Improving the energy efficiency of transport equipment in ore mining

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Abstract. The article presents a General principle for evaluating the norms of specific energy consumption rates for ore extraction at mining enterprises, including the determination of daily well penetration and conversion coefficients of specific consumption for individual operations. Specific norms of electric power consumption for excavating and drilling are determined according to the developed methods. Analyzing the nature of the waveforms, it can be concluded that the greatest energy consumption during excavation is accounted for by the scooping process. When comparing individual cycles on oscillograms, it is seen that at almost the same maximum power, equal to 0.465 MW, a significant difference in the energy consumed per cycle (from 4.9 to 8.2 MW·s) occurs due to different scooping times. The economic feasibility of improving the crushing of rock mass by explosion to reduce the specific cost of electricity was determined, which allowed us to conclude that it is not advisable to make additional investments in drilling and blasting operations in order to reduce electricity consumption. As for drilling machines, the average electrical power consumed by one machine is determined based on the results of measurements. The power consumption was recorded taking into account the shunting operations of the machine. By integrating the load curve using the averaged area method, the amount of electricity consumed by the machine per shift is obtained.

1. Introduction

Mining enterprises are among the most energy-intensive, occupying a significant part of the country's energy balance. The increase in electricity consumption by the mining industry is determined by the growth in the volume of mineral extraction, changes in recent years in mining and geological conditions (increased overburden, increased rock strength, etc.), the use of modern powerful machines and mechanisms. These circumstances confirm the need for analysis, rational use of electricity consumption, scientifically based rationing and forecasting of specific electricity consumption. The technical justification of electricity consumption rates and the need to link them with indicators that characterize the influence of the most important production factors on the change in specific electricity consumption is relevant.

2. Methods and approaches

Statistical, experimental, and computational methods are used to establish specific energy consumption rates in the mining industry.
The power consumption of the quarries under consideration is due to the consumption of electricity for excavating and drilling. The share of other consumers (lighting, vulcanization of cable couplings, heating of residential premises of a complete distribution substation) is insignificant and can be estimated by taking into account the installed capacity of these consumers. Let's consider the possibility of using these methods to determine the specific rates of electric energy consumption for excavation and drilling.

The essence of the statistical method is that according to the reporting data, the monthly electricity consumption for the feeder to which excavators or machines are connected is divided by the monthly productivity of excavators or drilling machines. The disadvantage of the method is that it becomes impossible to judge the actual rational consumption of electric energy, i.e. there are no indicators of the quality of electric energy use [1-10].

3. General principle of estimation of specific energy consumption rates for open-pit mining

Rationing of electricity consumption and long-term planning of electricity consumption for ore extraction is carried out using technological specific rates for individual operations. At the quarries of the mining enterprise, electric power consumers are EKG-4.6 excavators and SBSH-250 drilling machines. The cost of lighting faces and sites can be taken into account additionally, based on the required specific lighting power.

If the specific power consumption (spc) for excavating and drilling is known, then the absolute specific consumption can be defined as:

\[ E_{spc.quarry} = \sum E_{spc}, \text{kWh} \]  \hspace{1cm} (1)

If in formula (1) the performance of the operation is represented in a tonne / day, then we get the result of the specific power consumption per day, if in a tonne / month, then the specific consumption will be monthly. In General, given the erratic nature of the quarry's work, the daily or monthly values of the quarry may not match.

The right part of the equation (1) consists of the specific rate for excavation and drilling. Since the drilling performance is measured in linear meters of the well, passed per day (month), the \( E_{spc.drilling} \) defined in kWh / m. At the same time, it is necessary to know the specific consumption of explosives per 1 tonne of rock mass.

