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Optimisation of air exchange and heat transfer using coaxial air ducts

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Abstract. In modern industrial premises, it is important to ensure effective air exchange with minimal energy consumption, which necessitates the optimisation of ventilation systems, particularly through the development of new air duct designs. The aim of this article was to develop a combined exhaust-supply air duct structure to improve the efficiency of air exchange in industrial spaces and reduce energy consumption for air heating. A comprehensive analysis was conducted of current scientific sources published in various countries, covering advanced technologies in air exchange, ventilation, and microclimate regulation. Theoretical justification of the design and mathematical modelling of heat transfer processes between the exhaust and supply air ducts were applied. Methods of heat conduction, convection, and radiation were also used to analyse the physical processes. As a result, a coaxial air duct structure was developed, consisting of an inner exhaust and an outer supply pipeline, with their diameter ratio optimised by the formula $D = 1.4 \cdot d$. Calculations confirmed the equality of exhaust and supply air volumes, ensuring stable air exchange. Modelling showed that the system effectively ensures uniform air distribution in the working zone, improving the overall performance of the ventilation system. A reduction in energy consumption was achieved by using the heat from the exhaust air to preheat the supply air. The calculations and modelling confirmed the effectiveness of the proposed design, which allows for a reduction in energy consumption for air heating and an improvement in air exchange in industrial spaces, contributing to the creation of comfortable working conditions. Overall, the developed ventilation system design is aimed at optimising air exchange processes in industrial premises and offers several advantages: energy efficiency – through the use of secondary heat resources; compactness – as the structure allows a reduction in the volume of ventilation equipment; versatility – since the system can be implemented across various industrial enterprises, including workshops with high levels of air pollution; improved occupational safety – as the new system contributes to the creation of comfortable conditions in the working area

Keywords: ventilation; industrial premises; heat conservation; aerodynamic characteristics; energy-saving technologies; air balance

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Introduction

Ventilation in industrial premises plays a key role in ensuring safe working conditions, particularly in the mining, metallurgical and chemical industries. The issue of removing harmful impurities and supplying clean air remains relevant for workshops where raw materials are processed, transported, and where finished products are manufactured. Existing ventilation systems are insufficiently effective. During the cold season, air requires heating, whereas in the warm season, it must be cooled. Moreover, such systems can be bulky and energy-consuming.

O. Lapshyn *et al*. (2022) described modern methods of maintaining an optimal microclimate, including air purification and recirculation technologies. They emphasise the importance of maintaining a proper balance between the supply of fresh air and the removal of polluted air. V. Korbut & S. Rybachov (2021) conducted experimental studies on the efficiency of dual-level air enclosures for industrial baths. They demonstrated that such a system significantly improves the removal of harmful emissions, which is especially important in production environments with high concentrations of contaminants.

V. Deshko *et al*. (2024) investigated the relationship between ventilation systems and the energy balance of buildings. Using EnergyPlus and DesignBuilder software packages, the authors modelled the impact of ventilation on building energy efficiency and indoor air quality. The results indicate the necessity of precise ventilation system design to ensure maximum efficiency. T. Tkachenko & V. Mileikovskyi (2020), in their studies, examined natural methods of improving indoor air quality. They focused on the influence of natural air ionisation, which makes it possible to significantly reduce the concentration of harmful substances in the air.

O. Voznyak *et al*. (2021) explored physical models of ventilation system elements under special conditions. They confirmed that adapting ventilation equipment to specific industrial conditions can significantly improve ventilation efficiency and enhance the microclimate in work areas. X. Wei *et al*. (2023) analysed the effectiveness of personalised air supply systems in reducing the impact of pollutants on workers. Their studies confirmed that a directed air stream improves air quality in the working zone.

E. Dudkiewicz & P. Szałański (2020) considered heat recovery technologies in ventilation systems of large industrial premises. They emphasised the significant potential for reducing heating costs by introducing heat exchangers into ventilation channels. N. Farouk *et al*. (2022) studied the influence of ventilation systems on CO_2 emissions in buildings equipped with phase-change materials. They concluded that energy-efficient ventilation solutions can substantially reduce greenhouse gas emissions while maintaining a comfortable indoor microclimate.

The reviewed scientific sources indicate the need for a comprehensive approach to optimising ventilation systems in industrial buildings. The main directions of research include the improvement of air duct designs, reduction of energy consumption, and enhancement of pollutant removal efficiency. The studies by V. Korbut & S. Rybachov (2021), O. Lapshyn *et al*. (2022), and V. Deshko *et al*. (2024) demonstrate that mathematical modelling is an effective tool for analysing air exchange parameters. At the same time, the studies by E. Dudkiewicz & P. Szałański (2020) and N. Farouk *et al*. (2022) confirm the feasibility of integrating heat recovery technologies into ventilation systems to reduce energy consumption.

However, the issue of optimising the design and parameters of air ducts in industrial premises remains insufficiently explored. Existing studies focus either on general aspects of ventilation or on local experimental research. The aim of this study was to develop a combined exhaust-supply duct design capable of ensuring effective air exchange in industrial premises while reducing energy consumption for air heating.

Literature review

Optimisation of ventilation systems in industrial premises is an important aspect of ensuring effective air exchange and reducing energy consumption. Research in this field covers various methods for improving ventilation processes, including enhancements to air duct design, the application of energy-saving technologies, and the use of mathematical models for analysing airflows.

A. Murga *et al*. (2020) conducted a study on hybrid emergency ventilation systems aimed at reducing the impact of pollutants in industrial spaces. Their work focused on evaluating the effectiveness of ventilation strategies in worst-case air pollution scenarios, such as accidental releases of toxic gases or particulate matter. The authors explored various air exchange regimes by modelling the spread of pollutants using CFD (Computational Fluid Dynamics). The results showed that integrating traditional mechanical ventilation systems with localised air purification sources can significantly reduce harmful emissions in the working zone. The study also highlights the need to consider the aerodynamic characteristics of the premises when designing emergency ventilation systems. The method proposed by the authors may be effective for industrial facilities with high contamination risks.

X. Zhao & Y. Yin (2024) in their study investigated modern pollution control strategies in industrial spaces and their impact on ventilation efficiency. They found that the most effective solutions were adaptive ventilation systems with dynamic regulation of airflow based on pollution levels. These systems use sensors to monitor the concentration of harmful substances, allowing automatic adjustment of airflow velocity and direction. The study placed significant emphasis on the relationship between microclimate parameters and worker productivity. The authors note that advanced ventilation strategies can not only improve air quality but also increase worker comfort, reducing the risk of occupational illnesses. The proposed pollution control methodology is considered promising for implementation in enterprises operating in challenging conditions, such as the metallurgical, chemical, and mining industries.

A. Pakari & S. Ghani (2021) analysed the effectiveness of various mechanical ventilation systems in cattle barns using CFD modelling and field measurements. They demonstrated that airflow optimisation contributes to improved microclimate conditions and animal productivity. Although their study relates to the agricultural sector, the findings may also be applicable to industrial premises. O. Tykhenko *et al*. (2024) investigated the factors influencing air ionisation in indoor spaces. They found that increasing the concentration of negatively charged ions promotes the removal of harmful particles, which is important for industrial facilities with high levels of dust pollution.

E. Zender-Świercz (2021) studied the impact of decentralised façade ventilation devices on indoor air quality. The author notes that such devices can effectively operate in combination with traditional ventilation systems, increasing the overall energy efficiency of buildings. T. Catalina & C. Lungu (2021) examined the effect of decentralised ventilation systems in classroom environments and their ability to maintain a high level of air quality. Their research showed that such systems can effectively remove air pollutants and improve comfort for occupants. M.I. Elhadary *et al*. (2021) carried out a comparative analysis of forced ventilation systems in industrial premises to improve worker comfort. They determined that combining mechanical ventilation with natural methods can significantly reduce heat loads and enhance working conditions.

Overall, the studies conducted by various authors expand the scientific understanding of alternative approaches to improving air exchange, including air ionisation, airflow optimisation, and the use of local ventilation devices. The relevance of energy-efficient ventilation is also confirmed by numerous studies. However, further development in this field requires the design of new, more effective technological solutions tailored to specific industrial conditions.

Materials and Methods

Regulatory documents such as the DSTN 3.3.6.042-99 (1999), DSTU-N B V.1.1-27:2010 (2010), and DBN V.2.5-67:2013 (2013) regulate the microclimate parameters in industrial premises, including permissible values for temperature, humidity, and air velocity. These requirements form the basis for the calculation and design of ventilation systems. Analytical and experimental methods were used in the study to evaluate the effectiveness of the proposed coaxial air duct (Patent No. 156625, 2024) in an industrial facility for the beneficiation of titanium-zirconium ores at the branch of the Vilnohirsk Mining and Pro cessing Plant of JSC UMCC, specifically in the drying workshop. The primary materials for analysis included design data of existing ventilation systems, results of laboratory measurements of microclimate parameters, and numerical modelling of airflow.

A comparison was made between the microclimate parameters specified in the above-mentioned regulatory documents and the actual values obtained during experimental measurements in the industrial facility. Parameters of the air environment (temperature, humidity, and airflow velocity) were measured using electronic anemometers, thermohygrometers, and gas analysers. The obtained data were subjected to mathematical processing to identify patterns and assess the effectiveness of the ventilation solutions. The solution to the heat exchange problem was performed using the Bernoulli method (formula 19) on a computer using Microsoft Excel. The equipment used included:

- anemometers for measuring airflow velocity;
- thermohygrometers for determining air temperature and humidity;
- gas analysers for monitoring carbon dioxide concentration and other harmful impurities;
- Microsoft Excel software for numerical modelling of the physical heat transfer process in the premises.

The applied methods made it possible to conduct a comprehensive analysis of the air duct system's effectiveness, assess its compliance with regulatory requirements, and develop recommendations for its optimisation.

Results and Discussion

The proposed air duct design consists of coaxially arranged exhaust and supply pipes: the exhaust duct has a diameter d, while the supply duct is determined using the formula (1), which ensures the required air exchange:

$$D = 1.4 \cdot d, \text{ m}. \tag{1}$$

The problem was solved by applying the formula for calculating the cross-sectional area:

$$Se = \pi \cdot d^2/4; \tag{2}$$

$$Ss = \pi \cdot D^2/4, \tag{3}$$

where Se – cross-sectional area of the exhaust air duct, m^2; Ss – cross-sectional area of the supply air duct, m^2.

This design provides uniform air exchange. The duct layout, as shown in Figure 1, includes exhaust and supply air ducts as well as a dispersing nozzle equipped with a swivel mechanism (coupling).

