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Modeling assessment of power consumption efficiency at iron ore mining enterprises

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ABSTRACT

Today's world requires controlling the process of power consumption and supply. The control system should respond proactively and preventively to external disturbances. Among such disturbances for iron ore mining enterprises, the most significant are changes in the technology of operating modes of stationary power receivers, taking into account power costs. General methodological approaches to forming models that relate power consumption indices for a given volume of ore mass mined are investigated. Methods of formalizing components of the power system of iron ore mining enterprises engaged in underground mining of iron ore raw materials are under study. Methods for building a mathematical model of optimal power consumption efficiency are studied. The synthesized model makes it possible to determine the mode of operation required to mine a given amount of ore mass, while minimizing the cost of power consumption. A target function is built considering the cost of power consumed by an iron ore underground mining enterprise. Minimization of the power consumption cost is formed as a task of reducing the functional in terms of the active power consumed at a certain period of time. The proposed solution is limited to the condition that the cost of active power is time dependent, i.e. it is a piecewise-constant function. As a result, the power cost is given by a piecewise-constant function with two values. A qualitative graphical representation of the considered time dependence of the active power cost is presented. Based on visual and graphical analysis, an analytical function of the active power cost according to time of day is formed.

Keywords: Enterprise; power; model; iron ore materials; energy efficiency

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INTRODUCTION
FORMULATION OF THE PROBLEM

Problems of Ukraine's power engineering were considered near 'dramatic' in early 2022 for a variety of reasons, but crossed that line and became catastrophic as a result of the Russian military invasion.

To find a way out of this situation, creative efforts are needed from both power generating facilities and industrial enterprises, which are the main power consumption complexes in the mining and metallurgical sector of Ukraine, 20 % of which make the raw material base of the country's metallurgy [1, 2].

Since these types of industries are the main contributors to the gross domestic product and foreign exchange earnings of Ukraine's budget, attention to them should be focused at the state level. In other words, the problem of energy efficiency in mining is a priority among other economic problems of industrial enterprises in Ukraine. The odious aspect of the above-mentioned and necessary for the state decisions is the fact that it is impossible to reduce power consumption by these enterprises and reach the desired levels of energy efficiency. This is due to the constant growth of the mining depth for these types of minerals, which dictates the need to increase power consumption [3]. In the current option, the real problem here is to control power consumption by consumers, according to the production technology and time of day, since power tariffs are formed on an hourly basis.

It is logical that to control power consumption modes is not an easy task, and the option of 'manual control' is not effective here, since the levels of power consumption by consumers of mining enterprises are stochastic and unpredictable in time [4]. Moreover, the expected automated control system (ACS) should adaptively and preventively respond to challenges of certain disturbing factors, i.e. impact parameters. That is, the process of power consumption by ore mining enterprises should be controlled on the basis of a smart ACS.

In turn, efficiency of such an ACS will depend on the quality of the input data and the ability to process it quickly in time in order to issue required control commands. Therefore, the first step in creating the above-mentioned ACS involves establishing a list of input parameters and assessing them for its operation.

The logical direction in this regard is to determine these parameters by experimental methods with further analysis of the data obtained. However, in the conditions of operating mining enterprises, including iron ore underground mines, this does not seem realistic. In turn, given the potential of modern modeling methods, and based on real indices of functioning parameters of the power system of the above-mentioned enterprises, it is possible to do this by receiving, formalizing and assessing the final option of the search for the necessary data.

1. LITERATURE REVIEW

The search for alternative solutions to this problem is receiving considerable attention in modern scientific research. The research results show that there are many various approaches to improving energy efficiency of mining enterprises. However, these studies are limited in their approach to selecting the structure of power supply systems for underground mining enterprises.

Therefore, taking into account the latest trends, the problem of controlling energy flows at mining enterprises is formulated and considered in [3]. Given the significant scientific and practical contribution of modern scholars, it should be noted that these studies do not provide specific solutions in full. The deterioration of technological conditions, which has led to an increase in iron ore mining depth, raises the issue of improving energy efficiency of iron ore mining to a new level of scientific search. This is confirmed by the fact that most of the known studies [4] are conducted for iron ore mining conditions at up to 1000 m depth. Currently, these marks have crossed the 1500-2100 m level. It is clear that power consumption at such depths, and therefore the influence on the total cost of iron ore mining, has increased and will continue to increase. All this suggests the need to assess efficiency of power consumption by iron ore underground mining enterprises.