The volume of the well: \( V_{well} = \pi \cdot D^2 \cdot l \) (m³), is related to the mass of explosives (ME) through the density of ME in the charge \( \gamma \):

\[ V_{well} = \frac{m}{\gamma} \cdot \text{m}^3 \]

Daily well penetration, resulting in daily productivity by rock mass:

\[ l_{specific} = \frac{m}{\gamma \cdot \pi \cdot D^2} \cdot \text{m} / \text{tonne} \]

We introduce the transition rates of the specific consumption of individual operations:

\[ E_{spc.op} = k_{op} \cdot E_{spc.op} \]  \hspace{1cm} (2)

In the expression (2):

\( E_{spc.op} \) - specific energy consumption for a specific operation (op), attributed to 1 tonne of ore produced;

\( E_{spc.op} \) - technological specific power consumption for this operation, kWh / unit of production. For example, for an excavator-kWh / tonne or kWh / m³, and for drilling – kWh / m;

\( k_{op} \) - the transition rate from the process specific consumption of electricity for mining a specific flow rate:
\[ k_{op} = \frac{P_{1day}}{P_{day}}, \]

where \( P_{1day} \) is the daily productivity of a unit of equipment (for example, an excavator); \( P_{day} \) – daily productivity of the quarry for the corresponding type of work.

4. Determination of the specific rate of electricity consumption for excavating operations

EKG-4,6 and EKG-8I excavators used in mining enterprises are the most energy-intensive consumers, so the study pays special attention to the issue of improving the accuracy of determining the specific rate of electricity consumption for excavator operations [11-20].

The calculation method for determining the specific power consumption rate for excavating is proposed to be implemented using the dependence \( E'_{spc}, \text{kWh/m}^3 \):

\[
E'_{spc} = \frac{k_m \cdot k_{lr} \cdot c \cdot \left( k_{lf,l} \cdot P_l \cdot t_l \cdot \frac{1}{\eta_l} + k_{lf,h} \cdot P_h \cdot t_h \cdot \frac{1}{\eta_h} + k_{lf,t} \cdot P_t \cdot t_t \cdot \frac{1}{\eta_t} \right)}{k_{fr} \cdot q},
\]

where \( E'_{spc} \) – specific power consumption;
\( k_m \) – coefficient that takes into account the power consumption for maneuvers (m) and preparation of the face;
\( k_{lr} \) – coefficient of loosening of rock (lr) in the bucket of the excavator;
\( c \) – coefficient that takes into account the efficiency of the network engine, generators, and power consumption by auxiliary mechanisms;
\( k_{fr} \) – the filling ratio (fr) of the bucket loosened rock;
\( q \) – bucket capacity, m\(^3\);
\( k_{lf}, P, \eta, t \) – load factor (lf), rated power, efficiency and duration of operation during the cycle of the lift (l), head (h) and turn (t) engines, respectively.

It is obvious that the calculation by expression (4) can only be performed for a special case, for a certain cycle time \( t \) and the engine load factor \( k_{lf} \).

Given that the product \( c \cdot \left( k_{lf,l} \cdot P_l \cdot t_l \cdot \frac{1}{\eta_l} + k_{lf,h} \cdot P_h \cdot t_h \cdot \frac{1}{\eta_h} + k_{lf,t} \cdot P_t \cdot t_t \cdot \frac{1}{\eta_t} \) \) in expression (4) represents the power consumption per cycle of excavation, it is possible to Refine the methodology with the results of statistical measurements of the power consumption per cycle. Indeed, if you install electricity meters at feeders of transformer substations, power shovels, it is possible, taking into account the losses of energy in the air networks of 6 kV cable lines, to determine with a specified degree of precision and accuracy, the amount of power consumption per 1 cycle. Let's denote this value \( E_{cycle} \).

5. Procedure for determining the \( E_{cycle} \) value

To determine the power consumption during the excavation cycle, the loading schedule was recorded for those feeders of the 6 kV complete distribution substation that feed either one excavator, or an excavator and a drilling machine. It is experimentally determined that the load of the SBSH-250 drilling rig remains constant for a considerable time, so the \( P_3(t) \) dependence graph can be converted into a load graph by subtracting the constant power component. This facilitates the conditions for conducting the experiment, without leading to a noticeable error in the results. Out of the obtained 126 oscillograms of excavator loads, 20 were selected, representing a representative sample. The representative criterion was the maximum repeatability of the load schedule with the number of excavator cycles corresponding to the average number of loading cycles per dump truck with an average body load of 154 tons. The load graphs were divided into intervals of 4 seconds (the abscissus axis), and to obtain the value of the
ordinate \( P(t) \), the values of the expectation value of instantaneous power \( M(P) \), the variance estimate \( D(P) \) (standard), and the standard deviation estimate \( \sigma \) were used. As a result of the analysis, a curve is obtained that characterizes the load graph of the main drive engine of the excavator, taking into account losses in the network with a confidence probability of 0.95.