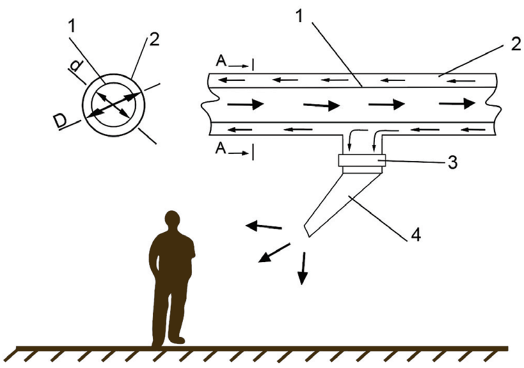

Figure 1. Combined air duct for ventilation of industrial premises

Notes: 1 – exhaust air duct; 2 – supply air duct; 3 – rotary mechanism (coupling); 4 – dispersing nozzle

Source: developed by the authors based on Patent No. 156625 (2024)

The operating principle of the air duct system is as follows. Polluted air from the source enters the exhaust duct via an extraction hood; the duct is located coaxially within the supply duct, and the air then flows through it to the air purification system. At the same time, clean air enters the room via the outer supply duct from the outside. Along the length of the supply duct, diffusing nozzles equipped with swivel mechanisms (couplings) are installed, forming clean air jets directed into the working zones of the industrial space.

The analysis and justification of air exchange parameters in industrial premises are carried out to verify the reliability of formula (1) and assess its applicability for ventilation system design. According to general regulations (DSTN 3.3.6.042-99, 1999; DSTU-N B V.1.1-27:2010, 2010; DBN V.2.5-67:2013, 2013), it is essential to maintain a balance between the volumes of extracted and supplied air in order to ensure effective ventilation in industrial environments:

$$Qe = Qs, \tag{4}$$

where Qe – volume of extracted air, m^3; Qs – volume of supplied air, m^3.

The thermal balance of the room is based on the law of conservation of energy, which states that energy is neither lost nor created, but only transformed or transferred between systems. Under industrial conditions, this balance takes the following form:

$$Qn + Qo + Qc = Qv + Qa, \text{J}, \tag{5}$$

where Qn – heat supplied through heating, ventilation, or solar radiation, J; Qo – heat generated by industrial equipment, J; Qc – heat from solar radiation, J; Qv – heat losses through enclosure structures and ventilation, J; Qa – heat accumulated in the building structures, J.

The main calculations of the air duct were carried out. To achieve thermal and ventilation balance, the geometric parameters of the air ducts were taken into account. According to the specified conditions, the diameter D of the supply duct was related to the diameter d of the exhaust duct by ratio (1). Given the exhaust duct diameter $d = 0.3$ m, the corresponding result was $D = 1.4 \cdot 0.3 = 0.42$ m.

Subsequently, the calculations were verified using several parameters:

1. Based on the cross-sectional areas of the air ducts.

Cross-sectional area of the exhaust air duct:

$$Se = \frac{\pi}{4} \cdot d^2 = \frac{\pi}{4} \cdot 0.3^2 \approx 0.07 \text{ m}^2. \tag{6}$$

Cross-sectional area of the supply air duct:

$$Ss = \pi/4 \cdot D^2 = \pi/4 \cdot 0.4^2 \approx 0.14, \text{m}^2. \tag{7}$$

The area of the annular section of the supply air duct was calculated as the difference between the supply and exhaust duct areas:

$$\Delta Ss = Ss - Se = 0.14 - 0.07 = 0.07 \text{ m}^2. \tag{8}$$

This indicated that the annular area of the supply duct (ΔSs) matched the area of the exhaust duct (Se), thereby ensuring air exchange balance.

2. Based on air volume:

The air velocities in both ducts were assumed to be equal:

$$\vartheta e = \vartheta s = 4 \text{ m/s}. \tag{9}$$

Volume of extracted air:

$$Qe = Se \cdot \vartheta e = 0.07 \cdot 4 = 0.28 \text{ m}^3\text{/s}. \tag{10}$$

Volume of supplied air:

$$Qs = \Delta Ss \cdot \vartheta s = 0.07 \cdot 4 = 0.28 \text{ m}^3\text{/s}. \tag{11}$$

Thus, the volumes of exhaust and supply air are equal: $Qe = Qs$. Calculations confirmed that formula (1) is reliable and may be applicable for the design of ventilation systems in industrial premises. The use of combined air ducts contributes to effective air exchange and reduced energy consumption, particularly through the utilisation of secondary heat. This was confirmed by experimental studies conducted under real conditions in the drying workshop of a titanium-zirconium ore beneficiation plant.

The physical process of heat transfer from the exhaust duct to the supply duct is based on the mechanisms of thermal conduction, convection, and possible partial participation of radiative heat exchange. Each aspect was therefore examined in detail:

1. Thermal conduction. The coaxial design, where the exhaust duct is located inside the supply duct, ensures thermal contact through their walls. The exhaust duct typically carries used warm air, the temperature of which may be significantly higher than that of the supply air. As a result, thermal energy is transferred through the walls of the inner duct to the supply air.

The heat transfer formula based on conduction is as follows:

$$Q = k \cdot A \cdot \Delta T / b, \text{J}, \tag{12}$$

where Q – amount of transferred thermal energy, J; k – thermal conductivity coefficient of the wall material, kg·m/(s^3·K); A – heat transfer area, m^2; ΔT – temperature difference between the exhaust and supply air, K; b – wall thickness, m.

2. Convection. The supply air in the outer channel moves and comes into contact with the walls of the exhaust duct. As a result, the thermal energy transferred through the walls is immediately absorbed by the flow of supply air. The convective process enhances the efficiency of heat transfer due to the continuous movement of air in the thermal contact zone. The formula for convection is as follows:

$$Q = h \cdot A \cdot \Delta T, \text{J}, \tag{13}$$

where h – heat transfer coefficient (dependent on the velocity and physical properties of the supply air), kg/(s^3 · K).

3. Thermal insulation. The coaxial design reduces heat losses to the surrounding environment, as the outer air duct acts as an insulating layer. This increases the efficiency of thermal energy utilisation from the exhaust air to heat the supply airflow. The supply air duct ensures the heating of incoming air, which enters the room and improves working conditions in the personnel area. Simultaneously, the exhaust duct is cooled, which helps to maintain a balanced temperature. The total thermal balance of the system can be expressed as:

$$Qt = Qin - Qout, \text{J}, \tag{14}$$

where Qt – total thermal balance, J; Qin – heat from the exhaust air, J; $Qout$ – heat from the supply air, J.

Thermal radiation is a natural physical process whereby all bodies with a temperature above absolute zero (0 K) emit energy in the form of electromagnetic waves. In a coaxial air duct system, thermal radiation arises due to the temperature difference between the contacting surfaces:

- the exhaust duct (inner) has an elevated temperature due to the warm used air;
- the wall material emits thermal energy in the form of infrared radiation;
- the supply duct (outer) partially absorbs this energy, adding it to the overall heat transfer.

Thermal radiation is described by Planck's law and the Stefan-Boltzmann equation:

$$Q = \sigma \cdot \epsilon \cdot A \cdot (T_1^4 \cdot - T_2^4), \text{J}, \tag{15}$$

where Q – amount of transferred heat, J; σ – Stefan-Boltzmann constant (5.67 · 10^{-8} W/m^2 · K^4); ϵ – emissivity coefficient of the material (ranging from 0 to 1); T_1 and T_2 – absolute temperatures of the surfaces, K.

It has been established that radiative heat transfer in the system does not always have a significant effect. If the inner duct wall has a high temperature and a low thermal conductivity coefficient, radiative exchange may contribute substantially to the overall heat transfer process. However, in most industrial ventilation systems, thermal conduction and convection remain the dominant mechanisms. In the system under consideration, radiative heat exchange functions only as an auxiliary mechanism, and its effect can be enhanced or diminished depending on material selection and design.

The development of a mathematical model of the air duct functioning as a heat exchanger enables the simulation of heat transfer processes within the working area (Spivak *et al.*, 2024). An important stage in building the model is the consideration of flow dynamics, which define the structure and parameters of the technological environment. Due to the complexity of hydrodynamic processes, it is typically only possible to formulate equations for single-phase flows (Navier-Stokes equations), the solutions of which are usually derived for individual cases. Therefore, simplified approaches are often applied during modelling, based on typical flow structures, such as ideal mixing or ideal displacement.

Flow models are described by systems of differential equations linking the key process parameters. For technological facilities, the most universal approach involves equations that describe changes in substance concentration or energy within the flow. In particular, when cooling or heating the workspace, it is appropriate to use the ideal mixing model, which assumes that the air entering the room is instantly distributed throughout the volume. In this case, the air temperature remains the same at any point in the room. To describe temperature changes over time in the mixing zone, the following notations are introduced: Tin – inlet air temperature, K; $T(t)$ – air temperature at any given time, K; Cp – specific heat capacity of air, m^2/(s^2 · K); V – volume of the mixing zone, m^3; V' – volumetric flow rate of the air, m^3/s; Qin – amount of heat in the incoming air or at any given point, J. The heat exchange equation can be expressed as:

$$Q = V \cdot Cp \cdot T, \text{J}. \tag{16}$$

For changing inlet temperature conditions, the ideal model was described by the following equation:

$$\frac{dT}{dt} + \frac{1}{\tau}T = \frac{1}{\tau}Tin, \tag{17}$$

where $\tau = \frac{V}{V'}$ – the average residence time of air temperature in the mixing zone.

In the presence of a heat source Qs, the equation is modified:

$$\frac{dT}{dt} + \frac{1}{\tau}T = \frac{1}{\tau}Tin + \frac{Qs}{Cp \cdot V}. \tag{18}$$

Solving the equation using the Bernoulli method provides an expression for air temperature:

$$T(t) = Tin + (T_0 - T_{in})e^{-\frac{t}{\tau}} + \frac{\tau \cdot Qs}{Cp \cdot V}, \text{K}. \quad (19)$$

The solution to the resulting equation allows the determination of air temperature dynamics, accounting for variations in inlet temperature, thermal radiation from heat sources, and the average temperature retention time in the mixing zone. This makes it possible to describe in detail the thermal regime in working spaces and to assess the influence of key parameters such as the mixing zone volume, air velocity, and presence of heat sources. One of the most important factors determining the efficiency of ventilation and the achievement of the required temperature regime is the air exchange rate.

The analysis of temperature changes in a specific case involving ventilation of a drying workshop demonstrates that the air exchange rate ($n = \frac{V'}{V}$) significantly affects process efficiency. According to L. Amanowicz *et al.* (2023), the correct selection of air exchange rate is a key factor in reducing the energy consumption of ventilation systems. M. Bezrodny & T. Misiura (2020) emphasise that the use of heat pumps in ventilation systems allows significant improvement in temperature control and reduced heating costs.