In [5] presents an optimal model of power consumption control and its application in a coal mine in South Africa. The scenario shows how an optimal control model can be applied to improving energy efficiency by controlling a conveyor. The power tariff is used as an input to the target function to obtain a solution that minimizes the power cost and thus maximizes the conveyor load shift during the time of day.

In [6] optimal integration of power consumption control for a petrochemical plant is presented, taking into account the uncertainty of power supply.

In [7] shows an original integrated model of a surface coal mine aimed to support energy-efficient solutions. It suggests a mixed integer linear programming used to formulate a general integrated model of operational power consumption of four general subsystems of open-pit coal mining: excavation and transportation, stockpiles, processing plants, and belt conveyors. Mines are represented as linked instances of the four subsystems in the form of a sequential operation, which are then customized to the data provided by mine operators. The integrated model solution synchronizes the operation of control subsystems, power consumption levels, and contributes to energy efficiency of the enterprise as a whole.

In [8] provides an assessment of energy efficiency for electric machines, which allows us to quickly identify many technological problems associated with the production cycle. The rapid growth of data mining techniques has opened up new opportunities for automated processing and analysis of large amounts of collected power consumption data. However, the data available from existing control systems is usually not ready for such analysis and requires complex preparation: cleaning, integration, selection, and transformation. The paper proposes methods for analyzing energy consumption data based on a knowledge discovery application. The input information includes observations of the production system's behavior and relevant power consumption data.

In [9] notes that the mining industry in South Africa acquired 13.8 % of power supplied by Eskom in 2015 at gold mines, using about 8 % of the total. Gold mines with deep levels require cooling and water recirculation systems to operate at extreme depths. These systems consume 40 % of the power supplied to a typical deep level mine. Therefore, increasing energy efficiency in these systems results in lower power and operating costs. Unique integration work is required for a particular underground mine, which will significantly improve energy efficiency. The strategy leads to successful implementation and integration of cooling and reticulation systems in the mine.

In [10] indicates that conventional projects implemented at gold mines are aimed at reducing consumption of large power consumers, such as cooling systems, pumps, ventilation, and compressed air. Therefore, the paper discusses different types of

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projects that can be identified using existing data sources. The specified parameters and ranges for these parameters are necessary to identify the potential of the project. The system identifies five projects and quantified potential savings for three of them. Total potential savings amount to 10.66 MW. It has been proven that some energy saving projects can be identified automatically using these parameters as part of EnNS.

In [11, 12] investigate the issues of improving energy efficiency of underground mines by increasing the capacity of their ventilation systems. It is shown that the power associated with ventilation of underground workings constitutes a significant portion of the underground mine's basic power demand and, accordingly, a large proportion of total operating costs. Ventilation systems can account for 25-40 % of the total power cost and 40-50 % of the total power consumption of an underground mine. The total capacity of fans installed in a single underground mine can exceed 10,000 kW. The paper shows how engineering design principles can be applied to improving the performance and efficiency of ventilation systems, leading to significant reductions in power consumption, operating costs, and greenhouse gas emissions.

2. PURPOSE AND OBJECTIVES OF THE RESEARCH

The research **aims** to develop a mathematical model for assessing energy efficiency at iron ore underground enterprises.

To achieve this aim, the following tasks are formulated:

– formalizing components of power consumption by iron ore underground enterprises;

– building a target function taking into account the complexity of their influence on power consumption by an iron ore mining underground enterprise;

– developing a mathematical model of optimal energy efficiency by an iron ore underground mining enterprise.

3. FORMATION OF A MATHEMATICAL MODEL OF OPTIMAL EFFICIENCY OF POWER CONSUMPTION BY AN IRON ORE UNDERGROUND MINING ENTERPRISE

In accordance with the research aim, the mathematical formulation of the problem is written in the form formatted in [5].

