy-intensive equipment. Ventilation fans and hoisting machines are traditionally considered among the most energy-intensive equipment. This study focuses on analyzing the operation of the main ventilation fans and hoisting equipment at the Molibden mine and on developing measures to ensure optimal operating conditions aimed at improving energy efficiency and reducing operating costs. The paper presents methods for evaluating the efficiency of mine ventilation systems, including analytical approaches applied in system design and performance assessment. The study draws on operational data from the Molibden mine. The analysis revealed that the ventilation fans were operating inefficiently, with excessive specific energy consumption. Consequently, the replacement of electric motors is proposed to reduce energy use and operational expenditures. Calculations indicate that the expected economic benefit from replacing the ventilation fan motors at the Molibden mine amounts to 4.9 million rubles per year. Based on an analysis of the hoisting equipment characteristics, a required motor power assessment was performed. The study demonstrates that the use of modern multi-rope hoisting systems with balanced designs is essential for improving operational efficiency. Measures to optimize equipment utilization are proposed, which would reduce the specific energy consumption associated with ore extraction. An analysis of eight years of data revealed an inverse correlation between ore output and specific energy use: a 10–15% increase in productivity results in a 2–5% reduction in specific energy consumption. Avoiding periods of low equipment utilization and implementing automated control systems can significantly enhance overall system efficiency. The findings of this study may be applicable to mining enterprises operating under similar conditions, particularly those engaged in deep-level mining.

Keywords
mine, energy efficiency, ventilation fans, mine ventilation systems, hoisting machines, electric motor, ore extraction, specific energy consumption, economic benefit

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ЭНЕРГЕТИКА, АВТОМАТИЗАЦИЯ И ЭНЕРГОЭФФЕКТИВНОСТЬ

Научная статья

Обоснование решений по повышению энергоэффективности вентиляторных установок и подъемных машин в условиях реконструкции рудника «Молибден»

Р.В. Клюев
Московский политехнический университет, г. Москва, Российская Федерация
✉ *kluev-roman@rambler.ru*

Аннотация
Экономическая эффективность высокопроизводительных горных предприятий во многом определяется параметрами и режимами работы энергоемких машин. Традиционно вентиляторные установки и подъемные машины считаются одними из самых энергоемких. Исследования направлены на анализ работы вентиляторных установок главного проветривания и подъемных установок рудника, а также на разработку мероприятий по обеспечению рациональных режимов их работы с целью повышения

энергоэффективности и снижения эксплуатационных затрат. В работе описаны методы расчета систем проветривания, включая аналитические, которые используются для проектирования и анализа режимов работы систем проветривания. В исследовании использованы данные о режимах работы систем рудника «Молибден». Выявлено, что вентиляторные установки работают неэффективно, с завышенным удельным расходом электроэнергии. В связи с этим предложены мероприятия по замене электродвигателей, что позволит снизить энергопотребление и эксплуатационные затраты. Расчеты показывают, что экономический эффект от замены двигателей вентиляторной установки на руднике «Молибден» составит 4,9 млн руб. в год. На основе анализа характеристик подъемных установок рудника проведен проверочный расчет мощности электродвигателей подъемных машин. Отмечено, что для повышения эффективности подъемных систем необходимо использовать современные многоканатные установки с уравновешенной конструкцией. Предложены меры по загрузке технологического оборудования, что позволит снизить удельный расход электроэнергии на добычу руды. Анализ данных за 8 лет показал обратную корреляцию между объемом добычи руды и удельным расходом электроэнергии. Увеличение производительности на 10–15 % снижает удельный расход энергии на 2–5 %. Исключение периодов низкой загрузки оборудования и внедрение автоматизированных систем управления позволят повысить эффективность установок в целом. Результаты исследования могут быть использованы для горнодобывающих предприятий с аналогичными условиями эксплуатации, особенно при глубокой разработке месторождений.

Ключевые слова

рудник, энергоэффективность, вентиляторные установки, системы проветривания, подъемные машины, электродвигатель, добыча руды, удельный расход электроэнергии, экономический эффект

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Introduction

Mine ventilation systems are essential engineering infrastructures that ensure safe and efficient working conditions in underground environments [1]. Unlike open-pit operations, where natural airflow plays a key role, underground mines are confined spaces with limited air exchange and an increased risk of emergencies [2, 3]. Ventilation systems are especially critical at gassy coal mines, where methane emissions into mine workings are difficult to predict [4, 5]. These emissions pose serious challenges for maintaining stable airflow, as well as for removing hazardous gases, dust, and excess heat generated by mining operations [6–8], particularly in relation to production output and the geometry of mine workings [9].

