V International Scientific and Technical Conference Actual Issues of Power Supply Systems

Analysis of the Statistical Characteristics of Electric Energy Consumption Modes in Mining Enterprises

AIPCP25-CF-ICAIPSS2025-00368 | Article

Analysis of the Statistical Characteristics of Electric Energy Consumption Modes in Mining Enterprises

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Abstract. This study presents a comprehensive statistical analysis of the active power consumption of major technological electricity consumers at the 7th Hydrometallurgical Plant of Navoiy Mining and Metallurgical Combinat. The research covers key energy-intensive units involved in ore transportation, grinding, and hydrotransport, including conveyors, mills, and pumps. Real industrial measurements collected across all seasonal operating conditions were analyzed using mathematical statistics and probability theory methods. The Kolmogorov-Smirnov goodness-of-fit test was applied to identify the most appropriate theoretical distribution for each consumer's electrical load. The results show that the active power consumption of conveyors and several pumping units follows a Normal distribution, mills exhibit an Exponential distribution, while high-capacity pumps demonstrate behavior consistent with the Weibull distribution. The obtained statistical parameters—including mean, standard deviation, skewness, kurtosis, and load factor—indicate that most technological equipment operates under low load levels, resulting in incomplete utilization of installed capacity and reduced energy efficiency. The findings provide a reliable scientific basis for improving the accuracy of electrical load forecasting, optimizing operational modes, and developing energy-efficient control strategies for mining enterprises.

INTRODUCTION

Efficient management of electrical energy consumption is a critical factor in ensuring the operational reliability and economic performance of mining enterprises. Ore extraction, crushing, grinding, and hydrotechnical processes require continuous operation of high-power technological equipment, leading to significant electrical load fluctuations. Understanding the statistical nature of these fluctuations is essential for optimizing energy use, improving equipment performance, and reducing operational costs [1-3].

The 7th Hydrometallurgical Plant of Navoiy Mining and Metallurgical Combinat represents a complex technological system in which conveyors, mills, and pumping units constitute the core electricity consumers. These units operate under varying technological conditions, including seasonal temperature changes, ore hardness variations, and fluctuating material flow rates. As a result, their power consumption exhibits stochastic behavior that must be analyzed using advanced statistical tools [4-9].

This study addresses the need for a deeper understanding of the probabilistic characteristics of electricity consumption in mining operations. By applying mathematical statistics, probability theory, and hypothesis testing, the research identifies the most representative distribution laws for the active power consumption of major technological consumers. The results contribute to the development of scientifically grounded methods for optimizing energy consumption and enhancing the overall energy efficiency of mining production systems [10-14].

EXPERIMENTAL RESEARCH

Mining enterprises are high electricity-consuming users, and their level of electric energy consumption is continuously increasing. This trend is associated with changes in the conditions of mineral extraction and processing, the decline in the content of valuable components in the ore, the use of mechanisms with high electricity demand, as well as the implementation of environmental protection measures.

In mining enterprises, the main electricity consumers are involved in the ore grinding process.

Electric energy consumption is characterized by the following aspects:

1. Electricity consumption covers all seasons — winter, summer, and transitional periods between winter–summer and summer–winter.

2. Electricity consumption encompasses both the main type of operation (ore processing) and its technological stages (ore transportation, crushing, hydrotransport).

3. The main technological electricity consumers of mining enterprises are included, such as conveyors, mills, pumps, and others.

4. As a result of electricity consumption, the following parameters were measured:

- *Average voltage in phases and in the three-phase system;*
- *Average current in phases and in the three-phase system;*
- *Active power in phases and in the three-phase system;*
- *Reactive power in phases and in the three-phase system;*
- *Active energy in single-phase and three-phase configurations;*
- *Reactive energy in single-phase and three-phase configurations;*
- *Power factor by phases;*
- *Harmonic components from the 3 rd to the 52 nd order;*
- *Frequency.*

The electricity consumption modes cover all major electricity consumers involved in the ore grinding process of the mining enterprise and can serve as a basis for establishing reliable statistical calculations [15-19].

The experimental data obtained on electricity consumption modes include almost all major electricity consumers used in the ore grinding process of the plant. These data can serve as a scientific foundation for developing reliable statistical evaluation criteria and forming strategies for the efficient use of electrical energy.