There are limitations in the form of the required amount of power consumption to select a given volume of ore mass:

$$\int_0^T W(t)dt = Q_0, \qquad (1)$$

where $W(t)$ is active power consumed at the central distribution station (CDS), at time t, kW;
– $[0, T]$ is the period of operation of mining equipment, h;
– Q_0 is the amount of power consumed for mining a given volume of ore mass, kW*h.

At the same time, limitations on the amount of active power consumed at the CDS should be observed.

$$0 \le W(t) \le W_{\max}, \qquad (2)$$

where W_{max} is the maximum value of the active power consumed at the CDS, kW.

Minimization of the power cost for mining a given volume of ore mass is formulated as the task of minimizing the functionality of the active power consumed at a certain period of time $[0, T]$

$$Z = \int_0^T c(t)W(t)dt \to \min_W, \qquad (3)$$

where $c(t)$ is the cost of active power depending on time, UAH/kW.

Thus, conditions (1), (2) and (3) determine the mathematical formulation of the problem of minimizing power costs, subject to a given volume of ore mass mined.

Let us consider the solution of the problem, limited to the condition that the active power cost, which is time dependent, acquires only two values, i.e. it is a piecewise-constant function. One value (smaller) refers to the night, the second value (large) refers to the daytime of operation of ore mass mining equipment.

Fig. 1 presents a qualitative graphic image of the considered time dependence of the active power cost.

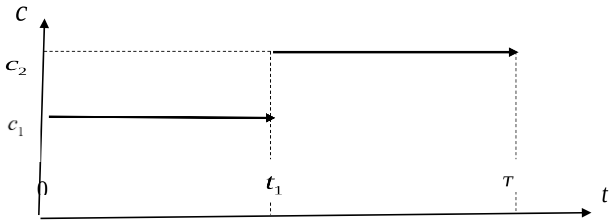

Fig. 1. **Dependence of the active power cost on time:**
c_1 – is the active power cost at night, i.e. in the interval $[0, t_1]$; c_2 – is the active power cost in the daytime, i.e. in the interval $[t_1, T]$
***Source:* compiled by the authors**

According to the graph presented in Fig. 1, analytically, the function of the active power cost, which is dependent on time of day, can be represented by the formula

$$c(t) = \begin{cases} c_1, & 0 \le t < t_1 \\ c_2, & t_1 < t \le T \end{cases}. \quad (4)$$

To solve problems (1), (2), (3), we use the type of function (4). Using the integral linearity, we find

$$\int_0^T c(t)W(t)dt = c_1\int_0^{t_1} W(t)dt + c_2\int_{t_1}^T W(t)dt. \quad (5)$$

We introduce the notation

$$Q_1 = \int_0^{t_1} W(t)dt, \qquad Q_2 = \int_{t_1}^T W(t)dt. \quad (6)$$

where Q_1, Q_2 is power consumption in areas of time where power costs are c_1 and c_2, respectively.

Then the functional (3) taking into account (6) will be written as follows

$$Z = c_1 \cdot Q_1 + c_2 \cdot Q_2.$$

In turn, the limitation (1) can be written as

$$\int_0^T W(t)dt = \int_0^{t_1} W(t)dt + \int_{t_1}^T W(t)dt. \quad (7)$$

Or, taking into account (1) and (6),

$$Q_1 + Q_2 = Q_0. \quad (8)$$

By integration, the limitation (2) on the first time interval will be presented in the form of

$$0 \le \int_0^{t_1} W(t)dt \le \int_0^{t_1} W_{\max}dt \quad (9)$$

.

According to (6), the inequality (9) will be written as

$$0 \le Q_1 \le \int_0^{t_1} W_{\max}dt. \quad (10)$$

Calculating the integral on the right side of the inequality (10), we finally find the limitation of power consumption on the interval of time where the power cost is c_1

$$0 \le Q_1 \le \overline{Q_1}. \quad (11)$$

where $\overline{Q_1} = W_{\max} \cdot t_1$.

The limitation (2) on the second time interval *[t1, T]* will be presented after integration as

$$0 \le \int_{t_1}^T W(t)dt \le \int_{t_1}^T W_{\max}dt. \quad (12)$$

According to (6), the inequality (12) after integration will be written as

$$0 \le Q_2 \le \overline{Q_2}, \quad (13)$$

where $\overline{Q_2} = W_{\max} \cdot (T - t_1)$.