A high air exchange rate indicates effective ventilation, which is essential for maintaining a healthy climate and reducing pollutant concentrations. H. Hetmanchuk (2024) notes that the level of natural air exchange depends on numerous factors, including internal and external environmental parameters, which must be considered when designing air ducts for ventilation systems. With increased air exchange rate, the time required to equalise temperature is significantly reduced, as confirmed by experimental calculations of V. Deshko *et al.* (2023).

According to V. Dzhedzhula (2021), ventilation systems of public buildings can serve as the basis for developing efficient industrial solutions. One of the critical aspects is the uniform distribution of airflows, which minimises heat loss and improves energy efficiency. As highlighted by V. Matviichuk *et al.* (2021), mathematical modelling of such systems is a crucial stage in developing optimal ventilation technologies.

The drying workshop of the beneficiation facility has technological equipment that emits a significant amount of heat, which directly affects the temperature regime in the premises and other microclimatic conditions. Under real operating conditions, the workshop has three drum dryers of various sizes, each equipped with two methane gas burners. The inlet temperature of these units reaches 600 ÷ 850°C, while the outlet temperature ranges from 80 ÷ 150°C. The volume of the room is a key parameter for determining the required air exchange rate. It is calculated using the formula:

$$V = H \cdot W \cdot L, \text{m}^3. \quad (20)$$

According to the parameters of the drying workshop, the premises have a height of $H = 3.8$ m, a width of $W = 20$ m, and a length of $L = 30$ m. Thus, its volume is $V = 3.8 \cdot 20 \cdot 30 = 2{,}280$ m^3. For service personnel, the recommended air supply rate is 30 m^3/h per person. These air supply standards for service personnel are based on the recommendations provided in DBN V.2.5-67:2013 (2013), which regulate the minimum volume of fresh air required to ensure a comfortable microclimate. Compliance with these standards is mandatory in the design and operation of ventilation systems to ensure healthy and safe conditions for work and rest. It should be noted that additional air exchange requirements may apply to different types of premises and activities and must be taken into account when designing ventilation systems. For example, if three people work in the drying workshop, the total required air volume for personnel is 90 m^3/h.

For drying premises, the air exchange rate depends on the type of contaminants and heat emissions. Recommended values range from 5 to 15 air changes per hour. Accordingly, the minimum required air volume for $n = 5$ is 11,400 m^3/h, while the maximum for $n = 15$ is 34,200 m^3/h. The total air volume, including personnel needs, at the minimum rate is 11,490 m^3/h, and at the maximum – 34,290 m^3/h. The air exchange rate in the actual conditions of the drying workshop of the beneficiation facility is: minimum – $n_{min} = \frac{11{,}490}{2{,}280} \approx 5$ 1/h; maximum – $n_{max} = \frac{34{,}290}{2{,}280} \approx 15$ 1/h.

This means that the entire volume of air in the premises must be replaced from 5 to 15 times per hour, depending on the intensity of work and microclimate requirements. The air exchange rate directly affects the temperature equalisation process in the premises. The more frequently the air in the room is replaced, the faster the temperature at any point approaches the supply air temperature. At the minimum rate of $n = 5$, the equalisation process takes more time due to the lower volume of fresh air. In the case of the maximum rate $n = 15$, thermal balance is achieved much more quickly, which is particularly important in rooms with high heat emissions.

In winter, the supply air temperature is usually increased to compensate for heat loss through walls, floors, ceilings, ventilation openings, and doorways. At a standard indoor temperature, the supply air temperature (*Tin*) in the air duct must be sufficiently high so that, after mixing with the indoor air or cooling, the required level is reached. The indoor temperature stabilises faster with a higher air exchange rate, as the supply air mixes more intensively with the internal air. For example, at $n = 5$, the temperature stabilisation time is approximately 12 minutes, whereas at $n = 15$, this time is reduced to 4 minutes. This enables more efficient maintenance of the required temperature regime and reduces the energy consumption of ventilation and air-conditioning systems. Thus, the optimal air exchange rate for a drying room should be from 5 to 15 times per hour. This ensures not only efficient ventilation but also rapid temperature equalisation, creating comfortable conditions for personnel and maintaining the necessary microclimate for technological processes. Table 1 and Figure 2 illustrate the dependence of air temperature on time for different air exchange rates. The results demonstrate that increasing the exchange rate accelerates temperature equalisation, ensuring effective ventilation of the premises.

Table 1. Calculation results of air temperature equalisation over time for different air exchange rates

t, min	*T* (*n* = 5)	*T* (*n* = 15)
0	10	10
10	21.37	28.37
20	26.27	29.87
30	28.39	29.99
40	29.31	30
50	29.7	30
60	29.87	30

Notes: the data presented in the table are the results of studies on temperature variation over time for different values of the air exchange rate parameter *n*
Source: developed by the authors based on original research

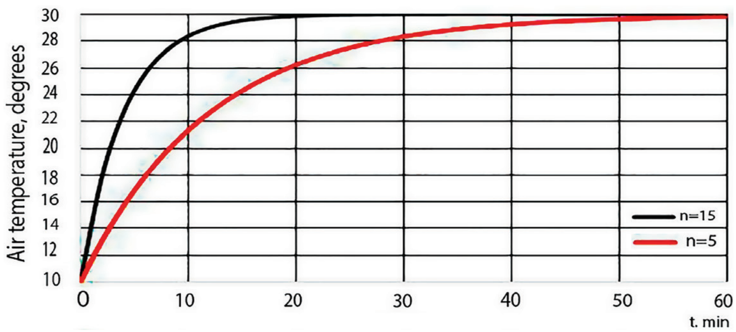

Figure 2. Graphs of air temperature versus time for different air exchange rates
Notes: the graphs show the dependence of air temperature on time for various values of the air exchange rate *n*; as the air exchange rate increases, the temperature stabilisation process accelerates
Source: developed by the authors based on original research

An increase in the air exchange rate contributed to faster temperature equalisation within the premises, which was particularly important under conditions of changing external thermal influences or the emergence of internal heat sources. At the same time, efficient ventilation ensured reduced adaptation time of the room to temperature changes, lower concentrations of pollutants, and the maintenance of a comfortable microclimate. The results of heat transfer modelling provided a basis for the development of workplace air shower systems (Fig. 1), aimed at ensuring thermal comfort and an optimal microclimate. When designing an air shower system, it was necessary to solve the problem of regulating airflow parameters depending on the season. In the warm season, the cross-sectional area of the air nozzle and the volume of supplied air were determined to ensure comfortable conditions. In the cold season, the air temperature at the nozzle outlet was calculated, taking heating into account. The following requirements were considered: the distance from the workplace to the nozzle should be ⩾ 1 m; the minimum cross-sectional area of the nozzle should be ⩾ 0.1 m^2; the air stream direction should be horizontal at chest level or at a 45° downward angle.

To reduce air temperature in summer, the evaporative cooling method with pre-humidification could be applied. The air passed through a humidifying filter, for example, a fabric filter moistened with water or a glycol solution, providing effective cooling. Heat exchangers were used to stabilise the process, maintaining the set air temperature. Porous inserts in the nozzle structure promoted uniform flow distribution and minimised turbulence. Evaporative cooling with pre-humidification was an effective method of reducing air temperature by evaporating water or aqueous solutions such as glycol. This process was widely used in various industries to improve indoor microclimate through air humidification and temperature reduction. The efficiency of such cooling depended on the area of wet surfaces and the rate of air flow over them. The use of porous materials moistened with water or solutions promoted intensive evaporation, resulting in a drop in air temperature. In the cold season, air showering through the nozzle ensured air heating to standardised temperatures in the working area. The calculations assumed a constant air supply velocity, allowing a balance to be maintained between comfort and system performance.

Thus, the proposed coaxial air duct system provided efficient transfer of thermal energy from the exhaust to the supply air, contributing to energy saving and improving conditions in industrial premises. Moreover, the proposed ventilation system was universal and could be adapted for operation in different climate zones, taking into account their specific characteristics. In regions with high average annual temperatures, the priority was to cool indoor air, which required significant energy input. The proposed system could be supplemented with integrated cooling modules based on the use of exhaust air, which typically had a lower temperature than the air in the working zone. Through the duct design, it was possible to organise cooling of the supply air without the use of additional cooling devices. The system could also include heat recovery modules, which enabled cooling of the supply air by exchanging heat with the exhaust air, reducing the thermal load on air-conditioning units. This solution reduced electricity consumption and maintained a comfortable microclimate even during periods of extreme heat.

In this way, the system was universal and could be configured to ensure energy savings under any climatic conditions. Based on the obtained results, it could be concluded that the use of a coaxial air duct system was advisable in facilities with various levels of heat emission, particularly in production workshops requiring significant air exchange. For premises with high heat loads, it was recommended to integrate additional cooling or heat recovery modules to reduce the load on air-conditioning systems. In areas with low heat emissions, the system could ensure an optimal balance between energy efficiency and comfort by minimising heat loss through ventilation. Proper sealing of joints between duct components had to be ensured to minimise thermal losses. It was recommended to additionally install an automated ventilation control system to monitor and optimise system performance in real time.

The study of the effectiveness of the coaxial air duct for industrial ventilation demonstrated its potential advantages in ensuring a stable microclimate and reducing energy consumption. Analysis of the obtained results enabled comparison of the effectiveness of the proposed design with traditional ventilation systems. Measurements of microclimate parameters showed a reduction in temperature gradients in the air exchange zone and uniform airflow distribution. It was established that the use of the coaxial duct allowed optimisation of thermal energy use, as confirmed by statistical data analysis (Table 1).

The analysis of literature sources by V. Korbut & S. Rybachov (2021) and O. Lapshyn *et al.* (2022) confirms that modern ventilation systems experience significant energy losses due to inefficient airflow distribution. The obtained results are consistent with the findings of E. Dudkiewicz & P. Szałański (2020), which indicate the feasibility of using combined air supply methods to reduce heat losses. The study by A. Murga *et al.* (2020) demonstrated the effectiveness of localised ventilation systems in reducing the impact of harmful emissions. A comparative analysis showed that the coaxial air supply configuration could serve as an alternative to traditional air exchange systems due to more efficient airflow distribution and energy saving.