The analysis of electricity consumption modes for ore processing and beneficiation in the production of finished products was carried out using probability theory and mathematical statistics methods. As a result of the analysis, the statistical characteristics of electricity consumption modes as stochastic processes were determined, including: mean value, median, mode, skewness, kurtosis, and standard deviation. The statistical characteristics of the electricity consumption of mining enterprise consumers are presented in Table 1 [20].

TABLE 1. Statistical Characteristics of the Active Power (kW) Distribution of Electric Energy Consumers in Mining Enterprises.

Electric Consumers (P, kW)	**Mean**	**Median**	**Mode**	**Skewness**	**Kurtosis**	**Standard Deviation**
Conveyor 1 (500)	228.78	234.0	245.0	-0.22	-0.17	26.87
Conveyor 2 (75)	40.27	39.4	39.4	0.53	0.34	4.70
Conveyor 3 (200)	100.54	100.85	80.50	-0.71	0.78	18.52
Weighing Conveyor (55)	27.44	27.30	26.10	0.48	-0.53	2.76
Ball mill 1 (4000)	2613.19	2541.50	2458.40	0.56	-0.33	254.09
Ball mill 2 (4000)	2703.24	2587.30	2501.70	0.59	-0.45	262.12
Ball mill 3 (2500)	797.83	797.50	897.20	-0.46	-0.53	80.46
Ball mill 4 (2500)	783.14	784.60	881.70	-0.44	-0.50	78.14
Zump Pump 1 (400)	285.54	284.60	310.40	0.25	-0.55	18.20
Zump Pump 2 (250)	189.47	188.94	205.70	0.19	-0.43	15.30
Pump 1 (630)	518.05	520.00	523.30	0.28	0.05	20.67
Pump 2 (1000)	618.42	616.30	613.70	0.92	0.62	24.35

Analysis of the statistical characteristics shows that the average load factors for the technological electricity consumers in terms of active power are as follows:

- *Conveyor 1: 0.40 – 0.65*
- *Conveyor 2: 0.42 – 0.69*
- *Conveyor 3: 0.38 – 0.62*
- *Weighing conveyor: 0.41 – 0.64*

- Ball mill 1: 0.49 – 0.81
- Ball mill 2: 0.50 – 0.80
- Ball mill 3: 0.28 – 0.41
- Ball mill 4: 0.29 – 0.43
- Zump Pump 1: 0.60 – 0.75
- Zump Pump 2: 0.60 – 0.75
- Pump 1: 0.60 – 0.79
- Pump 2: 0.58 – 0.81

Most of the technological electricity consumers exhibit statistically diverse load characteristics, indicating a polymodal distribution. This reflects the statistically varied operating modes of these technological devices.

The variation of active loads around their mean values is relatively low, which is confirmed by the values of the standard deviations. The obtained data indicate that, in practice, some electricity consumers operate with significantly lower loads. In general, at 7th Hydrometallurgical Plant, the electricity consumption modes of technological consumers in the ore grinding process can be characterized by underutilization of the installed capacity, meaning that the machines and equipment do not fully exploit their technological power capabilities. This, in turn, is one of the conditions leading to high power consumption [21].

The above data show that the main technological electricity consumers are not fully loaded, which leads to a deterioration in energy indicators and, consequently, a decrease in the efficiency of electricity usage. As a random variable, the variability of consumed active power is relatively low. Some electricity consumers exhibit statistically diverse characteristics of electricity consumption, reflecting instability in the operation of technological devices, which reduces the efficiency of electricity usage [22].

Using the Kolmogorov–Smirnov criterion (with a confidence probability of 0.95), the experimental distributions of electricity consumers' loads were tested for conformity with theoretical distributions: normal, beta, gamma, exponential, Weibull, and log-normal. Testing the statistical hypotheses showed that the experimental distributions best fit the normal distribution law, i.e., they can be generally represented as:

$$f(P) = \frac{1}{\sqrt{2\pi} * \sigma} e^{-\frac{(P - \overline{P})^2}{2 * \sigma^2}}, \quad (1)$$

where, P – mean load; σ – standard deviation.

In this case (for the ball mill), the experimental distribution fits the exponential law better:

$$f(P) = \lambda e^{\lambda * P}, \quad (2)$$

where, λ – distribution parameter describing the intensity of the process occurrence.