Taking into account the results obtained, and considering (11) and (13), the problem of minimizing power consumption (1), (2), (3) is recorded as

$$Z = c_1Q_1 + c_2Q_2 \to \min_{Q_1,Q_2}, \quad (14)$$

$$Q_1 + Q_2 = Q_0, \quad (15)$$

$$0 \le Q_1 \le \overline{Q_1}, \quad (16)$$

$$0 \le Q_2 \le \overline{Q_2}. \quad (17)$$

Analysis of (14)-(17) shows that this problem refers to linear programming [6] that can be solved both geometrically and analytically.

Let us consider an analytical solution, provided that a solution exists. To do this, we go to one variable, using the condition (15),

$$Q_2 = Q_0 - Q_1, \quad (18)$$

As a result, the target function (14) will be written in the form $Z = c_1Q_1 + c_2(Q_0 - Q_1) \to \min_{Q_1}$, or after regrouping as

$$Z = c_2 \cdot Q_0 - (c_2 - c_1) \cdot Q_1 \to \min_{Q_1}. \quad (19)$$

In turn, the condition (17) will take the form $0 \le Q_0 - Q_1 \le \overline{Q_2}$, or after algebraic transformations as

$$Q_0 - \overline{Q_2} \le Q_1 \le Q_0. \quad (20)$$

Taking into account (19) and (20), the task of reducing power consumption will be written in the form of

$$Z = c_2 Q_0 - (c_2 - c_1) \cdot Q_1 \to \min_{Q_1}, \quad (21)$$

$$0 \le Q_1 \le \overline{Q_1}, \quad (22)$$

$$Q_0 - \overline{Q_2} \le Q_1 \le Q_0. \quad (23)$$

Since the target functional Z is linearly dependent on the variable Q_1 and $c_2 > c_1$, the minimum value is achieved on the right side of the variable Q_1, i.e. the optimal value

$$\hat{Q}_1 = \bar{Q}_1. \quad (24)$$

With that,

$$\hat{Q}_2 = Q_0 - \bar{Q}_1. \quad (25)$$

The result obtained coincides with the one previously found by a geometric way. It should be emphasized that after solving problems (1), (2), (3), optimal power consumption for specified periods of time is determined by its differentiated cost, i.e.

$$\int_0^{t_1} W(t)dt = \hat{Q}_1, \quad (26)$$

$$\int_0^{t_1} W(t)dt = \hat{Q}_2. \quad (27)$$

According to (26), we find the average value of active power in the period of time *[0, t_1]*, where the power cost is c_1,

$$\overline{W_1} = \frac{\hat{Q}_1}{t_1}. \quad (28)$$

Considering (27), we write formula (28) as

$$\bar{W}_1 = \frac{\int_0^{t_1} W(t)dt}{t_1} = \frac{W_{\max} \cdot t_1}{t_1}, \quad (29)$$

i.e.

$$\bar{W}_1 = W_{\max}. \quad (30)$$

In turn, according to (28), we find the average value of active power for the period of time *[t_1, T]*, where the power cost is c_2, $\overline{W_2} = \frac{\hat{Q}_2}{T - t_1}$.

Considering (29), it can be written

$$\overline{W_2} = \frac{Q_0 - \bar{Q}_1}{T - t_1} = \frac{Q_0 - W_{\max} \cdot t_1}{T - t_1}. \quad (31)$$

Taking into account (31), the minimum value of the functional (21) consistently takes the form

$$Z_{\min} = c_2 Q_0 - (c_2 - c_1) \cdot \hat{Q}_1,$$
$$Z_{\min} = c_2 Q_0 - (c_2 - c_1) \cdot \bar{Q}_1, \quad (32)$$
$$Z_{\min} = c_2 Q_0 - (c_2 - c_1) \cdot W_{\max} \cdot t_1.$$

Further research requires the use of statistical data on power consumption at individual iron ore underground mining enterprises to confirm the results obtained.