The implementation of coaxial air ducts in industrial premises of various functions, particularly under elevated temperature conditions, makes it possible to ensure uniform air exchange, reduce the risk of local overheating, and optimise the use of energy resources. It has been established that the proposed solution can be integrated into existing ventilation systems without major structural changes, as the coaxial "pipe-in-pipe" design occupies less space compared to traditional ducts, enhancing its applicability in industrial settings. The study showed that the proposed ventilation system design has several advantages over conventional air exchange methods. L. Amanowicz *et al.* (2023) emphasise the importance of integrating energy-saving technologies into modern ventilation solutions. V. Deshko *et al.* (2023) highlight the feasibility of using parametric analysis of natural air exchange to assess system performance. The study by H. Hetmanchuk (2024) also confirms that natural ventilation can be significantly improved through adaptive technologies. Therefore, the conducted research confirms the effectiveness of the proposed ventilation system design and its potential for practical application in industrial facilities.

Conclusions

The proposed design of the combined air duct improves the efficiency of industrial ventilation by means of coaxial arrangement of the exhaust and supply ducts and provides a number of advantages, namely: the use of heat from the exhaust air to preheat the supply air significantly reduces heating costs, particularly during the cold season; the system can be implemented even in confined spaces, making it universal for use in various types of industrial workshops; the technology contributes to creating comfortable working conditions, reducing the risk of occupational illnesses and increasing overall workplace safety. Unlike traditional ventilation systems, the proposed design allows the integration of heat recovery mechanisms within a coaxial configuration while maintaining compactness and structural flexibility; it demonstrates high versatility, as it can be adapted to different climatic conditions and types of production; and it provides not only air exchange but also increases system energy efficiency by reducing heat loss. The combination of mathematical heat transfer modelling with engineering solutions for air shower systems enables optimisation of ventilation system parameters. This ensures effective thermal comfort in working spaces during both warm and cold periods. The results confirm the importance of correct selection of air exchange rate, nozzle area, and flow direction to achieve optimal microclimatic conditions. For future research, it is recommended to analyse system performance under various climatic conditions. In the warm season, it is essential to develop or refine automatic airflow regulation tools, such as systems for adjusting air velocity or volume, in order to maintain optimal parameters under changing industrial conditions. In the cold season, it is critically important to investigate heat transfer processes, particularly to determine how much heat is transferred to the supply air.

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Conflict of Interest

None.

References

[1] Amanowicz, L., Ratajczak, K., & Dudkiewicz, E. (2023). Recent advancements in ventilation systems used to decrease energy consumption in buildings – literature review. *Energies*, 16(4), article number 1853. doi: 10.3390/en16041853.

[2] Bezrodny, M., & Misiura, T. (2020). Heat pump system for air heating and ventilation of an industrial building with excessive moisture. *KPI Science News*, 2, 7-16. doi: 10.20535/kpi-sn.2020.2.205111.

[3] Catalina, T., & Lungu, C. (2021). Influence of a decentralized ventilation system on the indoor air quality of a primary school classroom. *IOP Conference Series: Earth and Environmental Science*, 664(1), article number 012039. doi: 10.1088/1755-1315/664/1/012039.

[4] DBN V.2.5-67:2013. (2013). *Heating, ventilation, and air conditioning*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=50154.

[5] Deshko, V., Bilous, I., & Hetmanchuk, H. (2023). Parametric analysis of natural air exchange in multi-apartment residential buildings. *Energy: Economics, Technology, Ecology*, 4, 57-68. doi: 10.20535/1813-5420.4.2023.290897.

[6] Deshko, V., Bilous, I., & Tymofieiev, M. (2024). Ventilation as a component of the energy dynamic balance in buildings. *Technologies and Engineering*, 1, 25-39. doi: 10.30857/2786-5371.2024.1.3.

[7] DSTN 3.3.6.042-99. (1999). *Sanitary norms of microclimate of industrial premises*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=14283.

[8] DSTU-N B V.1.1-27:2010. (2010). *Protection against hazardous geological processes, harmful operational impacts, and fire. Building climatology*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=26655.

[9] Dudkiewicz, E., & Szałański, P. (2020). Overview of exhaust gas heat recovery technologies for radiant heating systems in large halls. *Thermal Science and Engineering Progress*, 18, article number 100522. doi: 10.1016/j.tsep.2020.100522.

[10] Dzhedzhula, V. (2021). *Ventilation and air conditioning of public buildings*. Vinnytsia: VNTU.

[11] Elhadary, M.I., Alzahrani, A.M.Y., Aly, R.M.H., & Elboshy, B. (2021). A comparative study for forced ventilation systems in industrial buildings to improve the workers' thermal comfort. *Sustainability*, 13(18), article number 10267. doi: 10.3390/su131810267.

[12] Farouk, N., Abd El-Rahman, M., Sharifpur, M., & Guo, W. (2022). Assessment of CO_2 emissions associated with HVAC system in buildings equipped with phase change materials. *Journal of Building Engineering*, 51(1), article number 104236. doi: 10.1016/j.jobe.2022.104236.

[13] Hetmanchuk, H. (2024). *Assessment of dispersed natural air exchange levels in buildings considering variability of internal and external conditions*. (Doctoral dissertation, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine).

[14] Korbut, V., & Rybachov, S. (2021). Experimental researches of a two-level air-jet protection of an open surface of industrial baths of the big sizes. *Ventilation, Illumination and Heat-Gas Supply*, 36, 6-13. doi: 10.32347/2409-2606.2021.36.6-13.

[15] Lapshyn, O., Lapshyn, O., & Khudyk, M. (2022). *Industrial premises ventilation*. Kryvyi Rih: D.O. Cherniavskyi.

[16] Matviichuk, V., Veselovska, N., & Sharhorodskyi, S. (2021). *Mathematical modelling of modern technological systems*. Vinnytsia: Vinnytsia National Agrarian University.

[17] Murga, A., Long, Z., Yoo, S.-J., Sumiyoshi, E., & Ito, K. (2020). Decreasing inhaled contaminant dose of a factory worker through a hybrid emergency ventilation system: Performance evaluation in worst-case scenario. *Energy and Built Environment*, 1(3), 319-326. doi: 10.1016/j.enbenv.2020.04.007.

[18] Pakari, A., & Ghani, S. (2021). Comparison of different mechanical ventilation systems for dairy cow barns: CFD simulations and field measurements. *Computers and Electronics in Agriculture*, 186, article number 106207. doi: 10.1016/j.compag.2021.106207.

[19] Patent No. 156625. (2024). *Method of air exchange in industrial premises*. Retrieved from https://sis.nipo.gov.ua/uk/search/detail/1808982/.

[20] Spivak, O., Rezydent, N., Rezydent, D., & Tkach, N. (2024). Influence of geometric characteristics of the French on heat transfer heat exchange surface. *Modern Technologies, Materials and Structures in Construction*, 21(1), 154-160. doi: 10.31649/2311-1429-2024-1-154-160.

[21] Tkachenko, T., & Mileikovskyi, V. (2020). Increasing indoor air quality by a natural sanitizing interior. *E3S Web of Conferences*, 211, article number 02015. doi: 10.1051/e3sconf/202021102015.

[22] Tykhenko, O., *et al*. (2024). Study of air deionization factors. *Eastern-European Journal of Enterprise Technologies*, 2(10(128)), 26-33. doi: 10.15587/1729-4061.2024.300909.

[23] Voznyak, O., Myroniuk, Kh., Sukholova, I., Dovbush, O., & Kasynets, M. (2021). Physical models of ventilation system fittings in special conditions. *Theory and Building Practice: JTBP*, 3(1), 42-50. doi: 10.23939/jtbp2021.01.042.

[24] Wei, X., Xu, Y., Yu, Y., Ma, M., Niu, G., Cao, G., Wang, L., & Gao, J. (2023). Effectiveness of head-mounted air supply in reducing pollutant exposure: A static case. *Building and Environment*, 234, article number 110219. doi: 10.1016/j.buildenv.2023.110219.

[25] Zender-Świercz, E. (2021). Assessment of indoor air parameters in buildings equipped with decentralized facade ventilation device. *Energies*, 14(4), article number 1176. doi: 10.3390/en14041176.

[26] Zhao, X., & Yin, Y. (2024). Hazards of pollutants and ventilation control strategy in industrial workshops: Current state and future trend. *Building and Environment*, 251, article number 111229. doi: 10.1016/j.buildenv.2024.111229.

Оптимізація повітрообміну та теплопередачі за допомогою коаксіальних повітроводів

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Анотація. У сучасних промислових приміщеннях важливо забезпечити ефективний обмін повітря при мінімальних енергетичних витратах, що зумовлює необхідність оптимізації вентиляційних систем, зокрема шляхом розробки нових конструкцій повітроводів. Метою статті була розробка конструкції сумісного відсмоктувально-припливного повітроводу для покращення ефективності повітрообміну в промислових приміщеннях та зниження енергетичних витрат на підігрів повітря. Проведено ґрунтовний аналіз сучасних наукових джерел, опублікованих у різних країнах світу, що охоплюють передові технології повітрообміну, вентиляції та регулювання мікроклімату. Використано теоретичне обґрунтування конструкції та математичне моделювання процесів теплообміну між відсмоктувальним та припливним повітроводами. Також використовувалися методи теплопередачі, конвекції та випромінювання для аналізу фізичних процесів. У результаті розроблено конструкцію коаксіального повітроводу, що складається з внутрішнього відсмоктувального та зовнішнього припливного трубопроводу, співвідношення діаметрів яких оптимізовано формулою $D = 1{,}4 \cdot d$. Розрахунки підтвердили рівність обсягів повітря, що відсмоктується і подається, забезпечуючи стабільний повітрообмін. Проведене моделювання показало, що система ефективно забезпечує рівномірний розподіл повітря в робочій зоні, підвищуючи продуктивність вентиляційної системи. Зниження енергетичних витрат досягнуто завдяки використанню тепла від відсмоктувального повітря для підігріву припливного. Розрахунки та моделювання підтвердили ефективність запропонованої конструкції, що дозволяє знизити енергетичні витрати на підігрів повітря та покращити повітрообмін у промислових приміщеннях, що сприяє створенню комфортних умов для працівників. Загалом, розроблена конструкція вентиляційної системи спрямована на оптимізацію процесів повітрообміну в промислових приміщеннях, пропонуючи такі переваги: енергоефективність – за рахунок використання вторинних теплових ресурсів; компактність – конструкція дозволяє зменшити обсяг вентиляційного обладнання; універсальність – система може бути впроваджена на різних промислових підприємствах, включаючи цехи з високим рівнем забруднення повітря; підвищення безпеки праці – нова система сприяє створенню комфортних умов у робочій зоні

Ключові слова: вентиляція; промислові приміщення; теплозбереження; аеродинамічні характеристики; енергоощадні технології; повітряний баланс