As the mining industry advances, it becomes increasingly important to assess the risk of accidents, develop scientifically sound methods for evaluating mine aerological hazards [1, 3], and implement modern tools and algorithms for setting appropriate ventilation modes in underground operations [10–12]. The complexity and diversity of system components call for integrated solutions that ensure the core functions of mine ventilation systems [13]. At the same time, engineering decisions must also reflect energy and cost efficiency, both of which play a decisive role in the overall performance of mining operations [14–16].

Ventilation fans – often with installed capacities of 5–7 MW at large-scale mines – and hoisting machines are among the most energy-intensive equipment in the industry. Their performance directly affects overall productivity, as they are critical components of the mine's material handling and safety infrastructure [17]. Modern hoisting systems are typically equipped with variable-speed electric drives to ensure reliable and efficient operation. Improving energy efficiency and optimizing the operation of both ventilation and hoisting systems therefore remains a pressing priority.

Research object. This study focuses on the Tyrnyauz Tungsten-Molybdenum Plant (TTMP), which is scheduled to resume operations in 2025.

The aim of the study is to analyze the performance of the main mine ventilation fans and hoisting machines and to develop strategies for optimizing their operation.

Methods. Evaluating the operating modes of mine ventilation systems and fans, as well as the performance of hoisting machines and their electric drives, is a complex engineering task. It requires a combination of theoretical and empirical approaches, the analysis of experimental data, and the use of modern computational techniques. The proposed optimization strategies for ventilation and hoisting systems are based on a techno-economic assessment. The central idea of the study is to determine the appropriate power ratings for the electric drives used in the main ventilation and hoisting systems at the reconstructed mine, with the goal of improving energy efficiency.

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Existing ventilation system at the Molibden mine

The Molibden mine is divided into two sections, each with an independent ventilation layout and equipment: the North-Western section and Central Shafts No. 1 and No. 2. Ventilation at the mine is provided by three types of axial-flow fans: VOKD-3.0, VOKD-2.4, and VOD-21. The VOKD-3.0 and VOKD-2.4 models are designed for main ventilation in large underground mines and shafts. Both are based on the TsAGN-K-06 aerodynamic design and have a standardized construction. Airflow is periodically adjusted by turning the impeller blades, while fine-tuning is achieved through intermediate guide vanes. The synchronous motors are excited using thyristor-based excitation systems equipped with reversing devices. The VOD series consists of reversible axial fans intended to replace the older VOK and VOKD models. These fans are built on the K-84 aerodynamic design. Airflow reversal is achieved by changing the direction of the impeller's rotation, while the intermediate guide vanes are fixed at an angle of 104° relative to the plane of the impeller's rotation.

Inspection and analysis of the main ventilation fans at the Molibden mine of the Tyrnyauz Tungsten-Molybdenum Plant

The consolidated results of the inspection and performance analysis of the main ventilation fans (MVFs) provide a comprehensive overview of their operation. Table 1 presents key parameters describing the performance of the ventilation fans used in the mine's ventilation system.