To get the value of electricity consumed per cycle \( (E_{cycle}) \), need to integrate the value of instantaneous power \( P(t) \), i.e.:

\[
E_{cycle} = \int_{0}^{t_{cycle}} P(t) dt
\]

(5)

The integration of the \( P(t) \) curve is performed by the Simpson method. As a result of the calculation, the value \( E_{cycle} = 7.5 \text{ MW·s} \) is obtained for the confidence probability of 0.95. Knowing the value of \( E_{cycle} \), you can use the formula (4) to calculate the specific power consumption:

\[
E'_{spc} = \frac{k \cdot m \cdot k_{lr} \cdot E_{cycle}}{k_{fr} \cdot q}, \text{ kWh/m}^3
\]

(6)

If the production capacity is calculated in tons, enter the volume weight of the mineral in the array, \( \gamma \), tonne / m\(^3\) in (6). According to the data of the mining plant in question: \( \gamma = 2.8 \text{ tonne/m}^3 \) - for ore and 2.67-2.8 - for rock. Then:

\[
E_{spc} = \frac{E'_{spc}}{\gamma} = \frac{k \cdot m \cdot k_{lr} \cdot E_{cycle}}{k_{fr} \cdot q \cdot \gamma}, \text{ kWh/tonne}
\]

(7)

The \( k_m \) coefficient, which takes into account the power consumption for maneuvers and preparation of the face, is equal to 1.1-1.2 and for most literature data, it is assumed to be equal to 1.15. The \( k_{lr} \) and \( k_{fr} \) values are taken depending on the rock category for excavating. For a mining company, you should accept: \( k_{fr} = 0.95; k_{lr} = 1.35 \), which corresponds to the III category of rocks for excavation.

In this case:

\[
E_{spc} = \frac{1.15 \cdot 1.35 \cdot 7.5 \cdot 1000}{3600 \cdot 0.95 \cdot 8} = 0.425 \text{ kWh/m}^3.
\]

In terms of 1 ton of rock mass:

\[
E_{spc} = \frac{0.425}{2.8} = 0.125 \text{ kWh/tonne}.
\]

In the resulting result, for the specific power consumption for excavating, the error may be caused by the inaccuracy of determining the coefficient \( k_{fr} \), which takes into account the increase in power consumption for maneuvers by the excavator. To improve the accuracy of determining the cost of electricity for excavation, continuous oscillography of the power consumed by the high-voltage engine driving the power generator is carried out during the loading of 19 dump trucks that have shipped 2926 tons of ore to the ore pass, according to the operational data of the mining enterprise. On the oscillogram, 11-13 scoops were registered that characterize the loading of a single dump truck. The amount of energy determined by the entire sweep of the oscillogram for a working shift, obtained on the basis of the Simpson integral, is equal to 1710 MW·s. Based on this value, the unit cost of electricity for excavation:

\[
E_{spc} = \frac{1700 \cdot 1000}{3600 \cdot 2926} = 0.162 \text{ kWh/tonne}
\]
Analyzing the nature of the waveforms, it can be concluded that the greatest energy consumption during excavation is accounted for by the scooping process. When comparing individual cycles on oscillograms, it is seen that at almost the same maximum power, equal to 0.465 MW, a significant difference in the energy consumed per cycle (from 4.9 to 8.2 MW·s) occurs due to different scooping times. It is experimentally established that for the EKG-4,6 excavator, the duration of scooping can change from 6 to 10 seconds when the size of the average piece of rock mass changes from 20 to 60 cm.

