Journal of Kryvyi Rih National University

Journal homepage: https://journal-knu.com.ua/en

Vol. 23, No. 1, 2025

Article's History:
Received: 14.01.2025
Revised: 29.04.2025
Accepted: 30.06.2025

UDC 621.316.176:338.53

DOI: 10.31721/2306-5451-2025-1-23-80-91

Integration of enterprises electricity material costs into the structure of its consumption efficiency indicators

Ihor Sinchuk
PhD in Technical Sciences, Associate Professor
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0003-3938-0744

Tetyana Beridze
Doctor of Economics, Professor
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0003-2509-3242

Oleksii Mykhailenko*
PhD in Technical Sciences, Associate Professor
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0003-2898-6652

Oleksandr Yalovyi
Postgraduate Student
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0009-0006-1356-2987

Kostiantyn Shepeliev
Postgraduate Student
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0009-0006-3462-2707

Abstract. The purpose of the article was to consider the issues of increasing the level of efficiency of the use of electric energy – the main type of energy in the conditions of the functioning of mining enterprises, using the example of their types with underground mining methods. It is confirmed that changing the modes of electricity consumption by receivers of the analysed types of enterprises that operate in a continuous cycle of work – 24 hours a day, is one of the integral and effective measures to increase their energy efficiency. However, it is noted that the existing canonical formula for determining the level of energy efficiency of enterprises does not allow establishing the level of achievement of the effect in the analysed variant of the measure. It is emphasised that the inconsistency of this formula in determining the level of energy efficiency also applies to other modern variants of

Suggested Citation:
Sinchuk, I., Beridze, T., Mykhailenko, O., Yalovyi, O., & Shepeliev, K. (2024). Integration of enterprises electricity material costs into the structure of its consumption efficiency indicators. *Journal of Kryvyi Rih National University*, 23(1), 80-91. doi: 10.31721/2306-5451-2025-1-23-80-91.

*Corresponding author

increasing energy efficiency, including networks with distributed generation. It is proposed to determine the level of energy efficiency by the indicator of the corresponding material costs for the energy consumed. To confirm this proposal, a study of the variability of electricity consumption modes in the hours of the day, taking into account the variability of tariffs, was conducted. It has been analysed and proven that the consumption and control of the operating modes of electricity receivers during the hours of the day should be carried out in the format of a process. An analytical justification of the proposed process has been carried out and conclusions have been drawn

Keywords: energy efficiency; control; power supply systems; electric power engineering; linear programming; optimisation; price of electricity

Introduction

Modern operating conditions of mining enterprises require new approaches to improving energy efficiency, especially in light of recent changes in legislation and electricity billing formats. However, in practice, energy consumption management at such enterprises remains at a primitive level. This not only reduces equipment reliability but also diminishes overall economic efficiency. There is a need to develop theoretically grounded and controllable models for distributing electricity consumption. The relevance of this study lies in the urgent transition to more flexible and energy-efficient power supply systems that can ensure both resource savings and enhanced technological reliability.

The paper by X. Li *et al*. (2023b) addresses the need for industrial users to optimise electricity consumption strategies in light of electricity prices real-time fluctuations at the electricity market. Authors purposed method that utilises a TimesNet deep learning model to forecast electricity prices. Subsequently, they also build a multi-objective optimisation model that identifies electricity consumption across various industrial loads at different times, based on the predicted prices and the users' specific load demands. To solve optimisation task method employs the adaptive multi-objective particle swarm optimisation algorithm, which helps in obtaining a set of Pareto solutions. The effectiveness of the proposed method is validated through simulations using data from the magnesium industry.

The paper by D.A.G. Vieira *et al*. (2024) introduces a framework aimed at calculating hourly electricity prices by examining the interplay between energy consumption and pricing. This method employs an objective function that quantifies the distance from the desired consumption level, facilitating necessary adjustments. Two optimisation methods, the Trust-Region Constrained method and Sequential-Least Squares Programming, were tested, demonstrating the capability to model the dynamic relationship between consumption and price effectively. The results indicate that this framework encourages consumers to shift their energy usage to off-peak hours, which can help alleviate peak demand and enhance grid stability.

Authors C. Wang *et al*. (2023) consider the issue of regulating electricity consumption by energy-intensive loads from a slightly different perspective, namely, ensuring reliable operation of the power grid. In this paper, a two-level optimisation model was proposed. The inner optimisation focuses on the operational aspects, specifically the operational plans for industrial loads and thermal power units, while considering the integration of new energy sources. The outer optimisation deals with the planning aspects, particularly the development layout of industrial loads. The effectiveness of the method is demonstrated using the IEEE 39 bus system.

The paper by Y. Li *et al*. (2025) presents an electricity price optimisation model designed to tackle high energy costs in complex electricity markets. This price optimisation model unites an enhanced shuffle frog leaping and particle swarm optimisation algorithms. The research utilised electricity consumption data from power grids of large cities in China for validation and analysis. The authors noted that by optimising the cost of electricity, it is possible to regulate energy consumption and forecast it.

The work by L. Dengfeng *et al*. (2024) discusses the significance of time-of-use electricity pricing as a strategy to improve the balance between electricity supply and demand, enhance efficiency, and optimise usage patterns. Authors propose a combined method that first segments the current electricity pricing strategy using the Gaussian mixture model clustering algorithm, and then optimises it based on the determined profile of grid investments and the load characteristics of the power grid. The approach is validated through a case study of the Chongqing power system in China, with the goal of minimising peak load disparities and maximising the benefits of grid investments.

The work by J. Li *et al*. (2024) presents the use of electricity price to manage power consumption among a group of users. Users often do not want to share their private information, making it difficult for operators to optimise energy usage effectively. To address this challenge, the authors propose a two-time-scale incentive mechanism. This mechanism alternates between the system operator setting a price and users optimising their consumption based on that price. After that, the operator recalculates the electricity price. Then the process is iteratively repeated. In this way, the operator indirectly controls the electricity consumption.

Authors A. Gupta *et al*. (2024) use optimisation techniques to enhance electricity consumption in both residential and factory environments. The research specifically targets the optimisation of load profiles across various scenarios, namely for different seasons and days of the week. The goal is to optimise daily load distribution. By comparing electricity consumption before and after optimisation, while considering electicity price variations, the study identifies an improved load profile. This approach enables consumers to select their preferred electricity consumption strategy based on the electricity prices.