Table 1

Key performance parameters of main ventilation fans at the Molibden mine

No.	Parameter	Level 4 MVF-4	Level 4 MVF-1	Level 4 MVF-4a	Level 9 MVF-3	Level 6 MVF-6
1	Fan type	ВОКД-3,0	ВОКД-2,4	ВОД-21	ВОД-21	ВОКД-3,0
2	Impeller diameter, m	3	2.4	2.1	2.1	3.0
3	Impeller speed, rpm	600	735	750	750	600
4	Impeller peripheral speed, m/s	94.2	92.2	82.4	82.4	94.2
5	Airflow through the fan, m^3/s	90.4	64.7	56.0	76.0	96.7
6	Air delivered to the mine, m^3/s	73.7	47.9	42.7	61.3	91.4
7	Air losses in fan units, m^3/s	16.7	16.8	13.3	14.9	5.3
	Air losses, % of fan airflow	18.5	25.9	23.8	19.6	5.5
8	Total pressure generated by fan, mm H_2O	111.3	29.2	16.4	9.6	191.4
9	Total mine pressure drop, mm H_2O	90.7	21.0	16.4	10.0	0.9
10	Natural draught pressure, mm H_2O	1.2	1.5	–	1.4	2.3
11	Total mine depression, mm H_2O	91.9	22.5	16.4	11.4	3.2
12	Acoustic fluidity of the fan network, $kg \cdot s/m^5$	1.0	0.37	0.29	0.14	6.75
13	Resistance of sealing structures near the fan unit, kμ normal value, kμ	0.32 1.39	0.074 0.9	0.093 0.73	0.032 0.24	1.6 –
14	Mine resistance, kμ	0.0169	0.0114	0.009	0.0029	0.0218
15	Total resistance on fan, kμ	0.0138	0.0085	0.0052	–	0.02
16	Mine equivalent opening, m^2	2.9	3.6	4.0	7.0	2.7
17	Total equivalent opening for fan, m^2	3.3	4.2	5.3	–	2.6
18	Fan motor type	СДВ-15-64-10У3	А-13-42-8	СД-2-85-47-8У4	СД-13-42-8	СДВВ-15-39-10
19	Rated power, kW	1250	400	500	500	800
20	Power consumed from grid, kW	426.7	210	130	150	360
21	Shaft power of the fan, kW	393.4	187	116.3	135.5	326.5
22	Static efficiency of the fan: Based on electrical data weighted average	 0.25 0.7	 0.09 0.7	 0.08 0.72	 0.05 0.72	 0.55 0.7
23	Specific power consumption from the grid, kW/m^3: actual standard	 5.79 1.86	 4.74 0.48	 3.04 0.25	 2.45 0.15	 3.94 3.13

End of Table 1

No.	Parameter	Level 4 MVF-4	Level 4 MVF-1	Level 4 MVF-4a	Level 9 MVF-3	Level 6 MVF-6
24	Specific power consumption at the shaft, kW/m^3: actual standard	 5.33 1.73	 4.29 0.45	 2.72 0.24	 2.21 0.14	 3.57 2.95
25	Excess power use above standard, kW	289.6	188.7	119.0	141.0	74.0
26	Fan annual operating time, h	8570	8570	8570	8570	8570
27	Annual excess energy consumption of the fan unit, thousand kWh	2481.9	1617.2	1208.4	634.2	634.2
28	Electricity cost, RUB/kWh	6.0	6.0	6.0	6.0	6.0
29	Annual cost of excess fan energy consumption, thousand RUB	14891.4	9702	6118.8	7250.4	3805.2

Table 2

Fan specifications in the mine ventilation system

No.	Parameter	Fan specification				
		VOKD-2.4		VOKD -3.0		VOD-21
1	Impeller diameter, m	2400		3000		2100
2	Impeller speed (range), rpm	600	750	500	600	750
3	Airflow rate (range) Q, m^3/s	17–133	22–167	42–220	52–265	25–123
4	Static pressure H, kgf/m^2	300–110	475–170	340–94	450–135	350–100
5	Power consumption range, kW	50–400	100–780	125–825	200–1420	100–430
6	Static efficiency η_{fan}	0.6–0.77		0.6–0.77		0.6–0.81
7	Rotor moment of inertia, kg·m^2	4600		14200		2800
8	Fan weight (without motor), kg	18885		32000		11000
9	Installation dimensions, mm length height width	 18340 3500 3500		 18535 4480 4480		 13120 3190 3585

According to Table 1 (item 23), the main ventilation fans operate inefficiently in terms of energy use. Further investigation is required, along with the development of measures aimed at reducing the specific electricity consumption. As shown in Table 1 (items 19, 20, and 21), the installed motor capacities for MVF-4, MVF-1a, MVF-3, and MVF-6 significantly exceed the actual power drawn from the grid. A required motor power assessment should be carried out for the main ventilation fans.

Required motor power assessment for main ventilation fans

The motor power for ventilation fans is calculated using the following formula:

$$P = \frac{QH}{102\eta_{fan}}, \tag{1}$$

where Q is the airflow rate, m^3/s; H is the static pressure, kg/m^2; η_{fan} is the fan efficiency.

The motor is sized 10–15% above the calculated value to account for possible voltage drops:

$$P_{motor} = k_r P, \tag{2}$$

where k_r is the power reserve factor, k_r = 1.1–1.15.

The values of Q, H, and η_{fan} are presented in Table 2.

Table 3 provides information on the motors installed in the main ventilation fans.