Given that when the size of the average piece increases from 20 to 60 cm, the maximum power increases from 0.4 to 0.465 MW, and it can be assumed that improving the crushing of the array can, theoretically, reduce the power consumption of the excavator by 1.43 times. Accordingly, the specific consumption of electricity will be reduced by 1.43 times.

6. Determining the economic feasibility of improving the crushing of rock mass by explosion to reduce the unit cost of electricity

It is known that the change in the size of the average piece, with other equal parameters of fracturing, strength and rock category for explosiveness, can be achieved by variation in the specific consumption of explosives and increasing the running meters of wells by 1 ton of rock mass. Reducing the size of a piece from 60 cm to 20 cm in rocks of the V-th category of explosiveness can be achieved by increasing the specific consumption of explosives per 1 ton of rock mass from 0.65 to 0.9 kg / tonne. When loading wells in the manual way, ie by direct gravity precipitation, the density of explosives in the charge does not exceed 0.8 kg / dm$^3$, which corresponds to a well with a diameter of 255 mm, drilled at the mine of a mining complex with a capacity of explosives equal to 40 kg / 1 running meter. In the IV and V categories of rocks for explosiveness, the average yield of rock mass in quarries No. 1 and No. 2 is 35-40 m$^3$ per one linear meter of the well at the height of the ledge of 10 m. Therefore, to ensure annual production of 15,000 thousand m$^3$, which is approximately equal to the total productivity of quarries No. 1 and No. 2 in total, it is necessary to pass wells with a total length of:

$$l = \frac{15000 \cdot 10^3}{35} = 428 \cdot 10^3 \text{ m}$$

In order to reduce the size of the average piece to 20 cm, which provides a 1.43-fold reduction in electricity costs, it is necessary to increase the length of wells to be drilled by 1.38 times. Hence, $l' = 428 \cdot 10^3 \cdot 1.38 = 590.64 \cdot 10^3 \text{ m}$.

The total re-drilling of wells to achieve the previous performance will be: $\Delta l = 162.64$ thousand m.

The cost of improving crushing at the cost of 1 linear meter of the well 1400 rubles/m will be: Cost$\text{es} = 1400 \cdot 162.64 = 227.7$ million rubles.

Total electricity consumption for excavating the annual production volume at the mining enterprise:

$$W_{annual} = E_{spc} \cdot V_{annual} \div \gamma,$$  \hspace{1cm} (8)

where $\gamma$ - volume weight of ore (rock), tonne / m$^3$;
$V_{annual}$ - annual production of ore (rock), m$^3$.

$$W_{annual} = (0.162 - 0.152) \cdot \frac{15000 \cdot 10^3}{2.75} = 0.88 \cdot 10^6 \text{ kWh}$$

If the annual power consumption for excavating is reduced, which is achieved by improving crushing, the power consumption will be:

$$W_{annual} = \frac{0.88 \cdot 10^6}{1.43} = 0.62 \cdot 10^6 \text{ kWh}$$

Power saving: $\Delta W = 260 \cdot 10^3 \text{ kWh}$.

Cost of electricity saved (es):

$$C_{es} = \Delta W \cdot T,$$  \hspace{1cm} (9)
where \( T \) – the rate of payment for electricity, \( T=5.56 \) rubles / kWh.

\[ C_{ce}=260 \cdot 10^3 \cdot 5.56=1445.6 \text{ thousand rubles.} \]

Comparing the cost of electricity saved as a result of increasing the productivity of the excavation, with the costs that provide this savings, allows us to conclude that it is not advisable to make additional investments in drilling and blasting operations in order to reduce energy consumption.

7. Determination of the specific rate of electric energy consumption for drilling operations

Energy performance of drilling machines depends primarily on the type of drilling (type of machine) and physical and mechanical properties of rocks. In mining enterprises, rotary drilling with the help of roller bits has received the greatest use. Shock-robe drilling machines are not used. The quarries under consideration are provided with SH-250 machines with a 250 mm diameter roller bit. Based on the known data, the authors of which studied the power consumption during drilling, it is established that the power consumption during drilling is a random value that depends on the parameters and drilling modes. To apply the methods of probability theory to determine the regularities of power consumption, it is necessary to identify the factor that most fully takes into account the change in machine operating modes. Such a generalized factor is the category of rocks by drillability. The use of this factor is impractical for the following reasons:

- the value that characterizes the category of rocks by drillability is determined by the mechanical speed of drilling and is therefore an indirect value;
- classification of rocks by drillability is a very rough estimate of the properties of rocks in the local volume. Generalization of this parameter to the entire ledge on which preparations for the explosion are being made is illegal.