The format of the proposed levels, or rather, ways of approaching the solution of the problem of energy efficiency in order to achieve realistically possible indicators in most of the analysed publications, embodies a variety of directions which, in turn, are outlined as a number of local options – sub-options for the final solution option. Such an approach is not contraindicated; however, in accordance with the set goal, a holistic option for achieving the goal is still lacking. At the same time, it should be noted that there are few publications devoted to the issue of optimising energy consumption by iron ore mines. The work by O. Sinchuk *et al*. (2024) can be highlighted, however, given the high energy intensity of the processes, such work will help improve energy efficiency.

For a number of reasons, the idea of operational control over electricity consumption modes by individual receivers as a process with centralised management and with the ultimate goal of reducing material costs for this segment of the enterprise's budget expenditure was not sufficiently developed in the list of known studies. Thus, the purpose of the study was to substantiate the feasibility and format of assessing the material costs of mining enterprises for consumed electricity as an integral indicator of the efficiency of its use for the formation of an algorithm for economically achievable operational management of electricity consumption levels by consumers during the hours of the day.

Materials and Methods

Optimisation methods were used to determine the level of electricity consumption by the enterprise during the day. In particular, the optimisation problem of minimising the components of electricity costs according to the marginal market prices for the day ahead was a linear programming problem with constraints. To solve this problem, the simplex method implemented in Microsoft Excel software was used. To determine the minimum and maximum limits on electricity consumption, the daily schedules of electrical loads of both individual energy-intensive consumers and the entire iron ore mine in Kryvyi Rih (the name is not specified for security reasons) were analysed. This data was obtained by measuring electricity meters installed at the main step-down substation of the enterprise. A computational procedure was performed to determine the real optimal values of electricity consumption at the iron ore mine. The solution to the problem was carried out based on the provisions and principles of the system approach and system analysis. It should be noted that when studying the quality of electricity, as a system, it should be considered as an open system, that is, one that exchanges energy, matter and information with the external environment. As a limitation of the study, the cost-target parameters of the external environment remained outside the scientist's attention, they are the ones that determine the conflict of interests of the provider and consumer of services regarding electricity.

Results and Discussion

The Law of Ukraine No. 2019-VIII (2017), by changing the format of settlements for consumed electricity between consumers and generating organisations, potentially provided the first of the above-mentioned "actors" with creativity for the process of intensifying searches for increasing electricity efficiency and, including, attracting their own potential reserves of energy resources for this. However, despite the need to adopt creative approaches to implementing measures to increase their electricity efficiency in the practice of mining enterprises, this direction has not yet acquired the status of an "energy culture" of the relevant industry.

At the same time, along with the format of decision tactics in the generalised strategy for solving the problem of increasing energy efficiency, new non-trivial communication links also arise, which provoke the need to change existing canonical concepts and form their new formats, which in turn adjust the vision of ways to achieve the set goal, including docking or integration with perfect options. At the same time, it should be noted that often new solutions are based on non-trivial, non-canonical concepts. Thus, with the emergence of new options for power supply system structures (PSS), including with distributed generation (Kaczmarzewski *et al.*, 2021), the cohort of concepts that need to be decanonised for the possibility of real evaluation of the results obtained includes the format of the traditional interpretation of the concept of energy efficiency itself.

The need to change the formula for assessing energy efficiency is also dictated by the option of changing the format of electricity consumption in hours of the day, which also represents a segment of solutions in the complex of tasks for solving the problem of energy efficiency. In both the first and the second options, according to the existing concept of energy efficiency, there is no a priori effect in this assessment option, although, as a fact, there is a reduction in the material costs of the enterprise for the volume of electricity consumed. This is a system-forming positive aspect of such solutions.

However, returning to the above-mentioned ways of increasing energy efficiency, it should be noted that the option of changing the emphasis in the levels of electricity consumption in hours of the day in the format of existing daily tariffs can and should be applied in any variations of PSS structures. That is, this direction should be seen as the basic and at the same time starting point in the development of energy-efficient PSS options, or rather, the controllability in their structures of the distribution of electricity consumption levels between consumers in hours of the day.

To this should be added that mining enterprises are the types of electricity consumers that are most suitable for the implementation of this principle, since they operate in a continuous cycle – 24 hours a day, which provides sufficient variability in the practical implementation of this direction (Telbayeva *et al.*, 2024). However, here too, the implementation tactics have their own problems in organising the process of control, since electricity tariffs vary not only in hours of the day, but also in the days themselves. That is, monitoring and forecasting should be necessary in this process, with the subsequent selection of optimal tariffs in hours of the day and, accordingly, the development of an algorithm for controlling the distribution of electricity between consumers of the enterprise.

However, it should be added that speaking of the need for control of energy flows in the structures of energy complexes: electricity supply – energy consumption of mining enterprises, it will be correct to note that, in fact, control in hours of the day exists in the realities of the functioning of these enterprises, but in the pure primitivism of this concept. Moreover, such an insufficiently substantiated, in essence, technology of functioning of aggregate electricity consumers approach, often not only does not provide a positive effect in the operation of the electric power complex, but on the contrary, significantly reduces the reliability and service life of electrical equipment and electromechanical systems of electricity receivers and the power system in general (Bakare *et al.*, 2023). Electricity tariffs are also significantly affected (Siddiquee *et al.*, 2021; Golmohamadi, 2022; dos Santos *et al.*, 2023). Such a measure, as, by the way, all others in this direction, without the necessary theoretical and model justification, will not provide the expected and potentially achievable level of positive potential for increasing the level of energy efficiency and the economy of these enterprises as a whole.

The transmission of electricity via main power transmission lines is carried out by the National Energy Company "Ukrenergo" – a joint-stock company, 100% of whose shares are owned by the state. Tariffs for "Ukrenergo" are set by the National Commission for Energy and Utilities Regulation (NCEUR). The transmission of electricity is understood as the transportation of electricity through the networks of the transmission system operator (i.e. "Ukrenergo") from power plants to the points of connection of distribution systems. Electricity tariffs for industrial enterprises differ from electricity tariffs for the population. In general, the cost of electricity for industrial enterprises consists of: transmission system operator tariff (set by NCEUR for the single operator "Ukrenergo"); distribution system operator tariff (set by NCEUR for each energy distribution company operator); actual cost of electricity (the market price of electricity is determined daily by the state-owned company "Market Operator" based on the results of trading); the cost of the supplier's services, i.e. its margin (determined by each supplier, usually a few percent of the market value).