In some cases (for pumps), the experimental distribution fits the Weibull law better:

$$f(P) = \frac{\beta}{\eta} \left(\frac{P}{\eta}\right)^{\beta - 1} e^{-(P/\eta)^{\beta}} \ (P \geq 0) \quad (3)$$

where: P is the average load; β is the shape parameter, which characterizes the operational properties of the pump, i.e., the distribution of its operating life. If $\beta > 1$, it indicates that the probability of failure increases over time; if $\beta = 1$, the distribution resembles an exponential distribution (i.e., failures occur randomly at a constant rate); if $\beta < 1$, the pump fails more rapidly in the initial stages. η is the scale parameter, which defines the actual operating time or the average period until a failure occurs [23,24].

RESEARCH RESULTS

The parameters of the distribution laws for the active power of the main types of technological electricity consumers at the 7th Hydrometallurgical Plant of of Navoiy Mining and Metallurgical Combinat are presented in Table 2.

In this table, the distribution laws, as well as the corresponding mean and standard deviation, of various electricity consumers (conveyors, mills, and pumps) are presented. This data allows for the analysis of each consumer's electricity consumption. The analysis is carried out from the perspective of different distributions (Normal, Exponential, Weibull).

1. Normal Distribution (for conveyors and pumps 1-4) is often characterized by the mean and standard deviation. The data in the table with a normal distribution is described using these two parameters.

Mean represents the central tendency of the dataset, i.e., the average level of consumption.

Standard deviation indicates the variability (dispersion) of the dataset. A small standard deviation implies that the data points are close to the mean, whereas a large standard deviation indicates greater spread.

TABLE 2. Distribution laws of active power consumption for the main technological electricity consumers at the 7th Hydrometallurgical Plant.

Electricity Consumers	Distribution Law	Mean	Standard Deviation	λ	*β*
Conveyor 1	Normal distribution	228,78	26,87	-	-
Conveyor 2	Normal distribution	40,27	4,70	-	-
Conveyor 3	Normal distribution	100,54	17,52	-	-
Weighing Conveyor	Normal distribution	27,44	2,76	-	-
Ball mill 1	Exponential distribution	2613,19	254,09	0,01	-
Ball mill 2	Exponential distribution	2703,24	262,12	0,01	-
Ball mill 3	Exponential distribution	797,83	80,46	0,01	-
Ball mill 4	Exponential distribution	783,14	78,14	0,01	-
Slurry pump 1	Normal distribution	285,54	18,2	-	-
Slurry pump 2	Normal distribution	190,37	15,4	-	-
Pump 1	Normal distribution	518,05	20,67	-	-
Pump 2	Weibull distribution	618,42	24,35	-	0,67

For example:

- Conveyor 1: mean = 228.78, standard deviation = 26.87. This indicates that the conveyor's electricity consumption averages 228.78 units, with a variation of 26.87 units.
- Pump 1: mean = 644.52, standard deviation = 36.61. This shows that the pump's electricity consumption averages 644.52 units, with a variability of 36.61 units.

Normal distribution is suitable for systems where electricity consumption is relatively stable and exhibits low variability (conveyors and pumps 1-4). These systems tend to remain close to the mean value, with only rare deviations.

2. Exponential Distribution (for ball mills) is used to model variables primarily influenced by external events or occurrences. The exponential distribution is characterized by the mean and the rate parameter *λ*.

For example:

- Ball mill 1: mean = 2613.19, standard deviation = 254.09, λ=0.01;
- Bal mill 2: mean = 2703.24, standard deviation = 262.12, λ=0.01;