It is proposed to enter the accounting of machine mode parameters as a dependency of the type:

\[ 9 = k \cdot n^x \cdot P^y, \]  

(10)

where \( n \) – drilling speed;
\( n \) – the frequency of rotation of the bit, rpm;
\( P \) – axial load on the bit;
\( k, x, y \) – dimensionless empirical values that depend on the physical and mechanical properties of rocks and the type of bit.

The values of \( k, x \) and \( y \) were significantly different. Substituting their extreme values in the expression (10) gives a difference in determining the mechanical drilling speed of 2.3 times. In this regard, an experimental determination of the technological norm of power consumption was made. Measuring devices are installed on the chamber of the complete switchgear that feeds 1 and 2 drilling rigs. Based on the results of measurements, the average electrical power consumed by a single machine is determined. The power consumption was recorded taking into account the shunting operations of the machine. By integrating the load curve using the averaged area method, the amount of electricity consumed by the machine per shift is obtained.

Technological power consumption including shunting operations is determined by the expression:

\[ E = \frac{W}{M}, \]  

(11)

where \( W \) – the electricity consumption of the control shift (13 hours);
\( M \) – machine performance over the same time.

On average, for three SBSH-250 machines, the drilling performance was equal to 76.7 linear meters per machine per shift in the rocks of fortress 12-13 on the Protodiakonov scale. This corresponds to the average hourly productivity of the machine:

\[ 9 \text{ average} = \frac{M}{t} = \frac{76.7}{13} = 5.9 \text{ m / hour}. \]
The amount of electricity obtained from integrating the waveform: \[ W = 1450 \text{ kWh} \].

Specific power consumption: \[ E = \frac{1450}{76.7} = 18.9 \text{ kWh/m} \].

Dependence for analytical estimation of specific power consumption:

\[ E' = \frac{k \cdot P_{\text{average}}}{\eta_{\text{network}} \cdot \bar{v}_{\text{average}}} \]  

(12)

where \( k \) – coefficient that takes into account the power consumption for maneuvers, \( k = 1 \); 
\( P_{\text{average}} \) – average power developed by the machine (consumed from the network). Based on the results of the experiment: \( P_{\text{average}} = 111.54 \text{ kW} \);
\( \bar{v}_{\text{average}} \) – the average drilling speed. \( \bar{v}_{\text{average}} \) in the considered experiments was equal to 5.9 m/hour;
\( \eta_{\text{network}} \) – the efficiency of the network. \( \eta_{\text{network}} = 0.95-0.98 \). Take \( \eta_{\text{network}} = 0.96 \).

Then:

\[ E' = \frac{111.54}{5.9 \cdot 0.96} = 21.6 \text{ kWh/m}. \]

8. Conclusion

Specific norms of electric power consumption for the working cycle of the excavator, including scooping of rock mass with a bucket, its lifting, turning and unloading, reverse rotation of the bucket to the side, taking into account the loss of electricity in the elements of the electric network, are determined. Analysis of the oscillograms allowed us to establish that the highest power consumption corresponds to the scooping operation, the duration of which is determined by the lumpiness of the rock mass. The economic inexpediency of crushing rock mass by explosion in order to reduce the specific energy consumption and the time of the excavation cycle due to additional investment in drilling and blasting operations has been established. The result of processing graphs of power consumption by drilling machines is the technological power consumption of the SBSH, taking into account shunting operations. Calculation of economic efficiency based on a reasonable specific rate of electricity consumption, implementation of other recommendations for further reducing unproductive consumption and losses of electricity, improving the efficiency of technological equipment gives an amount exceeding 5 million rubles.

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