Electricity distribution tariffs for all regional energy companies are set by NCEUR. Thus, the NCEUR Commission is conducting a regulatory procedure to review the maximum prices in the relevant segments of the electricity market. According to the Resolution of the National Commission for State Regulation of Energy and Public Utilities No. 1976 (2024), the regulator proposes to set the following maximum prices in the day-ahead market and the intraday market from December 2024:

- from 0.00 to 7.00 – 5,600 UAH/MW · h;
- from 7.00 to 17.00 and from 23.00 to 0.00 – 6,900 UAH/MW · h;
- from 17.00 to 23.00 – 9,000 UAH/MW · h.

Figure 1 presents a graphical representation of the marginal prices on the day-ahead market and the intraday market.

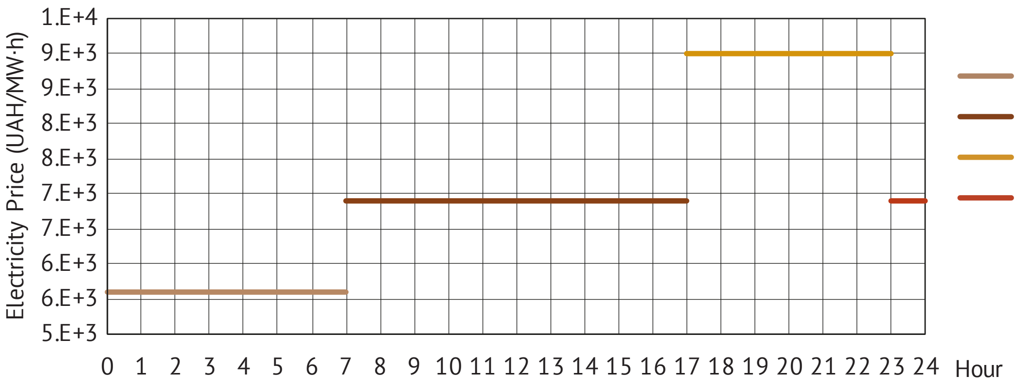

Figure 1. Charts of limit prices on the intraday market

Source: compiled by the authors

Compared to the Resolution of the National Commission for State Regulation of Energy and Public Utilities No. 1976 (2024), in the current study it is proposed to increase the maximum price in the time period from 11.00 to 17.00 from the current 5,600 UAH to 6,900 UAH per MW · h. At the same time, it is proposed to leave the maximum prices on the balancing electricity market unchanged. The revision of the maximum prices on the electricity market is due to the need to ensure conditions for commercial imports of electricity from European countries in order to cover a possible capacity deficit in the autumn-winter period during Russian terrorist attacks on the energy system. The organisation of the functioning of the electricity market in Ukraine is handled by JSC "Market Operator" (100% of whose shares are owned by the state and are not subject to privatisation). JSC "Market Operator" ensures the conduct of exchange trades in the purchase and sale of electricity for regional energy companies, enterprises and factories. The main market is the "day-ahead" market (DAM). This market sells and buys electricity for the day following the day of trading, and trading is actually conducted 24/7 (even on weekends).

Mining enterprises, taking into account the existing difference in hourly daily tariffs for electricity, which often reaches almost 5-fold values, a priori in the "manual control" option make corrections to the daily operating modes of, as a rule, energy-intensive consumers with the corresponding reflection of this process on the modes of electricity consumption (Diaz *et al.*, 2016; Gerami *et al.*, 2021). Giving a certain effect in the form of savings in payment levels for consumed volumes of electricity, such insufficiently justified measures also entail a number of technical difficulties for technological units, the modes of which change during the day in the range of loads from zero to maximum values (Sinchuk, 2019). Figure 2 shows real, experimentally obtained graphs of electricity consumption by an operating iron ore mine during the hours of the day. The format of this sample is typical for all iron ore mines. This is confirmed by studies conducted for all typical energy-intensive consumers (Maregedze *et al.*, 2022). This is also the case for certain groups of consumers, such as the main drainage complexes of groundwater in mines and quarries (Michlowicz & Wojciechowski, 2021; Mykhailenko *et al.*, 2023) and main ventilation installations (de Vilhena Costa & Margarida da Silva, 2020). Therefore, it is advisable to consider it an option for developing electricity flow control systems for these types of enterprises.

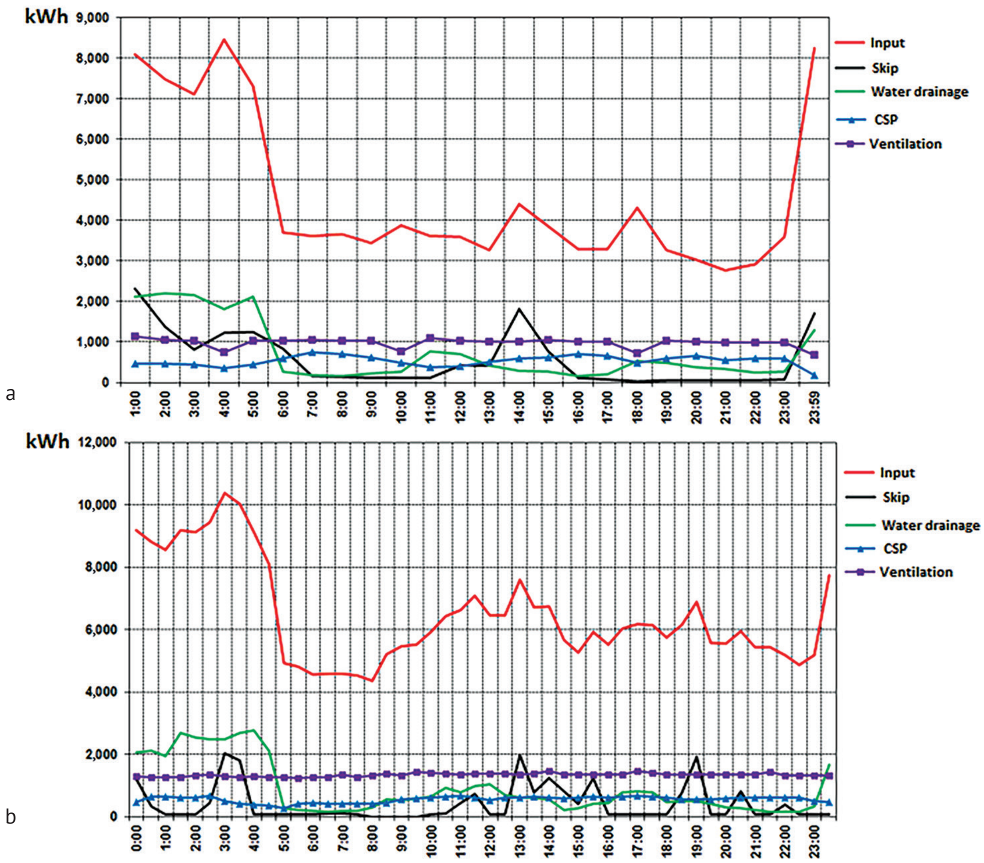

Figure 2. Electricity consumption by hours of the day by individual receivers of iron ore mine (Kryvyi Rih)