For MVF-1 (VOKD-2.4 fan), the required motor power assessment yielded the following results:

P = 170.7–463.9 kW; P_{motor} = 510.3 kW.

The installed motor is model A-13-42-8 with a rated power of 400 kW.

Similar calculations were performed for the other main ventilation fans, and the results are summarized in Table 4

The calculations showed that the installed motor power significantly exceeds the required power determined by the assessment (see Table 4). It would be reasonable to replace them with lower-power motors. The final decision should be based on a techno-economic analysis, elements of which are presented below.

Table 3

Main ventilation fan motor specifications

MVF ID	Fan model	Motor model	Quantity	Rated power, kW	Rated voltage, V	Rated current, A	Rated speed, rpm	Efficiency, %	Power factor cos φ
MVF-1	VOKD -2.4	A-13-42-8	1	400	6000	48	735	92.8	0.85
MVF -1a	VOD-21	SD-2-85-47-8U4	1	500	6000	57	750	95	0.9
MVF -3	VOD-21	SD-13-42-8	2	500	6000	57.1	750	94	0.9
MVF -4	VOKD -3.0	SDV-15-64-10U3	1	1250	6000	141	600	95.3	0.9
MVF -6	VOKD -3.0	SDVV-15-39-10	2	800	6000	90.5	600	94.3	0.8

Table 4

Required motor power assessment results

MVF ID	Motor power range, kW	Calculated motor power, kW	Rated motor power, kW	Suggested replacement motor
MVF-1	170.7–463.9	510.3	400	–
MVF -1a	142.9–201.0	221.1	500	SDV-15-34-12 motor, rated power: 400 kW
MVF -3	142.9–201.0	221.1	500	
MVF -4	382.3–584.5	642.9	1250	SDVV-15-39-10 motor, rated power: 800 kW
MVF -6	382.3–584.5	642.9	800	–

Brief description and technical characteristics of hoisting systems at the Molibden mine

Two hoisting systems are currently in operation at the Molibden mine, located at the Kapitalnaya and North-West shafts. The Kapitalnaya shaft uses a simple single-rope hoisting system equipped with a drum-type hoist (model ShPM 4×36). However, such systems are characterized by low productivity, poor static balance, and other limitations. To improve the efficiency and reliability of hoisting operations at modern mining enterprises, multi-rope hoisting systems with balanced configurations are widely used. These provide higher productivity and reduce vibration during operation.

The primary function of the hoisting machine is to transport personnel and materials between levels 12 and 4 in a double-deck cage (type 2UKN-3.6-1). The technical specifications of the hoisting system at the Kapitalnaya shaft are presented in Table 5.

At the North-West shaft, a multi-rope hoisting machine of the MK-2.25×4 type is installed. The hoist features a single-motor drive operating on a generator–motor system. Its purpose is to transport personnel and materials between levels 4 and 1. The system is statically balanced by two flat-strand tail ropes. The hoist operates with a counterweight. The MK-2.25×4 hoisting machine is equipped with a gearbox. The gearbox is connected to the motor shaft via specially designed extended gear couplings. The technical specifications of the hoisting system are presented in Table 6.

Table 5

Technical specifications of the hoisting system at the Kapitalnaya shaft

No.	Parameter	Specification
1	Shaft depth to the lowest level, m	597
2	Shaft inclination angle, degrees	90
3	Hoisting machine type	ShPM 4×36
4	Hoisting height, m	600
5	Headframe height, m	18
6	Head sheave diameter, mm	3000
7	Number of service levels	8
8	Average hoisting speed, m/s	11
9	Hoisting cycles per day	14
10	Over-travel height, m	18
11	Cage type	2UKN-3.6-1
12	Rope type	PK-RO (6×36)+(7×71)
13	Gearbox type	Single-stage gearbox
14	Gear ratio	9,5
15	Number of drums	1 (welded from two segments)
16	Drum diameter, mm	4000
17	Drum width, mm	3500
18	Number of rope layers	1
19	Speed limiter type	RSO-5912
20	Static rope tension, N	175000
21	Static tension difference, N	117600
22	Conveyance mass, kg	4412
23	Maximum design load, kg	3700
24	Counterweight mass, kg	6250
25	Number of underground personnel per shift	276

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Table 6

Technical specifications of the hoisting system MK-2.25×4 at the North-West shaft