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Creating a web-oriented human-machine interface for a SCARA robot physical model based on industrial Internet of Things technologies

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Abstract. Loading and unloading operations are one of the key links in many production processes in modern industry. Improving the accuracy, productivity, and velocity of control is essential for increasing the efficiency of loading and unloading processes. This can be achieved by integrating production processes into the web through the implementation of the "Industry 4.0" concept. The aim of this work was to develop a web interface for a system that simulates loading and unloading operations based on a SCARA robot, which ensures effective monitoring and control of the technological process. To determine the architecture of proposed system, modern approaches to the development of automated control systems using the "Industry 4.0" concept were analysed. To select the tools for creating the system components, technologies for software development that are suitable for this task were analysed and identified. A comprehensive control and monitoring system for the SCARA robot was developed using a web interface based on the "Industry 4.0" concept. The developed web interface demonstrated an effective approach to building interactive control systems, improving productivity and convenience for operators. The practical significance of the results lies in the creation of a unified solution for monitoring and controlling robotic complexes, which can be adapted and implemented on various production and educational platforms. Additionally, the developed solution can be used in the educational process for laboratory practice in normative disciplines

Keywords: automation; industry 4.0; internet of things; MQTT; OPC UA; PLC; web-based SCADA

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Introduction

In the industrial sector, increasing attention is being paid to automation and optimisation of production and logistics processes. SCARA robots play a key role in improving loading and unloading operations, providing high precision, productivity, and safety. This application opens up new opportunities for creating modern intelligent control systems. The necessity for efficient monitoring and management of complex technological complexes drives the continuous development of human-machine interfaces and web technologies that provide operators with full real-time control over technological processes.

The current stage of industrial development is characterised by profound transformations caused by the implementation of innovative technologies and changes in global economic conditions. One of the key trends is the transition to the concept of "Industry 4.0," which involves the integration of digital technologies into all aspects of the production process. It was noted in the study by M. Vlasenko & Yu. Khlaponin (2024), that the concept of "Industry 4.0" is based on technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), and machine learning (ML), which together form the foundation for the smart factories of the future.

It was emphasised in the study by A. King (2021) that one of the main drivers of the development of the "Industry 4.0" concept is the growing need for product personalisation and the associated shortening of production cycles, which requires enterprises to be more flexible and responsive. This stimulates the implementation of additive technologies (3D printing), robotic production lines, and predictive maintenance systems. In this context, supervisory control and data acquisition (SCADA) systems play a particularly important role, as they allow operators and managers to obtain a complete and up-to-date picture of production processes in real time. As noted in the study by F.J. Folgado *et al.* (2024), SCADA systems are used in almost all industries, including automotive, chemical manufacturing, energy, transport, agriculture, and others.

The study by S. Ardi *et al.* (2024) emphasised the feasibility and advantages of using SCADA systems, particularly the potential to improve production efficiency, ensure better equipment protection, and increase workforce productivity. The authors also highlighted the importance of early detection of abnormal operating modes and rapid notification of personnel through the integration of process data from sensors and enhanced communication capabilities. Modern visualisation systems integrate data from various sources, including IoT sensors, enterprise resource planning (ERP) systems, and manufacturing execution systems (MES), presenting them in a clear and intuitive format. The authors examined these advantages of SCADA through the example of implementing the Wonderware InTouch system in the automotive industry. This system offers a wide range of visualisation capabilities for unloading operations, including the creation of detailed schematic diagrams, interactive control panels, and real-time reports.

Another powerful SCADA system often used for visualising logistics processes is Siemens WinCC. This system is distinguished by its high scalability and reliability, making it an ideal choice for enterprises of various sizes. As noted in the study by D. Mencia *et al.* (2023), WinCC offers advanced 3D visualisation capabilities, which are especially useful for simulating complex loading and unloading operations using robotic systems such as SCARA robots. Another important aspect of analysing existing visualisation systems is the comparison between local and cloud-based solutions. Local visualisation systems, such as the previously mentioned Wonderware InTouch and Siemens WinCC, have certain distinctive features. As it was noted in the study by C. Bayılmış *et al.* (2022), local visualisation systems provide maximum speed in data processing and information display, which is critically important for emergency response. It was also stated, that local systems ensure complete control over data security, which is especially crucial for enterprises with high confidentiality requirements.

On the other hand, cloud visualisation systems, such as Amazon AWS IoT SiteWise or Microsoft Azure IoT Central, offer a range of unique advantages. The primary benefit of cloud solutions is their scalability and flexibility. Cloud systems also provide easy data access from anywhere in the world, which becomes increasingly important in the context of business globalisation and the spread of remote work practices. Moreover, cloud platforms often offer built-in analytics and machine learning tools that can be used to optimise logistical processes. However, when choosing between local and cloud-based solutions, it is essential to consider the specifics of their operation. The study conducted by O.A. Lawrence & M. Tariq Iqbal (2020) pointed out that for enterprises with mission-critical processes, where even a brief loss of connection can lead to significant losses, local systems remain the preferred choice. Conversely, for companies seeking maximum flexibility and minimal IT infrastructure costs, cloud solutions may be the optimal choice. It is also important to consider the growing trend of using mobile applications for process visualisation. According to the study by I. Qasim *et al.* (2020), many modern systems, both local and cloud-based, offer mobile interfaces that allow operators and managers to access key information and manage processes from mobile devices. This is especially useful for large warehouse complexes, where the speed of response to changing situations can significantly enhance operational efficiency.

Summarising the analysis of existing unloading operation visualisation systems, it can be concluded that the market offers a wide range of solutions capable of meeting the needs of enterprises of various scales and specificities. From powerful SCADA systems to specialised logistics platforms, from local solutions to cloud services – each approach has its advantages and limitations. In the context of developing a web interface for a visualisation system for a SCARA robot-based loading and unloading operations modelling complex, the analysis of existing solutions allows defining key requirements and best practices. In particular, it is important to ensure a balance between information display detail and interface simplicity, implement capabilities for qualitative visualisation of SCARA robot operations, provide for integration with other enterprise systems, and ensure access to information from various devices, including mobile ones. Therefore, the objective of this study was to develop an architecture for a web-oriented human-machine interface for a SCARA robot, based on industrial Internet of Things technologies and modern web frameworks. The proposed architecture is intended to serve a dual purpose – enabling its application both in industrial manufacturing and in educational settings for remote monitoring and control of a laboratory testbed.

Materials and Methods

The SCARA robot control system was based on the Siemens S7-1200 programmable logic controller (PLC), manufactured by Siemens (Germany), which provided reliable and efficient management of all stand components. Specifically, the CPU 1215C model (6ES7215-1AG40-0XB0) was used, which was optimally suited for robot control tasks and real-time data processing. Figure 1 shows a stand with a SCARA robot.

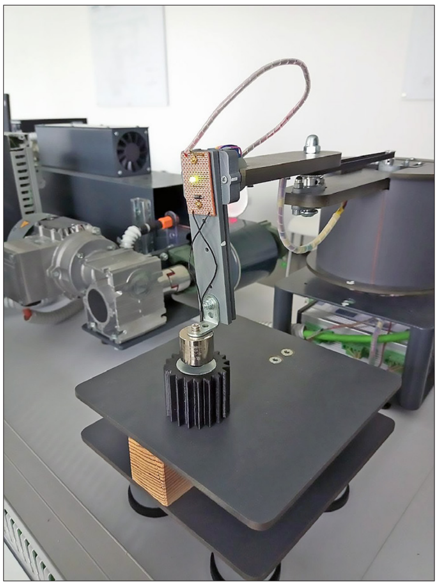

Figure 1. Stand with SCARA robot

Source: authors' photo

The SCARA Robot Test Stand was designed by LLC "Donenergoprommontazh" on the order of SE "Siemens Ukraine" for Kryvyi Rih National University, taking into account the requirements of compactness, functionality, and ease of use in laboratory conditions. All stand components are placed on a robust metal frame with overall dimensions of 275x350x190 mm.

The stand design includes the following main elements:

- frame: provides structural stability and reduces the impact of external vibrations;
- electrical Cabinet: sized 25x40 cm, located in the lower part of the frame. It is equipped with PLC, power supplies, and other electrical equipment;
- SCARA robot: mounted on the upper part of the frame, with a work zone optimised for demonstration and studying operational principles;
- test object zone: designed for placing loads and simulating various operational scenarios.

The stand features a visualisation system interface based on SIMATIC WinCC, which provides displaying current and target positions of robot mechanisms, control modes (manual, automatic, stop), monitoring the magnetic gripper state and other system parameters, real-time technological process visualisation. Although the existing HMI system provides basic control and monitoring functions, it has certain limitations, particularly the lack of remote access and limited analytics capabilities. With the formulated list of software and technical solutions, it was possible to develop a comprehensive toolkit structure necessary for web interface implementation, as well as a structural scheme that reflects the types of information flows in this system (Fig. 2).

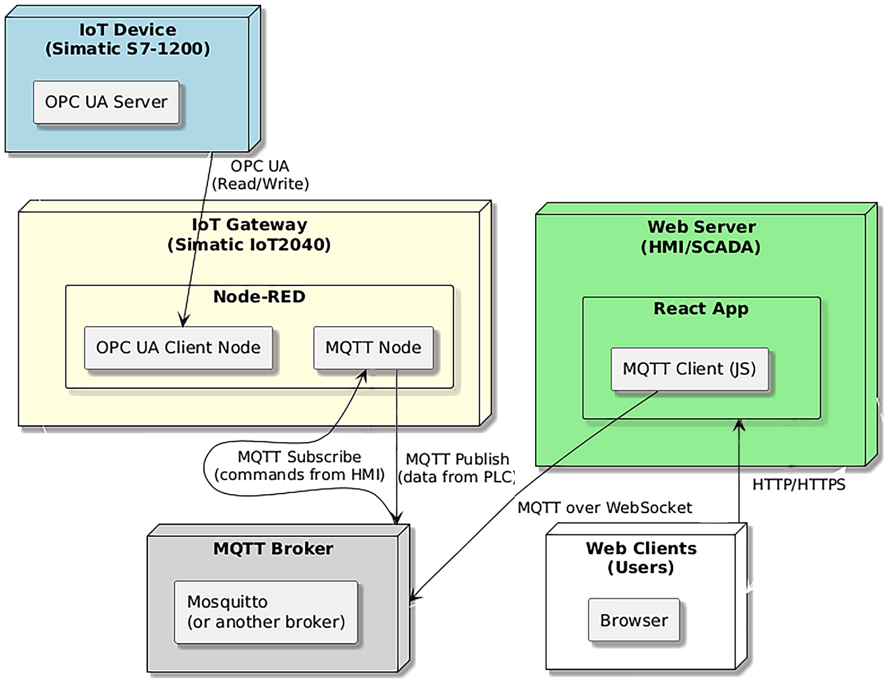

Figure 2. UML deployment diagram of the proposed system

Source: authors' development

Thus, UML deployment diagram in Figure 2 illustrates the physical architecture of the developed system, the distribution of computational functions across the nodes, and the interconnections between the software and hardware components of the system. At the lowest level of the hierarchy are sensors and actuators, namely: laser sensors, servo drives, conveyor motor, and others. They are connected to the Siemens S7-1200 PLC, which receives data from sensors and sends control commands to actuators. Data from the OPC UA server on the S7-1200 controller will be transmitted through a local network to IoT gateway with a Node-RED server installed. This software complex will perform initial processing (such as data logging or basic reading) and data aggregation, as well as provide visualisation of the system's main parameters in a user-friendly interface. For communication between the Node-RED server and React, the MQTT protocol can be used through the MQTT broker. Using a public MQTT broker simplified system deployment and eliminated the need to configure a proprietary infrastructure. This architecture reflects the basis of the conducted study, flexibility, scalability, and reliability of data transmission between system components, allowing easy integration of additional elements by connecting to appropriate MQTT topics.