Notes: a) 08/29/2021; b) 08/29/2022

Source: compiled by the authors

According to Figure 2, the dynamics of changes in the levels of electricity consumption by both individual consumers and the entire enterprise indicate a significant status of the fluctuation range. However, compliance with the possibilities and feasibility of controllability requires further substantiation and appropriate adjustment. However, compliance with the capabilities and feasibility of control requires its further justification and appropriate adjustment. From the point of view of ensuring the appropriate level of efficiency of the quality of consumed electricity during the day, it is important that this process corresponds to the lowest cost according to tariffs on the intraday electricity market. This makes it possible to mathematically formulate the corresponding task. First, it is necessary to determine the forecast volume of electricity that the enterprise needs to consume during the day:

$$W_0 = \int_0^T N(t)dt, \quad (1)$$

where W_0 – specified amount of electricity, MW · h; T = 24 hours (length of day); $N(t)$ – power of consumed electricity, MW.

At the same time, the power of electricity is limited by the limits:

$$N_{min} \leqslant N(t) \leqslant N_{max}, \quad (2)$$

where N_{min} – lower limit of electricity capacity, MW; N_{max} – upper limit of electricity capacity, MW.

In turn, electricity consumption during the day to ensure the required level of efficiency of its use must correspond to the lowest cost of electricity consumed according to the schedule on the intraday market, which is determined by the condition:

$$C = \int_0^T c(t)N(t)dt \rightarrow \min_{N(t)}, \quad (3)$$

where $c(t)$ – price of electricity depending on time according to the price tariff on the intraday market, MW · h.

Considering the piecewise constant method of setting the marginal price tariff on the intraday market, which is presented in Figure 1, the integral in condition (3) can be represented as the sum of integrals over segments of constant values, i.e.:

$$\int_0^T c(t)N(t)dt = \int_0^{T_1} c_1(t)N(t)dt + \int_{T_1}^{T_2} c_2(t)N(t)dt + \\ + \int_{T_2}^{T_3} c_3(t)N(t)dt + \int_{T_3}^{T} c_4(t)N(t)dt, \quad (4)$$

where T_1 = 7 hour; T_2 = 17 hour; T_3 = 23 hour; T_4 = 24 hour; c_1 = 5,600 UAH/MW · h; c_2 = 6,900 UAH/MW · h; c_3 = 9,000 UAH/MW · h; c_4 = 6,900 UAH/MW · h.

Given the constancy of tariff prices, their values can be taken outside the integral signs, that is, written in the form:

$$\int_0^T c_1 N(t)dt + \int_{T_1}^{T_2} c_2 N(t)dt + \int_{T_2}^{T_3} c_3 N(t)dt + \int_{T_3}^{T} c_4 N(t)dt = \\ = c_1 \int_0^{T_1} N(t)dt + c_2 \int_{T_1}^{T_2} N(t)dt + c_3 \int_{T_2}^{T_3} N(t)dt + c_4 \int_{T_3}^{T} N(t)dt, \quad (5)$$

or, according to (4):

$$\int_0^T c(t)N(t)dt = c_1W_1 + c_2W_2 + c_3W_3 + c_4W_4, \quad (6)$$

where $W_1 = \int_0^{T_1} N(t)dt$ – the amount of electricity consumed over a period of time [0; T_1]; $W_1 = \int_{T_1}^{T_2} N(t)dt$ – the amount of electricity consumed over a period of time [T_1; T_2]; $W_1 = \int_{T_2}^{T_3} N(t)dt$ – the amount of electricity consumed over a period of time [T_2; T_3]; $W_1 = \int_{T_3}^{T} N(t)dt$ – the amount of electricity consumed over a period of time [T_3; T].

Taking into account formula (1) and notation (6), a condition that is imposed on the amount of electricity consumed during the day can be formulated:

$$W_1 + W_2 + W_3 + W_4 = W_0. \quad (7)$$

Taking into account condition (2), there are limits on the amount of electricity consumed during the tariff time of day. For a time period can be written:

$$\int_0^{T_1} N_{\min} dt \leqslant \int_0^{T_1} Ndt \leqslant \int_0^{T_1} N_{max} dt, \\ N_{\min} \int_0^{T_1} dt \leqslant \int_0^{T_1} N_{dt} \leqslant N_{max} \int_0^{T_1} dt, \\ N_{\min} T_1 \leqslant W_1 \leqslant N_{max} T_1. \quad (8)$$

Limitations for the time period [T_1; T_2]:

$$N_{\min}(T_2 - T_1) \leqslant W_2 \leqslant N_{max}(T_2 - T_1). \quad (9)$$

Limitations for the time period [T_2; T_3]:

$$N_{\min}(T_3 - T_2) \leqslant W_3 \leqslant N_{max}(T_3 - T_2). \quad (10)$$

Limitations for the time period :

$$N_{min}(T_3 - T_2) \leqslant W_3 \leqslant N_{max}(T_3 - T_2). \quad (11)$$

Taking into account (3) and (6), the condition for optimising electricity consumption during the day can be written:

$$C(W_1; W_2; W_3; W_4) = c_1W_1 + \\ + c_2W_2 + c_3W_3 + c_4W_4 \rightarrow \min_{W_1, W_2, W_3, W_4}. \quad (12)$$

Taking into account the condition (12) and the limitations (7)-(11), it can be obtained the mathematical formulation of the problem of minimising the components of electricity costs in hours of the day on the intraday market according to the given marginal prices. From a mathematical point of view, taking into account the linearity of the minimised functional (12) and the linearity of the constraints (7)-(12), a linear programming problem occurs (Shufian & Mohammad, 2022), the solution of which is carried out by a standard algorithm using the "simplex method" (Yan *et al.*, 2019).