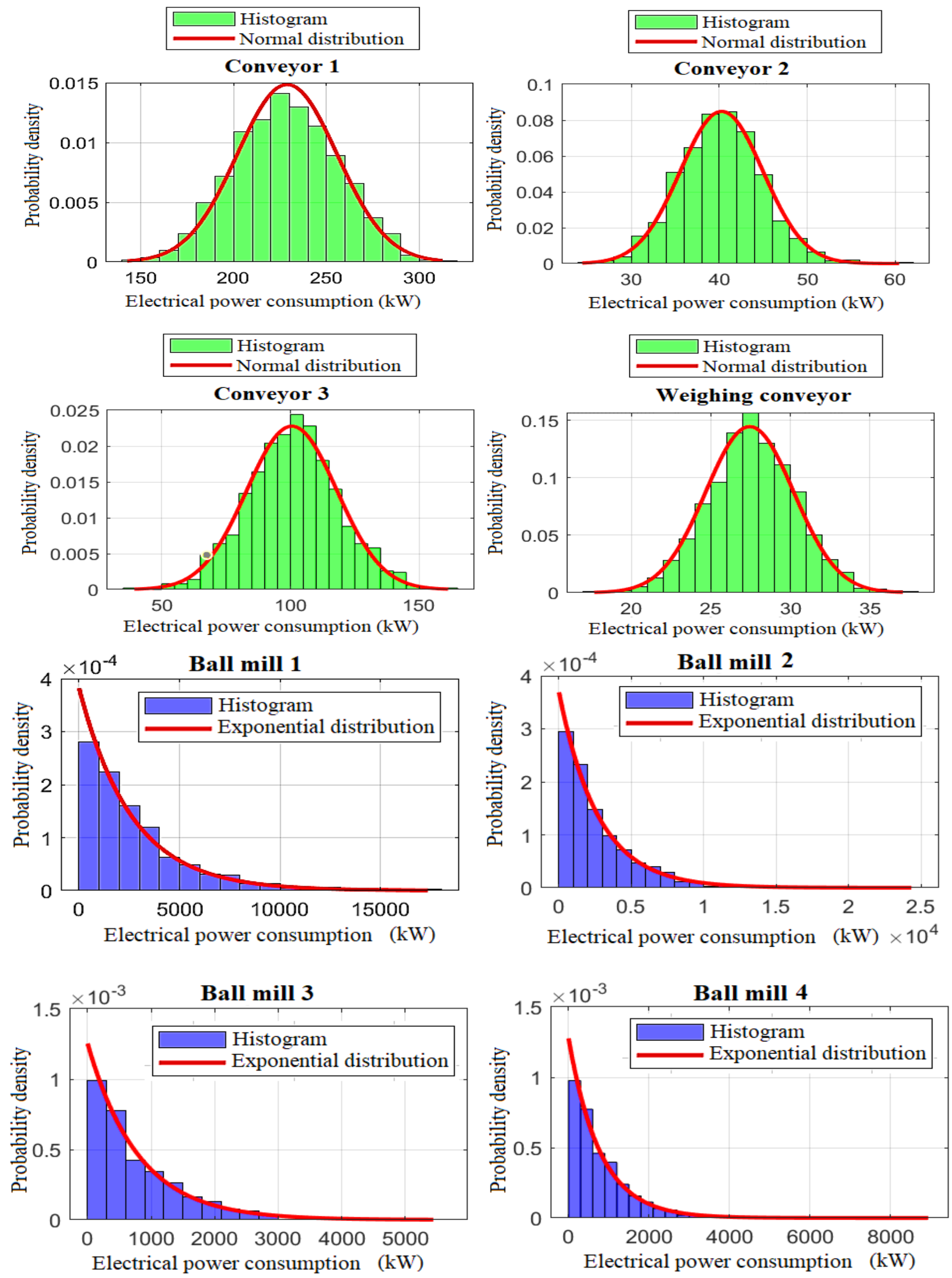
These parameters describe the gradual increase or decrease of electricity consumption for the mills, though their standard deviations indicate significant variability [25-54]. Exponential distribution models consumption over a specific interval, similar to a Poisson process, and is suitable for systems like mills where electricity consumption may change over time. This distribution emphasizes probability and time dependency.

3. **Weibull Distribution** (for pumps 2) is mainly used to assess the time to failure or lifetime. It is characterized by the standard deviation and the shape parameter *β*, which reflects variability and short- or long-term events.

For example:

- Pump 2: mean = 618.42, standard deviation = 24.35, β=0.67;

The Weibull distribution is suitable for systems like pumps 2 because they have a defined operating lifetime and tend to remain stable over short periods. The *β* value of 0.67 indicates that the pump's electricity consumption changes little over short time intervals. The histogram descriptions of the power consumption distributions for electricity consumers are shown in figure 1.