The client-side of the web-based human-machine interface for the physical model of the SCARA robot was developed using the JavaScript library React.The project architecture is built using modern approaches to creating interactive web applications, specifically the Single Page Application (SPA) concept with React.js. The selected technological solutions provided high performance, scalability, and development convenience for the modelling system user interface. The technology stack included React.js as the foundational library for building a component-based architecture, Material-UI for unified design and ready-to-use interface components, MQTT.js for ensuring communication with message brokers, and mechanisms for local application state storage.

Results

Figure 3 shows a UML sequence diagram that shows the order of interaction between the components shown in Figure 2. After launching the React application, an attempt is made to establish a connection with the MQTT broker. If the connection fails, a reconnection loop is initiated with a delay timer between attempts. In case of a successful connection, the client subscribes to a topic containing the PLC status data. Simultaneously, on the IoT Gateway node, Node-RED reads data from the OPC UA server on the PLC and sends it to the broker via MQTT. The React application receives these messages, updates its internal state, and displays the current information in the web interface. When a user interacts with the interface (e.g., by pressing a button), it triggers the formation of an MQTT command, which is published by the client to the appropriate topic. The MQTT broker forwards the command to the IoT Gateway, where Node-RED recognises it and performs a write operation to the PLC via OPC UA. This ensures full bidirectional communication: reading data for visualisation and sending commands to control the process in real time.

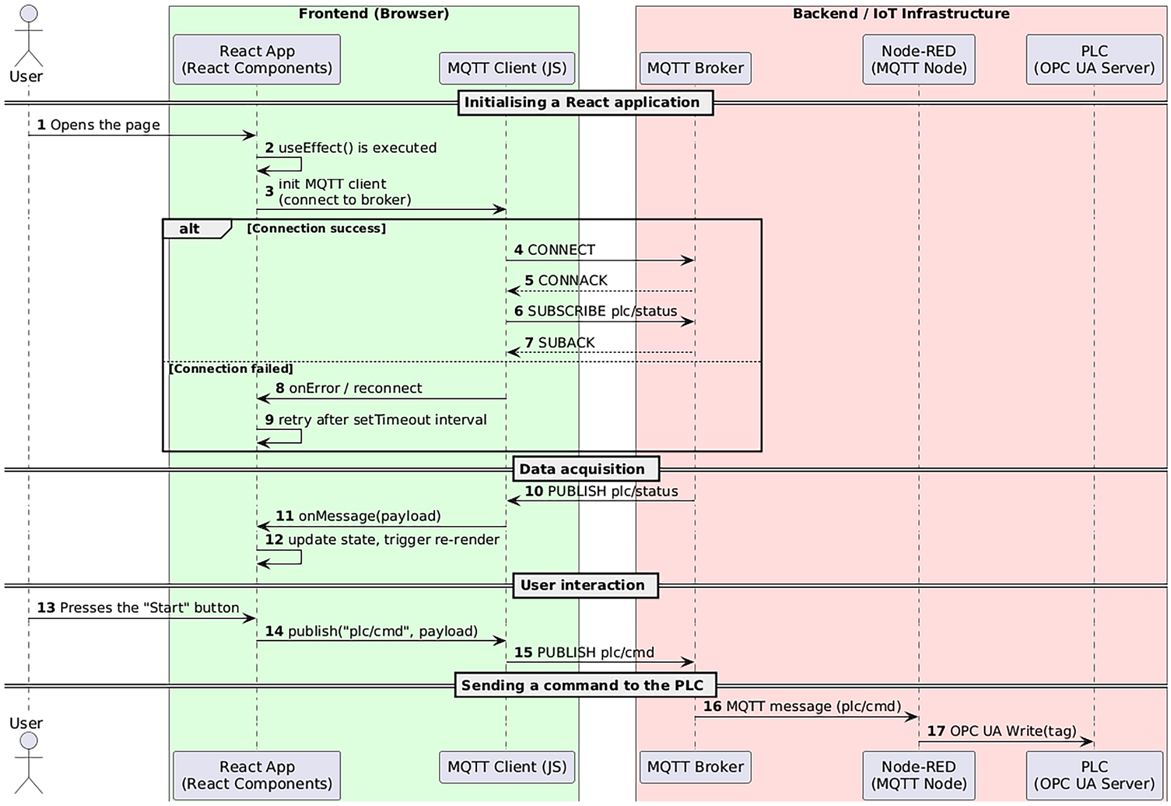

Figure 3. UML Sequence diagram of nominal scenario of communication between PLC and web- oriented HMI in the developed solution
Source: authors' development

The activity diagram in Figure 4 details the logic of implementing data read and write scenarios within the system, complementing the interaction sequence with internal flow control. After the React application is initialised, a loop of connection attempts to the MQTT broker is launched. In the event of failure, a delay timer is applied before the next retry. A successful connection results in a subscription to the topic from which data from the PLC will be received. Simultaneously, Node-RED on the IoT gateway reads this data from the PLC's OPC UA server and publishes it via MQTT, after which the React client receives the messages, updates the interface state, and displays the values to the user. Another activity branch describes the reverse action – transmitting commands from the user to the PLC. When the user interacts with the UI (for example, changes a parameter or presses a button), React forms a command and publishes it to the MQTT broker. Upon receiving the message, Node-RED interprets it and performs the appropriate write operation to a variable on the PLC via OPC UA. Thanks to the parallel structure of the diagram, it is evident that both flows (reading and control) operate independently but interact through the shared MQTT and OPC UA infrastructure, ensuring reliable bidirectional integration of the human-machine interface with the real process. The primary stage of software development for the stand is the implementation of an integration platform between the web interface and the stand, using the Node-RED tool. Software development for the given implementation can be divided into several stages: configuring connection to the OPC UA server; developing a data collection and monitoring mechanism; developing a control and recording mechanism (Baig *et al.*, 2021). The process begins with system initialisations – launching a node that periodically generates lists of topics for reading data from the OPC UA server. These topics correspond to tag identifiers in the system, the data of which need to be monitored and managed. Topic list generation is performed in the "Generate Topics" node on the block diagram (Fig. 5). Next, the OPC UA client, configured for data reading, cyclically polls the server, reading current values for each topic. These values are compared with previously saved ones, and in case of changes, new data is written to the Node-RED global context. The global context is used to store the current system state, which allows easily obtaining the necessary data at any moment. To work with MQTT in Node-RED, specialised nodes "mqtt in" (MQTT Control Input block on Fig. 5) and "mqtt out" (scada/data block on Fig. 5) are used. They allow subscribing to specific MQTT topics and publishing messages to other topics, respectively (Malhi *et al.*, 2023; Safitri *& Priambodo* 2023; Jadhav, 2024).

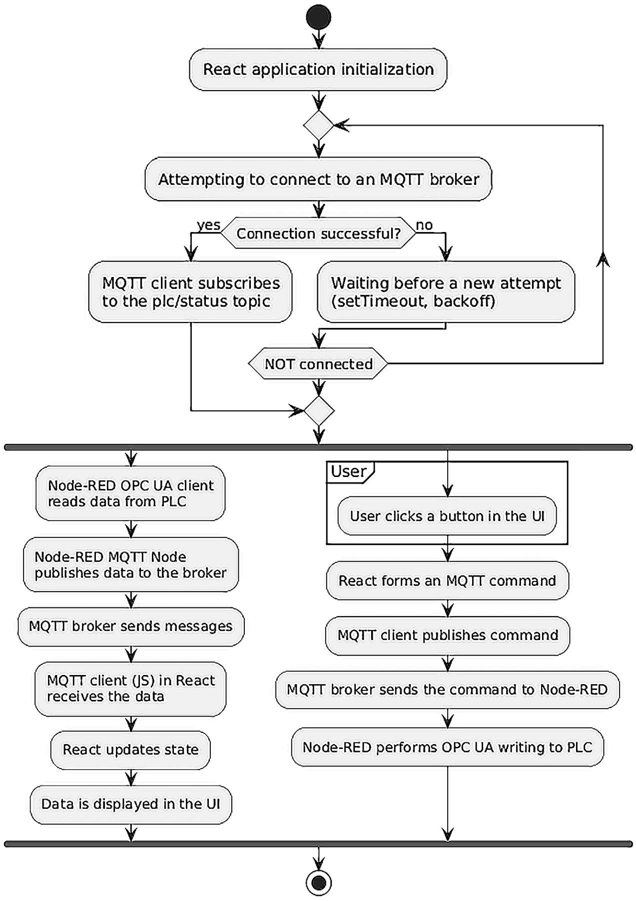

Figure 4. UML Activity diagram for modelling of the developed IoT solution for web-oriented HMI
Source: authors' development