To simplify the solution of the formulated problem (7)-(12), it seems advisable to switch to specific values, dividing all variables by the given volume of electricity consumption (1). As a result, the mathematical formulation of the problem of minimising the segments of electricity costs in hours of the day on the intraday market will take the form:

$$\hat{C}(\hat{W}_1; \hat{W}_2; \hat{W}_3; \hat{W}_4) = c_1\hat{W}_1 + + c_2\hat{W}_2 + c_3\hat{W}_3 + c_4\hat{W}_4 \to \min_{W_1,W_2,W_3,W_4}; \quad (13)$$

$$\hat{W}_1 + \hat{W}_2 + \hat{W}_3 + \hat{W}_4 = 1; \quad (14)$$

$$\frac{N_{min}T_1}{W_0} \le \hat{W}_1 \le \frac{N_{max}T_1}{W_0}; \quad (15)$$

$$\frac{N_{min}(T_2-T_1)}{W_0} \le \hat{W}_2 \le \frac{N_{max}(T_2-T_1)}{W_0}; \quad (16)$$

$$\frac{N_{min}(T_3-T_2)}{W_0} \le \hat{W}_3 \le \frac{N_{max}(T_3-T_2)}{W_0}; \quad (17)$$

$$\frac{N_{min}(T-T_3)}{W_0} \le \hat{W}_4 \le \frac{N_{max}(T-T_3)}{W_0}, \quad (18)$$

where $\hat{W}_i = \frac{W_i}{W_0}$, $(i = 1, \ldots, 4)$.

Then $\hat{C}(\hat{W}_1; \hat{W}_2; \hat{W}_3; \hat{W}_4) = \frac{C(W_1;W_2;W_3;W_4)}{W_0}$.

Let the solution of the problem using the Microsoft Excel programme using the "linear programming" algorithm give the following result:

$$\hat{W}_i = \hat{W}_{iopt} (i = 1,\ldots,4). \quad (19)$$

It is clear that:

$$\hat{C}(\hat{W}_{1opt}; \hat{W}_{2opt}; \hat{W}_{3opt}; \hat{W}_{4opt}) = \hat{C}_{min}. \quad (20)$$

When conditions (14)-(18) are met, then:

$$\hat{W}_{1opt} + \hat{W}_{2opt} + \hat{W}_{3opt} + \hat{W}_{4opt} = 1; \quad (21)$$

$$\frac{N_{min}T_1}{W_0} \le \hat{W}_{1opt} \le \frac{N_{max}T_1}{W_0}; \quad (22)$$

$$\frac{N_{min}(T_2-T_1)}{W_0} \le \hat{W}_{2opt} \le \frac{N_{max}(T_2-T_1)}{W_0}; \quad (23)$$

$$\frac{N_{min}(T_3-T_2)}{W_0} \le \hat{W}_{3opt} \le \frac{N_{max}(T_3-T_2)}{W_0}; \quad (24)$$

$$\frac{N_{min}(T-T_3)}{W_0} \le \hat{W}_{4opt} \le \frac{N_{max}(T-T_3)}{W_0}. \quad (25)$$

To get to the real values of quantities (19) and (20), it is needed to multiply them by the given volume of electricity consumption (1):

$$W_{iopt} = \hat{W}_{iopt} \cdot W_0 . (i = 1,\ldots,4); \quad (26)$$

$$C_{min} = C(W_{1opt}; W_{2opt}; W_{3opt}; W_{4opt}) = = \hat{C}(\hat{W}_{1opt}; \hat{W}_{2opt}; \hat{W}_{3opt}; \hat{W}_{4opt}) \cdot W_0. \quad (27)$$

The average value of the consumed electricity capacity in each section of the considered tariff grid during the day is determined by the formulas:

$$\overline{N}_{1opt} = \frac{1}{T_1} W_{1opt}; \quad (28)$$

$$\overline{N}_{2opt} = \frac{1}{T_2-T_1} W_{2opt}; \quad (29)$$

$$\overline{N}_{3opt} = \frac{1}{T_3-T_2} W_{3opt}; \quad (30)$$

$$\overline{N}_{4opt} = \frac{1}{T-T_3} W_{4opt}. \quad (31)$$

The obtained results (26)-(31) of solving the problem (7)-(12) determine the corresponding efficiency of electricity consumption during the day in the presence of a tariff of marginal prices on the intraday market, determined by the graphs in Figure 1. As an example, a numerical calculation of the solution of the problem of the declared efficiency of electricity consumption during the day in the presence of a tariff of marginal prices on the intraday market, determined by the graphs in Figure 1, with the following parameters was considered:

$$W_0 = 2{,}400 \text{ UAH/kW} \cdot \text{h}, N_{min} = 50 \text{ MW}, N_{max} = 150 \text{ MW}. \quad (32)$$

Taking into account (32), the problem of minimising electricity consumption (7)-(12) can be written as:

$$C(W_1; W_2; W_3; W_4) = 5{,}600 \cdot W_1 + + 6{,}900 \cdot W_2 + 9{,}000 \cdot W_3 + 6{,}900 \cdot W_4 \to \min_{W_1,W_2,W_3,W_4} \quad (33)$$

$$W_1 + W_2 + W_3 + W_4 = 2{,}400; \quad (34)$$

$$50 \cdot 7 \leqslant W_1 \leqslant 150 \cdot 7,\ 350 \leqslant W_1 \leqslant 1{,}050; \quad (35)$$

$$50 \cdot (17\text{-}7)\text{м} \leqslant W_2 \leqslant 150 \cdot (17\text{-}7),\ 500 \leqslant W_2 \leqslant 1{,}500; \quad (36)$$

$$50 \cdot (23\text{-}17) \leqslant W_3 \leqslant 150 \cdot (23\text{-}17),\ 300 \leqslant W_3 \leqslant 900; \quad (37)$$

$$50 \cdot (24\text{-}23) \leqslant W_4 \leqslant 150 \cdot (24\text{-}23),\ 50 \leqslant W_4 \leqslant 150. \quad (38)$$

The next step is to move on to specific quantities, which leads to the following problem statement:

$$\hat{C}(\hat{W}_1; \hat{W}_2; \hat{W}_3; \hat{W}_4) = 2.333 \cdot \hat{W}_1 + + 2.875 \cdot \hat{W}_2 + 3.75 \cdot \hat{W}_3 + 2.875 \cdot \hat{W}_4 \min_{\hat{W}_1,\hat{W}_2,\hat{W}_3,\hat{W}_4}; \quad (39)$$

$$\hat{W}_1 + \hat{W}_2 + \hat{W}_3 + \hat{W}_4 = 1; \quad (40)$$

$$0.146 \leqslant \hat{W}_1 \leqslant 0.4375; \quad (41)$$

$$0.208 \leqslant \hat{W}_2 \leqslant 0.625; \quad (42)$$

$$0.125 \leqslant \hat{W}_3 \leqslant 0.375; \quad (43)$$

$$0.0208 \leqslant \hat{W}_4 \leqslant 0.0625. \quad (44)$$

Solving the problem (39)-(44) using the Microsoft Excel programme with the "linear programming" algorithm gave the following result:

$$\hat{W}_{1opt} = 0.4375, \hat{W}_{2opt} = 0.4375,$$
$$\hat{W}_{3opt} = 0.4375, \hat{W}_{4opt} = 0.4375. \quad (45)$$