No.	Parameter	Specification
1	Shaft depth to the lowest level, m	597
2	Shaft inclination angle, degrees	90
3	Hoisting machine type	MK 2.25×4
4	Hoisting height, m	300
5	Number of service levels	4
6	Average hoisting speed, m/s	9.5
7	Sheave diameter, mm	2250
8	Over-travel height, m	7
9	Hoisting cycles per hour	18.2
10	Cage type	TKP-4.5
11	Sheave lining	PP-45
12	Number of ropes	4
13	Rope diameter, mm	21.5
14	End load, t: material hoisting personnel hoisting	 14.6 10
15	Counterweight mass, t	10
16	Number of tail ropes	2
17	Gearbox type	TsDN-130
18	Gear ratio	7.35
19	Conveyance mass, t	7.6
20	Payload capacity, t	7.0
21	Number of underground personnel per shift	276

Required motor power assessment for the hoisting machine

At the Kapitalnaya shaft, the following hoisting machines are in operation: a hoist equipped with a DA-170/29-12 electric motor rated at $P = 670$ kW; a hoist equipped with a PE-172-5K electric motor rated at $P = 630$ kW, operating on a generator–motor system. The estimated required power of the hoist drive motor at the Kapitalnaya shaft is determined by the following formula:

$$P_{cal} = \rho \frac{k}{\eta_g} P_{useful}, \quad (3)$$

where ρ is a coefficient determined from the dynamic operation characteristics, which depends on the moment of inertia of the hoist, its imbalance, and the velocity multiplier; k is a coefficient accounting for additional resistance-related load; η_g is the gearbox efficiency; P_{useful} is the useful power required for lifting a payload of mass m_{pl}, excluding system losses.

For a hoisting system with a single conveyance and a counterweight:

$$P_{useful} = \frac{(1-\psi) g m_{pl} \upsilon_{avg}}{1000}, \quad (4)$$

where ψ is a coefficient accounting for the degree of mass balancing between the payload m_{pl} and the counterweight; υ_{avg} is the average conveyance speed, m/s.

The coefficient ψ can be calculated using the following expression:

$$\psi = \frac{m_{cw} - m_{pl}}{m_c}, \quad (5)$$

where m_{cw} is the counterweight mass, kg; m_c is the conveyance mass, kg; m_{pl} is the payload mass, kg.

To account for potential voltage drops in the electrical network, the motor power is selected 10–15% higher than the calculated value:

$$P_{motor} = (1.1-1.15) P_{cal}. \quad (6)$$

For the hoisting system at the Kapitalnaya shaft (see Table 5): $m_{cw} = 6250$ kg; $m_c = 4412$ kg; $m_{pl} = 3700$ kg.

The calculated results of the hoisting motor power assessment are presented in Table 7.

Table 7

Results of required motor power assessment for the hoisting machine

Parameter	Value
Coefficient ψ	0.497
Useful power P_{useful}, kW	200.6
Estimated required power of the hoist drive motor P_{cal}, kW	453.12
Coefficient ρ	1.6
Coefficient k	1.2
Gearbox efficiency η_g	0.88
Motor power P_{motor}, kW	521.1

The calculated motor power satisfies the requirements of the motor currently installed on the hoisting machine at the Kapitalnaya shaft.

Methodology for estimating the economic benefit of optimal utilization of processing equipment

A study of the relationship between energy consumption and ore production volumes at the Molibden mine has shown that the specific energy consumption is strongly dependent on the mine's daily productivity. An analysis of data over an eight-year period revealed that the correlation between monthly ore production volumes and energy consumption ranged from 0.309 to 0.730. This indicates that an increase in ore output tends to result in a reduction in specific energy consumption.

An analysis of the ore production dataset showed a high degree of variability, as evidenced by a large standard deviation. Skewness and kurtosis were also observed, indicating an uneven distribution of values. Approximately 50% of the recorded values were significantly below the average, which suggests a predominance of periods with relatively low productivity. Therefore, reducing specific energy consumption at the Molibden mine requires limiting the duration of low-productivity operation and ensuring maximum equipment utilization.

To better understand how equipment utilization affects energy consumption, it is also necessary to analyze the structure of energy use at the mine. This involves disaggregating the total energy consumption into individual processes (such as drilling, blasting, transportation, crushing, and beneficiation) and examining the energy consumption of each technological stage. This analysis would allow for identifying the most energy-intensive operations and determining optimal operating modes for their implementation [18–20]. In addition, the potential for implementing automated production control systems should be considered. These systems can help maintain stable and high equipment utilization and minimize energy losses resulting from inefficient operating conditions.