4. EXAMPLE OF INVESTIGATING A MATHEMATICAL MODEL FOR OPTIMAL EFFICIENCY OF POWER CONSUMPTION BY AN IRON ORE UNDERGROUND MINING ENTERPRISE

We suggest considering a study of power consumption by underground mining enterprises of the PJSC “Kryvyi Rih Iron Ore Works”, Ukraine. Power generating enterprises (oblenergos) encourage consumers to reach ideal daily equalization of power production-consumption levels.

The pricing policy of power generating enterprises relative to power consumers corresponds to time intervals that form zone power tariffs.

Table 1 shows the relevant data for two-zone power consumption tariffs. Data analysis indicates that the power tariff changes during the day.

Table 1. **Zone tariffs for power consumption**

Zone tariffs	Costs, UAH/kW*h	Tariff limits
$c_н$ (night)	0.96	12pm-7am
$c_д$ (daytime)	2.20	7am-12pm

***Source:* compiled by the authors**

The highest power cost is during the daytime, which is associated with a large number of power consumers and the shortage of power. Conversely, at night the power cost is the lowest, which is explained by the number of operating power consumers and available surplus power.

Thus, enterprises in general and iron ore mining ones in particular are facing the two-part problem of distributing power consumption in hours while ensuring the continuity of the technology of production processes.

Fig. 2 presents daily curves of power consumption at the analyzed enterprise.

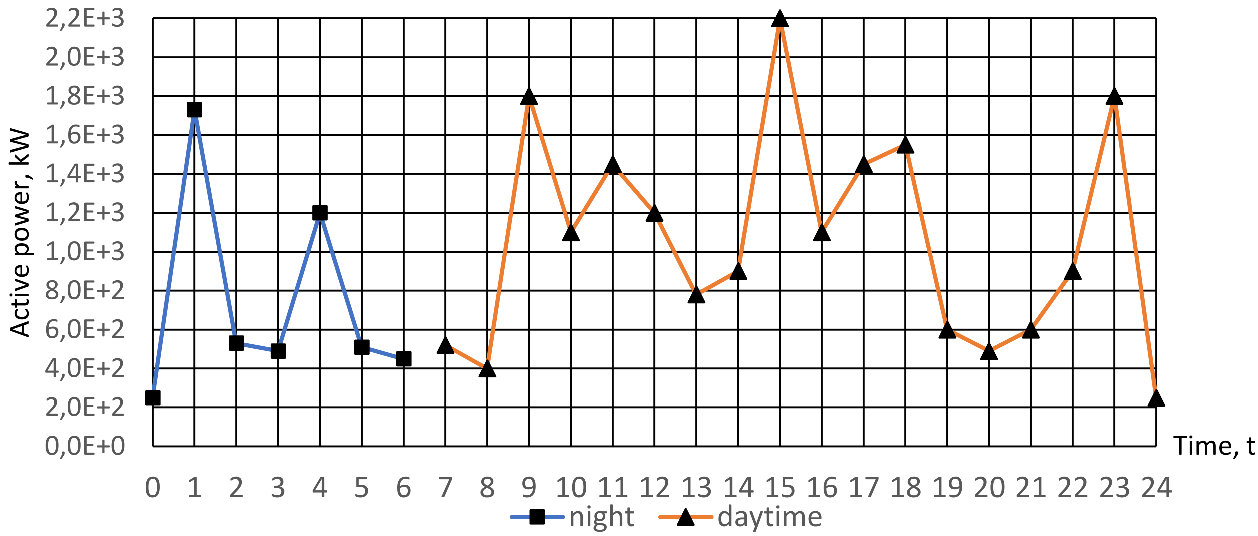

Fig. 2. **Daily curves of power consumption by an underground mining enterprise**
Source: **compiled by the authors**

We calculate integral characteristics of real power consumption, according to the graph in Fig. 2. Daily power consumption costs make

$$Q_0 = \int_0^{24} W(t)dt = 24000 \text{ kW*h} \quad . \tag{33}$$

We define the condition under which a solution to the problem exists (14), …, (17).

$$W_{\max} \geq \frac{Q_0}{T} = \frac{24000}{24} = 1000 \text{ Tariffs.} \tag{34}$$