In this case, the minimum value of the objective function (39) is:

$$\hat{C}_{min} = 6{,}593.75. \quad (46)$$

For transition to real values, use the formulas (45), (46), considering (26) and (27):

$$\hat{W}_{1opt} = 0.4375 \cdot 2{,}400 = 1{,}050 \text{ MWh}; \quad (47)$$
$$\hat{W}_{2opt} = 0.4187 \cdot 2{,}400 = 1{,}000.08 \text{ MWh}; \quad (48)$$
$$\hat{W}_{3opt} = 0.125 \cdot 2{,}400 = 300 \text{ MWh}; \quad (49)$$
$$\hat{W}_{4opt} = 0.0208 \cdot 2{,}400 = 49.92 \text{ MWh}; \quad (50)$$
$$C_{min} = 6{,}593.75 \cdot 2{,}400 = 15{,}825{,}000 \text{ UAH}. \quad (51)$$

The average value of the consumed electricity capacity in each section of the considered tariff grid during the day is determined, considering (47)-(51) by formulas (28)-(32):

$$\overline{N}_{1opt} = \frac{1{,}050}{7} = 150 \text{ MW}; \quad (52)$$
$$\overline{N}_{2opt} = \frac{1{,}000.08}{10} = 100.008 \text{ MW}; \quad (53)$$
$$\overline{N}_{3opt} = \frac{300}{6} = 50 \text{ MW}; \quad (54)$$
$$\overline{N}_{4opt} = \frac{49.92}{1} = 49.92 \text{ MW}. \quad (55)$$

Figure 3 shows graphs of optimal values of costs of a given amount of electricity (33) during the hours of the day. Analysis of the graphs shows that the highest costs occur at times of the day when the marginal prices on the intraday market are minimal. Thus, in the time interval from 0.00 to 7.00, the marginal price for electricity is minimal. Therefore, the electricity costs should be the highest. In the time interval from 17.00 to 23.00, the marginal price for electricity is the highest. Therefore, the electricity costs are the lowest.

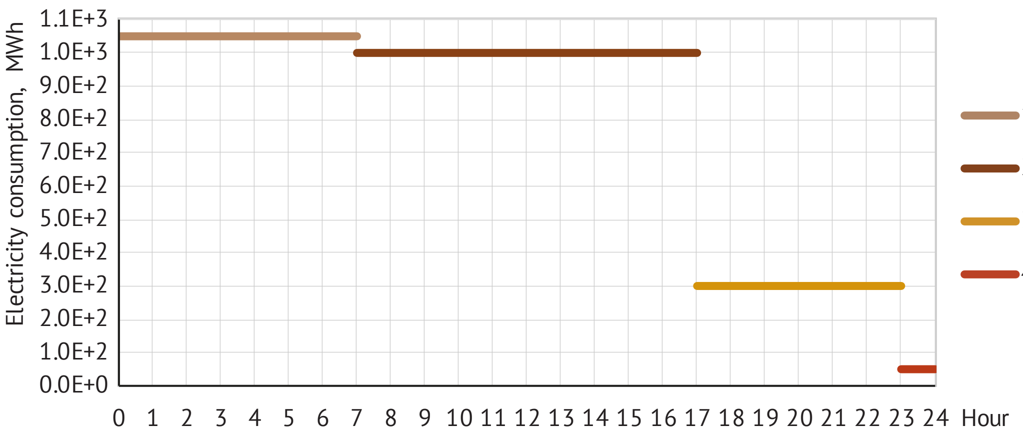

Figure 3. Graphs of optimal values of electricity consumption during the day
Source: compiled by the authors

The list of requirements for the efficiency of electricity use, which relate more to technical characteristics, is generally known (Nakhodov *et al.*, 2022). The study showed that it is logical to include in the cost the corresponding technical characteristics that ensure the quality of electricity in a technological sense. Electricity was considered from the position of cost-target indicators. Such an approach should solve the problem of synergy of quality-cost characteristics. The systematic nature of such an approach ensures the comprehensiveness of the study of the quality of electricity as a complex open system, which is characterised by the exchange of energy, information and matter with the external environment. That is, the principle of systematicity can be noted, which is manifested in the synergistic etiology of effects.

The proposed method for optimising daily electricity costs at an iron ore mine using linear programming focuses on short-term savings by taking into account changes in electricity tariffs and projected consumption. This approach allows minimising costs during the day, making it possible to optimally distribute consumption, reducing material costs for electricity and improving its quality and cost characteristics. The mathematical formulation of the problem, in particular the use of linear programming, provides an effective solution for short-term goals. This approach differs from the one proposed in T. Li *et al.* (2023a), where the authors focus on strategic planning on a monthly horizon, where companies must take into account market fluctuations, regulatory requirements and changes in energy consumption due to a large share of renewable energy sources. While the approach to the proposed daily optimisation focuses on accurate and efficient consumption allocation to reduce energy costs, monthly planning allows for a wider range of economic and environmental factors that determine the efficiency of energy companies over a longer time horizon.

Also, the proposed method is focused on industrial consumers who receive power from the centralised power system, unlike the one considered in the article by S. Wang *et al*. (2024), where strategies for combined purchase and sale of electricity are focused on consumers who can simultaneously generate electricity. These strategies include pricing and package offers that consider individual consumer needs and behaviour, and consider the integration of renewable energy sources and the development of smart grids. However, it is also used for long-term optimisation, which, due to market volatility, cannot always be immediately realised. The method does not require additional procedures before optimisation, such as clustering (Dengfeng *et al.*, 2024) of tariffs or deep learning for preliminary forecasting (Li *et al.*, 2023b). The method of optimising electricity costs does not require complex calculations and can be implemented by almost any software that contains tools for solving linear programming problems.

Also, the optimisation is carried out according to the most appropriate criterion, such as the cost of electricity consumed by the iron ore mine, unlike in the study by F.R. Albogamy (2022), where the criterion of peak-to-average ratio in terms of power consumption is minimised. The criterion of electricity purchase costs more objectively reflects the economic efficiency of consumption, as it takes into account the real cost of electricity, which may vary depending on prices, load schedules and supply conditions. It allows assessing the financial impact of the system and find optimal energy management strategies. The ratio between peak and average consumption can only characterise the uniformity of the load, but does not provide direct information about costs, so its use without analysing financial indicators can lead to suboptimal decisions.