Table 8 presents the results of the statistical analysis of the ore production dataset. Both the complete dataset (including all recorded values) and a truncated version (excluding values below the mean) were analyzed. This approach was used to evaluate the impact of excluding low-productivity periods on the overall statistical characteristics of the ore mass distribution.

The statistical parameters of the truncated data set were calculated using a theoretical method based on the Gram–Charlier distribution. The initial moment S of the random variable $Q \geqslant m_Q$ is defined as:

$$d_S = \frac{1}{P(Q \ge m_Q)} \int_{m_Q}^{\infty} Q^S f(Q) dQ, \quad (7)$$

where $P(Q \geqslant m_Q)$ is the probability that the values of Q in the truncated data set exceed the mean value m_Q of the original data set:

$$P(Q \ge m_Q) = \int_{m_Q}^{\infty} f(Q) dQ; \quad (8)$$

and $f(Q)$ is the theoretical differential probability density function of the random variable Q.

When the mean value of the extracted ore increases by

$$\Delta m_Q = m'_Q - m_Q \quad (9)$$

the specific energy consumption decreases by the amount $\Delta\omega$:

$$\Delta\omega = (a_2 m_Q + b_2) - (a_2 m'_Q + b_2) = a_2 \Delta m_Q, \quad (10)$$

where a_2 and b_2 are the coefficients of the regression equation: $\omega = a_2 Q + b_2$ (see Table 1);

$$\Delta\omega\% = \frac{\Delta\omega}{m_\omega} \cdot 100\%, \quad (11)$$

and m_ω is the mean specific energy consumption.

The annual energy savings due to improved equipment utilization is calculated as:

$$\Delta W = \Delta\omega m_Q \cdot 12. \quad (12)$$

Table 9 presents the results of the eight-year calculation.

The relationships between the mean extracted ore mass and energy savings, along with the corresponding approximating functions, are presented in Fig. 1.

Table 8

Results of ore production parameter calculations for the original data set (Q) and the truncated data set (Q')

Year	Parameters of the original data set (Q)				Parameters of the truncated data set (Q')				$P(Q \geqslant m_Q)$
	Mean $m_{Q'}$	Std. deviation $\sigma_{Q'}$	Skewness $A_{Q'}$	Kurtosis $E_{Q'}$	Mean $m_{Q'}$	Std. deviation $\sigma_{Q'}$	Skewness $A_{Q'}$	Kurtosis $E_{Q'}$	
1	316654	17684.7	0.0242	−0.884	331276	10110.2	0.515	1.81	0.498
2	321507	19443	0.628	−0.149	338543	13826.6	1.09	3.93	0.458
3	307690	26296	−0.11	−1.333	329750	14257	0.252	1.15	0.509
4	293556	29153	0.453	−0.708	319041	19075.5	0.853	3.25	0.47
5	313330	17720	1.25	1.57	329176	15817.6	1.303	3.84	0.417
6	324532	16496	1.05	0.129	339753	13151.6	1.106	3.69	0.43
7	327409	13743	0.146	0.084	338556	8708.1	1.111	4.25	0.49
8	324966	12102	0.512	−0.959	335743	7900	0.761	2.93	0.466

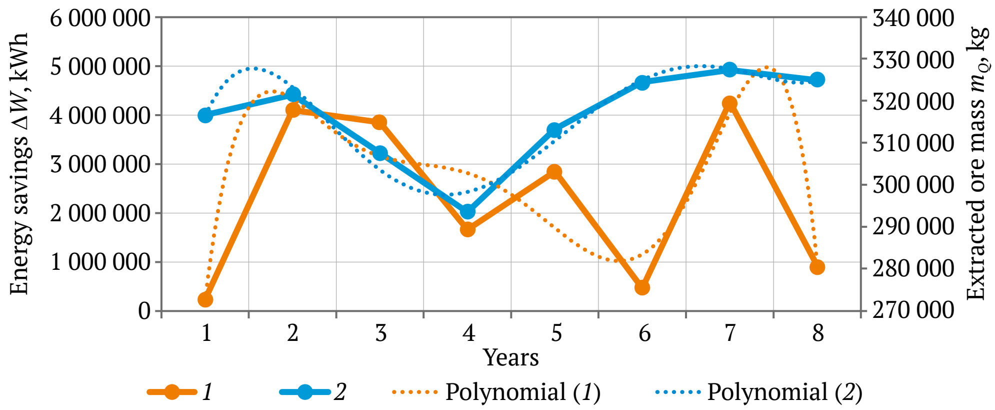

Fig. 1. Energy savings and extracted ore volume, along with their corresponding approximating functions: *1* – annual variation in energy savings; *2* – annual variation in extracted ore mass; trend lines represent polynomial models used for approximation of dependencies (*1*) and (*2*)