According to Fig. 2, it can be accepted that

$$W_{\max} = 2200 \text{ kW} \quad . \tag{35}$$

Next, we calculate the power cost according to the type of the functional (7). According to (6), we preliminarily find power consumption for zone tariffs "night" and "daytime", respectively,

$$Q_н = \int_1^7 W(t)dt = \text{ kW*h,} \tag{36}$$

$$Q_д = \int_7^{24} W(t)dt = 18840 \text{ kW*h.} \tag{37}$$

Using the data from Table 1, we find the total cost of daily power consumption in UAH,

$$Z = c_н \cdot Q_н + c_д \cdot Q_д = 0{,}96 \cdot 5160 + 2{,}20 \cdot 18840 = 4953{,}6 + 41448 = 46401{,}6 \tag{38}$$

We determine the minimum value of the total power cost in UAH

$$Z_{\min} = 0.96 \cdot 15400 + 2.2 \cdot 8600 = 33704 \text{ UAH} \tag{39}$$

Application of the algorithm for reducing power consumption levels of iron ore mining enterprises, which is represented by formulas (14)-(17), shows that in these types of enterprises there is an appropriate reserve for optimizing power consumption levels, which is based on effective consideration of power tariffs.

We find the value of the relative decrease in the enterprise's power consumption during the day

$$\frac{Z - Z_{\min}}{Z} \cdot 100\% \approx 27.4\% \tag{40}$$

Thus, daytime power consumption of stationary equipment at an iron ore underground mine can be reduced by 27.4 %, while maintaining total power consumption.

A feature of the problem-solving method recommended for practical use to develop the ACS "Power Supply and Power Consumption of Control Systems with Artificial Intelligence" [13, 14], [15, 16], [17, 18], [19, 20], [21, 22], [23, 24], [25] is that time dependence of the power cost is set as a piecewise-constant function. As a result, the power price is given by a piecewise-constant function with two values.

CONCLUSIONS

1. In the current conditions of iron ore underground mining associated with further increasing of the mining depth, a more thorough targeted analysis of power consumption by different consumers is needed to form the basis for building a target func-

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tion that considers power consumption by time of day.

2. A unique feature of the mathematical model proposed by the author is that the dependence of power costs is set as a piecewise-constant function. Comparison of the obtained theoretical results with real data leads to the conclusion that there exists an appropriate reserve for optimizing power consumption levels.

3. Qualitative optimized values of power consumption costs are obtained for an iron ore underground mine, where power consumption of stationary equipment, which consumes the most power during the day, is reduced by 27.4 % while maintaining the total power consumption.

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Моделювання оцінювання ефективності електроспоживання на залізорудних підприємствах

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АНОТАЦІЯ

Сьогодення вимагає керування процесом споживання – постачання електричної енергії. Система управління повинна адаптивно-превентивно реагувати на зовнішні збурення. Серед таких збурень для залізорудних підприємств найбільш суттєвими є зміни в технології режимів функціонування електроприймачів стаціонарних установок з урахуванням тарифів на електричну енергію. Досліджені загальні методологічні підходи щодо формування моделей в яких пов'язані показники споживання електричної енергії за умови заданого обсягу забору рудної маси. Методи формалізації складових електроенергетичної системи залізорудних підприємств із підземним способом видобутку залізорудної сировини. Методики побудови математичної моделі оптимальної ефективності електроспоживання. Синтезована модель дозволила визначити необхідний режим роботи пристрою забору руди, щоб вибрати заданий обсяг рудної маси, при цьому мінімізувати вартість споживання електроенергії. Побудована цільова функція, що враховує вартість електроспоживання підприємством із підземним способом видобутку залізорудної сировини. Мінімізація вартості за споживання електроенергії формується як завдання мінімізації функціоналу по активній потужності електроенергії, що споживається, за виділений проміжок часу. Пропонується рішення обмежуючись умовою, щодо вартості активної потужності електроенергії в залежності від часу, тобто є кусково-постійною функцією. Внаслідок цього, ціна електроенергії задається кусково-постійній функцією з двома значеннями. Представлено якісне графічне зображення розглянутої залежності вартості активної потужності електроенергії від часу. На підставі візуально-графічного аналізу сформована аналітично функція вартості активної потужності електроенергії в залежності від часу доби.

Ключові слова: Підприємство; електрична енергія; модель; залізорудна сировина; енергоефективність

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