The method is simpler and more focused on the individual consumer, while, for example, X. Wang *et al*. (2024) consider the optimisation of electricity purchases, taking into account the interaction between different market participants, such as producers, suppliers and consumers, as well as the influence of regulatory authorities. The study of optimising the cost of purchasing electricity for an industrial enterprise is more effective because it is aimed at a specific consumer with clearly defined consumption conditions, tariffs, and load management capabilities. This makes it possible to develop real cost-cutting measures, such as changing the equipment operating schedule, using alternative energy sources, or implementing energy management systems. Analysis on the scale of the entire electricity market is much more complex due to the large number of interrelated factors, such as government regulation, supply, demand, and pricing mechanisms, which makes it difficult to formulate specific solutions for individual consumers. Focusing on the enterprise allows for quick and practical results that have a direct economic impact. For industrial enterprises of the mining and metallurgical complex, which were the target object of this study, this approach is too much to apply.

Conclusions

The establishment of market relations in the electric power industry leads to the fact that electricity is considered a commodity that must meet certain criteria of this definition. It is advisable to determine electricity on the scale of its application technology – consumption by receivers of mining enterprises, not only unilaterally, according to technical characteristics, but also to take into account its cost-target component, which is determined through electricity tariff indicators. Knowing the grid of electricity tariffs during the day and the predicted required volume of electricity consumption per day, it is possible to distribute the costs of the entire volume of electricity consumption so that the total amount of electricity consumption per day is minimal. This approach to the use of electricity makes it possible to save material costs for paying for electricity, that is, to ensure its appropriate quality and cost characteristics. The mathematical formulation of the problem of minimising the cost of electricity during the day led to the problem of linear programming. The solution to the problem showed that by optimising electricity consumption by energy-intensive consumers during hours of the day, it is possible to achieve a significant reduction in electricity purchase costs by shifting the operation of energy-intensive consumers to times when the cost of electricity is low. The possibility of solving this problem by using standard software opens the way to its widespread use in practice, which is confirmed by a corresponding example. Further research will be devoted to analysing the use of various optimisation methods to minimise the costs of the proposed target function for the purchase of electricity by iron ore mines in terms of convergence and accuracy of determining the extremum.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Albogamy, F.R. (2022). Optimal energy consumption scheduler considering real-time pricing scheme for energy optimization in smart microgrid. *Energies*, 15(21), article number 8015. doi: 10.3390/en15218015.

[2] Bakare, M.S., Abdulkarim, A., Zeeshan, M., & Shuaibu, A.N. (2023). A comprehensive overview on demand side energy management towards smart grids: Challenges, solutions, and future direction. *Energy Informatics*, 6(1), article number 4. doi: 10.1186/s42162-023-00262-7.

[3] de Vilhena Costa, L., & Margarida da Silva, J. (2020). Cost-saving electrical energy consumption in underground ventilation by the use of ventilation on demand. *Mining Technology*, 129(1), 1-8. doi: 10.1080/25726668.2019.1651581.

[4] Dengfeng, L., Zhonghao, L., Xiaoju, L., Juan, Y., Mincai, Y., & Xinyu, L. (2024). Optimization method of time-of-use electricity price for the cost savings of power grid investment. *Frontiers in Energy Research*, 12, article number 1361116. doi: 10.3389/fenrg.2024.1361116.

[5] Diaz, S., Gil, E., & Palacios, A. (2016). Demand Side management, an imperative asset for the mining industry. In *3rd international seminar on energy management in mining*. Santiago: ENERMIN. doi: 10.13140/RG.2.2.35427.14884.

[6] dos Santos, S.A.B., Soares, J.M., Barroso, G.C., & de Athayde Prata, B. (2023). Demand response application in industrial scenarios: A systematic mapping of practical implementation. *Expert Systems with Applications*, 215, article number 119393. doi: 10.1016/j.eswa.2022.119393.

[7] Gerami, N., Ghasemi, A., Lotfi, A., Kaigutha, L.G., & Marzband, M. (2021). Energy consumption modeling of production process for industrial factories in a day ahead scheduling with demand response. *Sustainable Energy, Grids and Networks*, 25, article number 100420. doi: 10.1016/j.segan.2020.100420.

[8] Golmohamadi, H. (2022). Demand-side management in industrial sector: A review of heavy industries. *Renewable and Sustainable Energy Reviews*, 156, article number 111963. doi: 10.1016/j.rser.2021.111963.

[9] Gupta, A., Rathi, D., Chatterjee, S., Brahmachary, R., & Godwal, S.D. (2024). Optimizing load profiles for improved demand response: A comparative study of residential and factory scenarios. In *4th international conference on sustainable energy and future electric transportation (SEFET)* (pp. 1-6). Hyderabad: IEEE. doi: 10.1109/SEFET61574.2024.10717995.

[10] Kaczmarzewski, S., Olczak, P., & Sołtysik, M. (2021). The impact of electricity consumption profile in underground mines to cooperate with RES. *Energies*, 14(18), article number 5775. doi: 10.3390/en14185775.

[11] Law of Ukraine No. 2019-VIII "On Electricity Market". (2017, April). Retrieved from https://zakon.rada.gov.ua/laws/show/2019-19#Text.

[12] Li, J., Motoki, M., & Zhang, B. (2024). Socially optimal energy usage via adaptive pricing. *Electric Power Systems Research*, 235, article number 110640. doi: 10.1016/j.epsr.2024.110640.

[13] Li, T., Liu, Q., Yuan, H., & Guo, H. (2023a). Strategy of monthly purchase and sale of electricity by sales companies under the weight of renewable energy consumption responsibility. In *8th international conference on energy materials and electrical engineering (ICEMEE 2022)* (pp. 200-204). Guangzhou: SPIE. doi: 10.1117/12.2672940.

[14] Li, X., Zhu, K., Jing, D., & Qiao, Y. (2023b). Electricity strategy optimization for industrial users with real-time price estimation in the electricity market transition. In *9th international conference on computer and communications (ICCC)* (pp. 2514-2520). Chengdu: IEEE. doi: 10.1109/ICCC59590.2023.10507536.

[15] Li, Y., Su, Y., Zhao, Q., Wuda, B., Qu, K., & Tang, L. (2025). An electricity price optimization model considering time-of-use and active distribution network efficiency improvements. *AIMS Energy*, 13(1), 13-34. doi: 10.3934/energy.2025002.