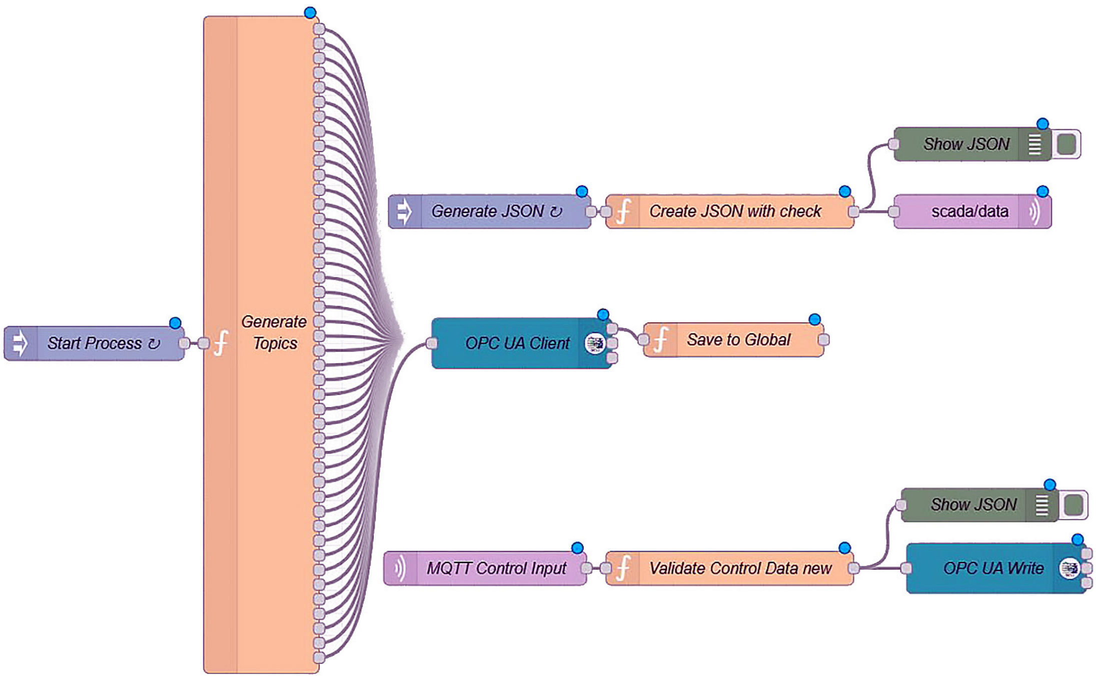

Figure 5. Basic nodes and data flow in Node-RED for implementation of data exchange between PLC and MQTT-broker
Source: authors' development

The HMI panel (HMIPanel) is a key interface component that provides interactive system control. Developed using reactive programming approaches, the panel offers users a comprehensive set of controls for managing the primary parameters of the modelling complex. The component architecture is constructed using advanced React patterns, specifically component memoisation via React.memo to optimise performance. Each subcomponent (ControlUnit, TemperatureControl) has its own logic for handling user interactions and transmitting control commands. The Visualisation component implements graphical representation of the system's state. Utilising SVG graphics allows for creating a dynamic and interactive visualisation with the ability to instantly update colours and element states based on received data. The approach to building the graphical interface was based on principles of adaptability and informativeness.

The Notification System (NotificationStack) provides user feedback through a mechanism of pop-up messages. Implemented using custom-configured Material-UI components, the system delivers instant information about connection status, command execution results, and system events. An important aspect of the architecture is the mechanism for local application state storage. Utilising localStorage allows the application to retain its current state between page reloads, enhancing the user experience and ensuring continuity in system interaction. The application adheres to the principles of reactive programming, enabling efficient interface updates as new data is received from the MQTT broker. The graphical design is implemented using Material Design, providing a modern, intuitive, and minimalist interface.

Structurally, the site consists of the following key elements:

▼ control panel. The central part of the interface that provides the user with complete control over the stand's operation (Fig. 6).

▼ Visualisation block. A section of the page where the movement of the robot, conveyor, and the status of the deployed sensors are dynamically displayed (Fig. 7).

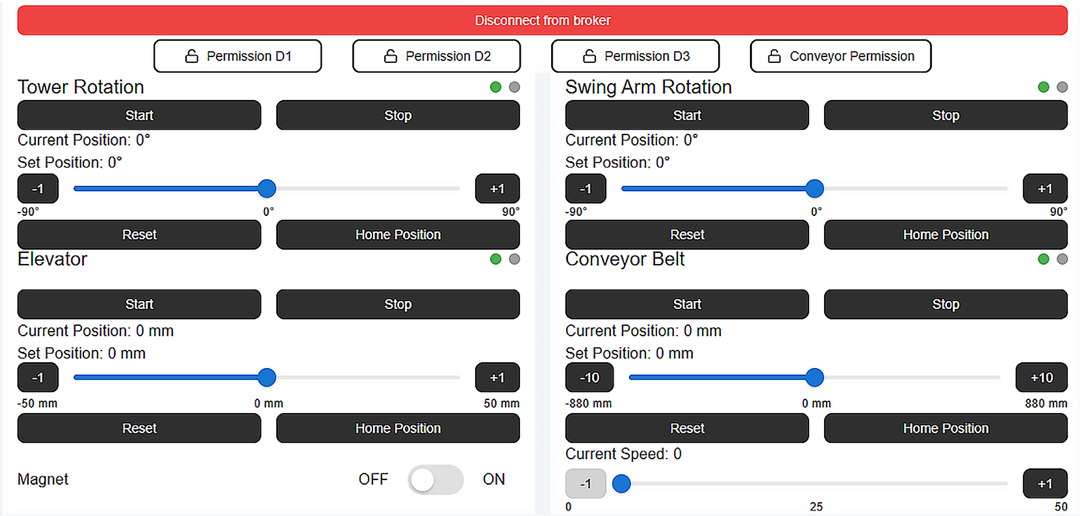

Figure 6. Control panel web interface

Source: authors' development

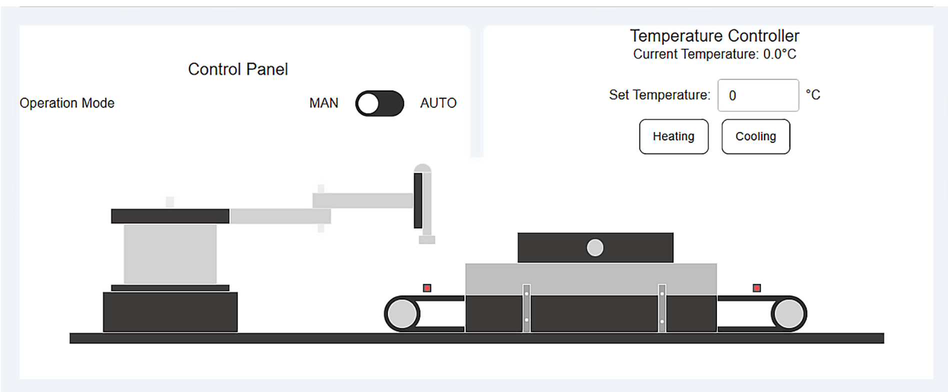

Figure 7. Visualisation block of the stand

Source: authors' development

The developed web interface serves as a visualisation and control system for load-handling operations involving a SCARA robot. The platform is a comprehensive tool for monitoring and managing the technological complex built on the educational stand, ensuring functionality and ease of use. The primary functional purpose of the site is to provide the user with a convenient and intuitive toolkit for managing all aspects of a SCARA robot's operations. The operator gains the ability to both observe the current state and process of operations execution, as well as directly intervene in the technological process, adjusting the robot's operating parameters and those of other machines. Thus, the website represents a comprehensive solution that combines the functionality of monitoring, control, and visualisation of key aspects of the SCARA robot's operation.

Discussion

The developed software and methodological complex demonstrated effective integration of modern industrial automation technologies with educational and research purposes. Its architecture was based on five logically interconnected nodes, enabling a visual, interactive, and flexible approach to studying and managing automated systems. The developments presented in this work for the SCARA robot-based stand demonstrated effective integration of modern industrial automation and Internet of Things (IoT) technologies. The use of the Simatic S7-1200 programmable logic controller (PLC) as an OPC UA server ensured a standardised approach to data exchange between system components. A similar approach was applied in the study by A.H. Embong *et al*. (2024), where the Siemens S7-1200 was used for real-time monitoring and control of asynchronous motors via Node-RED, highlighting the effectiveness of such integration in both laboratory and industrial settings.

The use of an IoT gateway based on the Simatic IoT2040 with Node-RED installed for processing data from the OPC UA server and transmitting it via an MQTT broker is an important step toward ensuring system flexibility and scalability. The study conducted by M. Rozan *et al*. (2024) demonstrated a similar approach, where Node-RED and OPC UA were used for monitoring an automated warehouse, highlighting the effectiveness of this solution in industrial applications. Additionally, the use of an IoT gateway implemented segmentation of the industrial Internet of Things network, which, as indicated in the study by R. Yatagha *et al*. (2023), is a highly recommended protection policy in accordance with international standards.

The use of MQTT as a data exchange protocol between system nodes aligns with current trends in industrial automation. In the work by J. Odier *et al*. (2024), the process of integrating OPC UA and MQTT using Node-RED was described, emphasising the advantages of such an approach in ensuring a continuous data flow and improved real-time monitoring. It was demonstrated in the study by K. Ferencz & J. Domokos (2020) how this platform can be used to integrate various industrial devices and systems, providing flexibility and ease of configuration. Particular attention should be paid to the implementation of the visualisation and remote control subsystem, which was developed as a web application based on React. This approach supports the concept of using web technologies to create human-machine interfaces in industrial applications. It aligns with current trends in both industry and education, allowing for the development of flexible, user-friendly HMI systems with remote access support. This enables students and researchers to control the test bench in real time from any device with internet access.

The use of the system in educational settings, especially under conditions of remote learning, is highly relevant. The studies by A.F. Santacruz *et al*. (2021) and S.V. Kandala *et al*. (2025) emphasised the importance of implementing remote laboratories for education, enabling students to gain practical skills without being physically present in the lab. The development and deployment of remote laboratories based on SCARA robots contributed to improving the quality of education in the fields of robotics and automation (Faridan *et al*., 2023). The article by T. Kaarlela *et al*. (2022) described the creation of a platform for remotely controlling robots, allowing students to interact with real robotic systems over the internet, which is particularly important in situations with limited access to laboratory equipment.

In addition, the architecture that utilises MQTT as an intermediary for data exchange ensures system scalability and allows the connection of an unlimited number of clients, making the system convenient for collaborative work or remote laboratories. This is especially relevant in the context of distance learning, where providing a practical component in education presents a challenge. Considering other studies in this field, the work by D.R. de Sousa *et al*. (2024) is noteworthy, proposing a methodology for creating semantic digital twins using Node-RED and OPC UA. The authors described a sequence of steps covering data collection, semantic annotation, and asset modelling, generating a graph of nodes and connections stored in a graph database. This study emphasised the importance of semantic data integration and the creation of digital twins for modernising legacy systems, which aligns with the approach used in the developed system in the current study.

Additionally, the article by P. Kuriščák *et al*. (2022) presented a modular platform for remote control of robotic manipulators through a digital twin. The authors conducted a survey involving 37 participants who used various controllers to operate robots remotely and demonstrated the usability of the platform. This study highlighted the importance of creating intuitive interfaces for remote robot control, which was also taken into account during the development of React-based web application in the current study.