Table 9

Results of calculations for changes in specific power consumption Δω and electricity losses Δ*W*

Year	Δω, kWh/t	Δω, %	Δ*W*, kWh
1	0.061	0.315	231135
2	1.063	5.75	4101347
3	1.043	5.11	3852665
4	0.471	2.41	1660842
5	0.757	3.88	2847939
6	0.119	0.636	465320
7	1.09	5.63	4265685
8	0.238	1.32	928772

The expected energy savings are defined as the expected value of ΔW:

$$m_{\Delta W} = \frac{\sum_{i=1}^{n} \Delta W}{n}, \quad (13)$$

where $m_{\Delta W}$ = 2,294,213 kWh.

The cost of electricity under a two-rate tariff scheme is calculated as:

$$C = P_{\max} a + Wb. \quad (14)$$

The monetary savings are then determined as:

$$\Delta C = C_1 - C_2, \quad (15)$$

where C_1 is the electricity cost at the current consumption level: $C_1 = P_{\max} a + W_1 b$.

The electricity cost at full equipment utilization is as follows:

$$C_2 = P_{\max} a + W_2 b.$$

where a = 4300 rubles/kW and b = 6.0 rubles/kWh.

Thus,

$$\Delta C = (W_1 - W_2)b = \Delta Wb. \quad (16)$$

Economic benefit from replacing fan motor drives

According to the calculations (see Table 4), the electric motors installed in MVF-4, MVF-1a, and MVF-3 are significantly oversized relative to the actual load. For example: MVF-4: P_{cal} = 642.9 kW; P_{rated} = 1250 kW; MVF-1a and MVF-3: P_{cal} = 221.1 kW; P_{rated} = 500 kW. It is proposed to replace the motor of MVF-4 with an SDVV-15-39-10 motor rated at 800 kW, and the motors of MVF-1a and MVF-3 with SDV-15-34-12 motors rated at 400 kW.

The economic benefit of motor replacement is calculated as:

$$\Delta R = 0.12\Delta K + \Delta C_W, \quad (17)$$

where

$$\Delta K = K_1 - K_2,$$

here, K_1 is the total cost of the currently installed motors: 8.47 million rubles; K_2 is the total cost of the proposed replacement motors: 8.20 million rubles; ΔK = 0.27 million rubles. The motor cost values are presented in Table 10.

The cost of saved electricity is calculated using the two-rate tariff C.

Motor power losses, kW:

$$\Delta P = \Delta P_1 - \Delta P_2, \quad (18)$$

where ΔP_1 and ΔP_2 are the power losses of the existing and replacement motors, respectively.

Table 10

Motor costs

Motor type	Motor cost, million rubles
SDV-15-64-10U3	5.51
SD-2-85-47-8U4 SD-13-42-8	0.99
SDVV-15-39-10	4.0
SDV-15-34-12	1.4

Electricity losses, kWh:

$$\Delta W = \Delta P T, \qquad (19)$$

where T is the annual operating time of the fans, $T = 8570$ h.

Main electrical losses in the stator winding, kW:

$$P_{e1} = m I^2_{rated\ avg} r_1 10^{-3}, \qquad (20)$$

where r_1 is the active resistance of the stator winding, Ω, calculated as,

$$r_1 = \frac{\rho_\upsilon \omega_1 l_{avg}}{n_e q_e a}, \qquad (21)$$

where ρ_υ is the conductor resistivity adjusted for temperature (75 or 130°): $\rho_{\upsilon(75)} = (1/47)\cdot 10^{-6}$, Ω·m; $\rho_{\upsilon(130)} = (1/39)\cdot 10^{-6}$, Ω·m; ω_1 is the number of winding turns; $l_{avg} = 2(l_1 + l_2)$ is the average turn length; $n_e q_e$ is the effective conductor cross-section, mm²; a is the number of parallel branches in the winding.