[16] Maregedze, L., Chingosho, H., & Madiye, L. (2022). Use and cost optimization for underground mines electrical energy: A case of a mine in Zvishavane. *Energy*, 247, article number 123374. doi: 10.1016/j.energy.2022.123374.

[17] Michlowicz, E., & Wojciechowski, J. (2021). Energy consumption analysis of the main dewatering pumps in underground mines. *Mining – Informatics, Automation and Electrical Engineering*, 546(2), 47-54. doi: 10.7494/miag.2021.2.546.47.

[18] Mykhailenko, O., Baranovskyi, V., Shchokin, V., Karabut, N., & Kolomits, H. (2023). Power consumption control of multi-pump systems of the main water drainage in underground mines based on the Mamdani fuzzy inference system. *IOP Conference Series: Earth and Environmental Science*, 1254(1), article number 012046. doi: 10.1088/1755-1315/1254/1/012046.

[19] Nakhodov, V., Borychenko, O., & Cherniavskyi, A. (2022). Formation of a strategy for increasing the energy efficiency of metallurgical enterprises as guarantee of decarbonization of the Ukrainian economy. *POWER ENGINEERING: Economics, Technique, Ecology*, 68(2), 48-56. doi: 10.20535/1813-5420.2.2022.261493.

[20] Resolution of the National Commission for State Regulation of Energy and Public Utilities No. 1976 "On Marginal Prices in the Day-Ahead Market, Intraday Market and Balancing Market". (2024, November). Retireved from https://zakon.rada.gov.ua/rada/show/v1976874-24#Text.

[21] Shufian, A., & Mohammad, N. (2022). Modeling and analysis of cost-effective energy management for integrated microgrids. *Cleaner Engineering and Technology*, 8, article number 100508. doi: 10.1016/j.clet.2022.100508.

[22] Siddiquee, S.M.S., Howard, B., Bruton, K., Brem, A., & O'Sullivan, D.T.J. (2021). Progress in demand response and it's industrial applications. *Frontiers in Energy Research*, 9, article number 673176. doi: 10.3389/fenrg.2021.673176.
[23] Sinchuk, I. (2019). *Methodological basis for assessing the electricity efficiency of iron ore enterprises*. Kremenchuk: PE "Shcherbatykh O.V.".
[24] Sinchuk, O., Rogoza, M., Mykhailenko, O., Kobeliatskyi, D., & Fedotov, V. (2024). Heuristic control of power consumption by up to 1000 V electrical loads at mining enterprises. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 1, 84-91. doi: 10.33271/nvngu/2024-1/084.
[25] Telbayeva, S., Nurmaganbetova, G., Avdeyev, L., Kaverin, V., Issenov, S., Janiszewski, D., Smagulova, K., & Nurmagambetova, G. (2024). Development of mathematical models of power consumption at coal plants. *Eastern-European Journal of Enterprise Technologies*, 5(8(131)), 22-32. doi: 10.15587/1729-4061.2024.313932.
[26] Vieira, D.A.G., e Horta, G.D.L., Silva, G.R.L., & Tavares, L.D. (2024). Dynamic pricing-driven framework for optimizing energy consumption. In *16th seminar on power electronics and control (SEPOC)* (pp. 1-11). Santa Maria: IEEE. doi: 10.1109/SEPOC63090.2024.10747424.
[27] Wang, C., Liu, W., Zhang, J., & Liu, H. (2023). Potential development and planning method of industrial load regulation. In X. Dong, Q. Yang & W. Ma (Eds.), *The proceedings of the 10th frontier academic forum of electrical engineering* (*FAFEE2022*) (pp. 1195-1203). Singapore: Springer. doi: 10.1007/978-981-99-3408-9_107.
[28] Wang, S., Cao, F., & Jia, J. (2024). Optimization of provincial agent-based electricity purchasing time-of-use pricing considering multi-level market interactive influence. In *3rd international conference on energy and electrical power systems (ICEEPS)* (pp. 773-779). Guangzhou: IEEE. doi: 10.1109/ICEEPS62542.2024.10693174.
[29] Wang, X., Liu, C., Wu, B., Wang, W., Sun, Y., Peng, J., Liu, X., & Zhang, K. (2024). Design strategy of electricity purchase and sale combination package based on the characteristics of electricity prosumers in power system. *Processes*, 12(12), article number 2836. doi: 10.3390/pr12122836.
[30] Yan, C.-H., Liu, F., Hu, C.F., Cui, H., & Luo, Z.Q. (2019). Improved simplex method algorithm used in power market clearing. *Journal of Physics: Conference Series*, 1304(1), article number 012025. doi: 10.1088/1742-6596/1304/1/012025.

Інтеграція матеріальних витрат підприємств на електроенергію в структуру показників ефективності її споживання

Ігор Сінчук
Кандидат технічних наук, доцент
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0003-3938-0744

Тетяна Берідзе
Доктор економічних наук, професор
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0003-2509-3242

Олексій Михайленко
Кандидат технічних наук, доцент
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0003-2898-6652

Олександр Яловий
Аспірант
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0009-0006-1356-2987

Костянтин Шепелєв
Аспірант
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0009-0006-3462-2707

Анотація. Метою статті було розглянути питання підвищення рівня ефективності використання електричної енергії – основного виду енергії в умовах функціонування гірничодобувних підприємств на прикладі їх типів з підземним способом видобутку корисних копалин. Підтверджено, що зміна режимів споживання електричної енергії електроприймачами аналізованих типів підприємств, які працюють у безперервному циклі роботи (24 години на добу) є одним з невід'ємних і дієвих заходів підвищення їх енергоефективності. Однак зазначено, що існуюча канонічна формула визначення рівня енергоефективності підприємств не дозволяє встановити рівень досягнення ефекту в аналізованому варіанті заходу. Підкреслено, що суперечливість цієї формули при визначенні рівня енергоефективності поширюється і на інші сучасні варіанти підвищення енергоефективності, в тому числі на мережі з розосередженою генерацією. Запропоновано визначати рівень енергоефективності за показником відповідних матеріальних витрат на спожиту енергію. Для підтвердження цієї пропозиції проведено дослідження мінливості режимів електроспоживання за годинами доби з урахуванням мінливості тарифів. Проаналізовано та доведено, що споживання та управління режимами роботи електроприймачів за годинами доби має здійснюватися у форматі процесу. Проведено аналітичне обґрунтування запропонованого процесу та зроблено висновки

Ключові слова: енергоефективність; управління; системи електропостачання; електроенергетика; лінійне програмування; оптимізація; ціна на електроенергію