Conveyor 1
Histogram
Normal distribution
Probability density
Electrical power consumption (kW)
Conveyor 2
Histogram
Normal distribution
Probability density
Electrical power consumption (kW)
Conveyor 3
Histogram
Normal distribution
Probability density
Electrical power consumption (kW)
Weighing conveyor
Histogram
Normal distribution
Probability density
Electrical power consumption (kW)
Ball mill 1
Histogram
Exponential distribution
Probability density
Electrical power consumption (kW)
Ball mill 2
Histogram
Exponential distribution
Probability density
Electrical power consumption (kW)
Ball mill 3
Histogram
Exponential distribution
Probability density
Electrical power consumption (kW)
Ball mill 4
Histogram
Exponential distribution
Probability density
Electrical power consumption (kW)

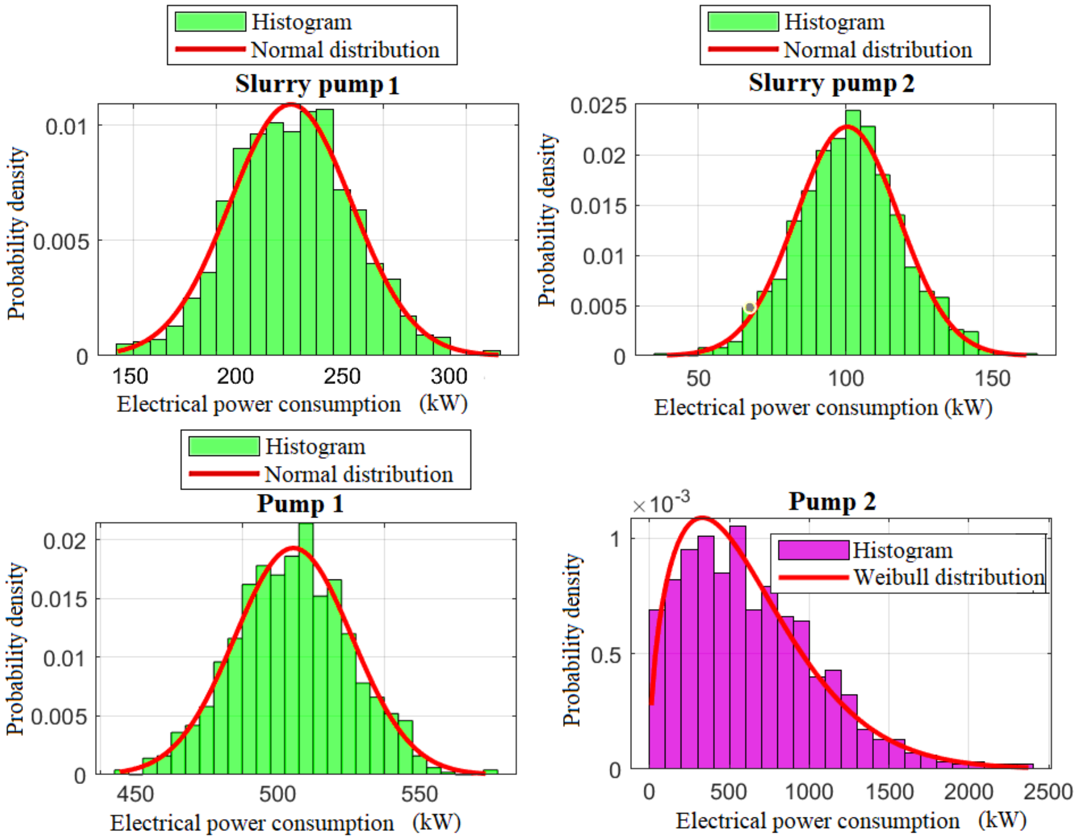


FIGURE 1. Histogram characteristics of the power consumption distribution of electricity consumers. for conveyors; for ball mills; for pumps.

CONCLUSIONS

The graphs clearly show that the electricity consumption of conveyors and pumps 1–4 follows a normal distribution, indicating that the data is concentrated around the mean value. In the histograms, the bars are shown in green, while the distribution function is depicted in red. This demonstrates that these units operate with small fluctuations and maintain a stable operating mode.

The ball mills exhibit an exponential distribution, where the data tends to vary significantly and may display large deviations. Mills often show considerable changes during long-term operation, meaning that in some cases the power consumption may increase sharply; however, their probability density decreases rapidly.

The Weibull distribution is effective for pumps because it represents uncertainties related to operating time or system lifetime. Pumps typically operate steadily, and their probability density is high at the beginning and then gradually decreases.

The obtained distribution laws reliably describe the electrical load patterns of the active power consumption modes of the main technological equipment, machinery, and devices of the plant during ore processing.

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