Excitation losses, kW:

$$P_v = \frac{(I^2_{vrated} r_v + 2\Delta U_{bc} I_{vrated})\cdot 10^3}{\eta_v}, \qquad (22)$$

where $\Delta U_{bc} = 1$ V – voltage drop at the brush contact; $\eta_v = 0.80–0.85$ – excitation system efficiency; and r_v is the field winding resistance, Ω,

$$r_v = \rho_\upsilon \frac{2p\omega_1 l_{avg}}{q_l}. \qquad (23)$$

Mechanical losses, comprising bearing friction and ventilation losses, kW:

$$P_{mech} = 3.68p\left(\frac{\upsilon_r}{40}\right)^3 \sqrt{l_1}, \qquad (24)$$

where υ_r is the rotor peripheral speed, m/s; and l_1 is stator length, m.

Additional load losses, kW:

$$P_{add} = 0.005 P_{rated}. \qquad (25)$$

Total motor losses, kW:

$$\Delta P_1 = P_e + P_v + P_{mech} + P_{add}. \qquad (26)$$

The results of the motor loss calculations are provided in Table 11.

Total electricity losses and the corresponding are presented in Table 12.

Table 12

Total energy losses and economic benefit

Parameter	Value
Total losses in the first motor ΔP_1, kW	216.91
Total losses in the first motor ΔP_2, kW	129.5
Loss difference ΔP, kW	87.4
Energy losses ΔW, kWh	749,018
Cost savings ΔC, million rubles	4.87
Economic benefit ΔR, million rubles	4.9

Conclusion

1. The main mine ventilation fans at the Moliben mine operate with excessive specific energy consumption. An inspection of the fan units revealed that actual energy consumption significantly exceeds the standard values (for example, for MVF-4 the actual consumption was 5.79 kW/m³ compared to the standard 1.86 kW/m³). Required motor power assessments showed that the installed motors are oversized (e.g., 1250 kW for MVF-4 versus the calculated requirement of 642.9 kW). It is proposed to replace the motors with more appropriately rated units (e.g., 800 kW instead of 1250 kW for MVF-4), which will reduce energy consumption and operating costs. The expected annual economic benefit from motor replacement is 4.9 million rubles due to reduced energy losses.

2. An eight-year data analysis revealed an inverse correlation between ore output and specific energy consumption. A 10–15% increase in productivity leads to a 2–5% decrease in specific energy consumption. Reducing periods of low equipment utilization and implementing automated control systems can help minimise energy losses. The estimated annual energy savings amount to 4.87 million rubles.

3. The Kapitalnaya shaft currently operates with an outdated single-rope hoisting system (ShPM 4×36), which has limited productivity and lacks static balance. It is recommended to upgrade to modern multi-rope

Table 11

Power loss calculation results for all motors

Motor type	Electrical losses in the stator winding P_e, kW	Excitation losses P_v, kW	Mechanical losses P_{mech}, kW	Additional load losses P_{add}, kW	Total motor losses ΣP, kW
SDV-15-64-10U3	90.66	16.1	16.4	6.25	129.4
SD-2-85-47-8U4 SD-13-42-8	10.1	14.5	2.07	2.5	29.17
SDVV-15-39-10	32.98	20.8	7.83	4	65.6
SDV-15-34-12	6.28	10.82	2.21	2	21.3

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systems (e.g., MK-2.25×4), which provide higher performance, reduced vibration, and a statically balanced design. Required motor power assessments confirmed that the installed motor capacity (670 kW) meets the calculated requirements. In addition, modernizing the control systems could further improve the overall efficiency of the hoisting operation.

4. A theoretical method based on the Gram–Charlier distribution was used to calculate the statistical parameters of the truncated dataset. Equations were derived to calculate and forecast ore production volumes and the corresponding energy savings.

5. The implementation of the proposed measure will not only improve energy efficiency but also enhance environmental performance by reducing emissions. The findings of this study may be applicable to other mining operations with similar working conditions.

6. Future research may explore the use of artificial intelligence for forecasting equipment operating modes and optimizing energy consumption in real time. A detailed breakdown of energy use across key processes (e.g., crushing, transportation) is needed to enable targeted efficiency improvements.

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Information about the author

Roman V. Klyuev – Dr. Sci. (Eng.), Professor of the Department of the Automation and Control, Moscow Polytechnic University, Moscow, Russian Federation; ORCID 0000-0003-3777-7203, Scopus ID 57194206632; e-mail kluev-roman@rambler.ru

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