Overall, the system not only ensures effective interaction between hardware and software but also lays the groundwork for further functionality expansion. Potential directions include integration with cloud platforms, real-time data analytics, and the use of artificial intelligence for predictive analysis. The developed system meets current industrial automation requirements and contributes to the improvement of the educational process, providing students with access to advanced technologies and tools for remote learning and research.

Conclusions

The architecture of the developed system was based on modern IIoT principles and demonstrated a fundamentally new approach to building communication control systems. The proposed solution implemented a three-tier model comprising the hardware layer, the data transmission layer, and the analytics layer, ensuring maximum flexibility, scalability, and efficiency in component interaction. At the hardware configuration level within TIA Portal, a significant controller upgrade was performed updating the processor version to enable support for the OPC UA protocol. The integration platform Node-RED has been implemented as a powerful communication layer, providing reliable data exchange between the OPC UA server and the MQTT broker. The developed algorithm minimised system load by publishing only changed values, thereby enhancing data transmission efficiency.

The client web interface was developed using modern React.js technologies. Its architecture is modular, reactive, and user-friendly, achieved through a well-designed component structure and the application of Material-UI libraries. The developed solution represents a comprehensive monitoring and control system for a SCARA robot, offering a full range of functional capabilities – from establishing connections to real-time visualisation and management of the technological process. A key advantage of the developed web interface is its ability to provide full-scale real-time monitoring of the technological process, offer intuitive control tools, and promptly respond to system state changes. The use of modern technological solutions, such as OPC UA, Node-RED, MQTT, and React.js, has enabled the creation of a high-performance, secure, and easily integrable software product.

The next step in this work could involve offloading part of the computational workload to cloud services (such as AWS IoT, Azure IoT Hub, or Google Cloud IoT). This would enhance the scalability of the system, enable big data analytics, and improve the reliability of data storage. Another promising direction is the implementation of machine learning (ML) algorithms for failure prediction, control parameter optimisation, or user behavior analysis, which unlocks a new dimension in managing robotic systems. In particular, it would allow the system's responses to be adapted to specific industrial or educational scenarios. Based on the current platform, it is possible to build a modular infrastructure for remote laboratories. This is especially relevant in hybrid or distance learning settings, where students can simultaneously connect to the system, observe its behavior, and interact with it via a web browser.

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Conflict of Interest

None.

References

[1] Ardi, S., Ningsih, N.D., Hidayat, M., Fairus, S., & Ponco, A. (2024). The application of SCADA systems on wrapping machines using PLC and Wonderware InTouch in the automotive manufacturing industry. *Jurnal Pendidikan Teknologi dan Kejuruan*, 30(2), 297-309. doi: 10.21831/jptk.v30i2.78902.

[2] Baig, M.J.A., Iqbal, M.T., Jamil, M., & Khan, J. (2021). Design and implementation of an open-source IoT and blockchain-based peer-to-peer energy trading platform using ESP32-S2, Node-Red and, MQTT protocol. *Energy Reports*, 7, 5733-5746. doi: 10.1016/j.egyr.2021.08.190.

[3] Bayılmış, C., Ebleme, M.A., Çavuşoğlu, Ü., Küçük, K., & Sevin, A. (2022). A survey on communication protocols and performance evaluations for Internet of Things. *Digital Communications and Networks*, 8(6), 1094-1104. doi: 10.1016/j.dcan.2022.03.013.

[4] de Sousa, D.R., Caldana, V., & Godoy, E.P. (2024). Upgrading legacy systems for Industry 4.0 with Node-RED and OPC-UA. In *5th South American international conference on industrial engineering and operations management*. (pp. 10004-10016). Bogota: IEOM Society International. doi: 10.46254/sa05.20240068.

[5] Embong, A.H., Asbollah, L., & Abdul Hamid, S.B. (2024). Empowering industrial automation labs with IoT: A case study on real-time monitoring and control of induction motors using Siemens PLC and Node-RED. *Journal of Mechanical Engineering and Sciences*, 18(2), 10004-10016. doi: 10.15282/jmes.18.2.2024.3.0790.

[6] Faridan, M., Kumari, B., & Suzuki, R. (2023). ChameleonControl: Teleoperating real human surrogates through mixed reality gestural guidance for remote hands-on classrooms. In *Proceedings of the 2023 CHI conference on human factors in computing systems*. (article number 203). Hamburg: ACM. doi: 10.1145/3544548.3581381.

[7] Ferencz, K., & Domokos, J. (2020). Using Node-RED platform in an industrial environment. In *35th anniversary Kandó conference*. (pp. 52-63). Budapest: Kandó Technology Transfer Centre.

[8] Folgado, F.J., Calderón, D., González, I., & Calderón, A.J. (2024). Review of Industry 4.0 from the perspective of automation and supervision systems: Definitions, architectures and recent trends. *Electronics*, 13(4), article number 782. doi: 10.3390/electronics13040782.

[9] Jadhav, A.M. (2024). Communication protocols for IoT applications. *International Journal for Research in Applied Science and Engineering Technology*, 12(4), 5875-5877. doi: 10.22214/ijraset.2024.61338.

[10] Kaarlela, T., Arnarson, H., Pitkäaho, T., Shu, B., Solvang, B., & Pieskä, S. (2022). Common educational teleoperation platform for robotics utilising digital twins. *Machines*, 10(7), article number 577. doi: 10.3390/machines10070577.

[11] Kandala, S.V., *et al*. (2025). Engineering end-to-end remote labs using IoT-based retrofitting. *IEEE Access*, 13, 1106-1132. doi: 10.1109/access.2024.3523066.

[12] King, A. (2021). *Programming the Internet of Things: An introduction to building integrated, device-to-cloud IoT solutions*. Sebastopol: O'Reilly Media.

[13] Kuriščák, P., Rossa, P., Fernandes, H., & Silva, J.N. (2022). Design and implementation of a framework for remote experiments in education. In *8th international engineering, sciences and technology conference (IESTEC)* (pp. 259-265). Panama: IEEE. doi: 10.1109/iestec54539.2022.00046.

[14] Lawrence, O.A., & Tariq Iqbal, M. (2020). Design and implementation of a low-cost, open source IoT-based SCADA system using ESP32 with OLED, ThingsBoard and MQTT protocol. *AIMS Electronics and Electrical Engineering*, 4(1), 57-86. doi: 10.3934/ElectrEng.2020.1.57.

[15] Malhi, A., Javed, A., Yousefnezhad, N., & Främling, K. (2023). IoT open messaging standards: Performance comparison with MQTT and CoAP protocols. In *10th international conference on future Internet of Things and cloud (FiCloud)* (pp. 130-135). Marrakesh: IEEE. doi: 10.1109/ficloud58648.2023.00027.

[16] Mencia, D., Ramos, M., Núñez, F., & Ordóñez Ávila, J.L. (2023). Cinematic design and force analysis of a SCARA robot with pneumatic actuators. In *Leadership in education and innovation in engineering in the framework of global transformations: Integration and alliances for integral development*. (pp. 1-9). Buenos Aires: LACCEI. doi: 10.18687/LACCEI2023.1.1.1279.

[17] Odier, J., Lambert, F., Fulachier, J., Jaume, M., & Delsart, P.-A. (2024). Using MQTT and Node-RED to monitor the ATLAS Meta-data Interface (AMI) stack and define metadata aggregation tasks in a pipelined way. *EPJ Web of Conferences*, 295, article number 01055. doi: 10.1051/epjconf/202429501055.

[18] Qasim, I., Anwar, M.W., Azam, F., Tufail, H., Butt, W.H., & Zafar, M.N. (2020). A model-driven mobile HMI framework (MMHF) for industrial control systems. *IEEE Access*, 8, 10827-10846. doi: 10.1109/access.2020.2965259.

[19] Rozan, M., Dwiyaniti, M., & Muhammad, N. (2024). Implementation and testing of an IoT system using Node-Red and OPC UA for monitoring an automated storage warehouse. *Seminar Nasional Teknik Elektro*, 10(1), 183-188.

[20] Safitri, N.A., & Priambodo, A.S. (2023). MQTT and CoAP communication protocol analysis in Internet of Things system for strawberry hydroponic plants. *Journal of Robotics, Automation, and Electronics Engineering*, 1(1), 45-56. doi: 10.21831/jraee.v1i1.69.

[21] Santacruz, A.F., Villalobos, J., Sanchez, I.Y., Paredes, C.A., & Martell, F. (2021). Virtual SCARA robot with reduced dynamics in a real-time simulation scheme for robotics and control engineering education. In *International conference on electrical, computer and energy technologies (ICECET)* (pp. 1-6). Cape Town: IEEE. doi: 10.1109/ICECET52533.2021.9698437.

[22] Vlasenko, M., & Khlaponin, Yu. (2024). The Internet of Things (IoT) in world practice: Review and analysis. *Underwater Technologies*, 13, 21-27. doi: 10.32347/uwt.2023.13.1202.

[23] Yatagha, R., Waedt, K., Schindler, J., & Kirdan, E. (2023). Security challenges and best practices for resilient IIoT networks: Network segmentation. In *INFORMATIK 2023 – designing futures* (pp. 2051-2070). Bonn: Gesellschaft für Informatik. doi: 10.18420/inf2023_204.

Створення веб-орієнтованого людино-машинного інтерфейсу для фізичної моделі робота SCARA на основі технологій промислового Інтернету речей

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Анотація. Навантажувально-розвантажувальні операції є однією із ключових ланок багатьох виробни-чих процесів у сучасній промисловості. Для підвищення ефективності процесів навантаження та розвантаження важливим є підвищення точності, продуктивності та швидкості керування. Цього можна досягти шляхом інтеграції виробничих процесів у web через впрова-дження концепції «Industry 4.0». Метою цієї роботи була розробка веб-інтерфейсу для системи, що імітує навантажувально-розвантажувальні операції на базі робота SCARA, що забезпечує ефективний моніторинг та керування технологічним процесом. Для визначення ар-хітектури запропонованої системи було проаналізовано сучасні підходи до розробки автоматизованих систем керування з використанням концепції «Industry 4.0». Для вибору інструментів для створення компонентів системи було проаналізовано та визначено технології розробки програмного забезпечення, що підходять для цього завдання. Було розроблено комплексну систему керування та моніторингу робота SCARA з використанням веб-інтерфейсу на основі концепції «Industry 4.0». Розроблений web-інтерфейс демонструє ефективний підхід до побудови інтерактивних систем керування, підвищення продуктивності та зручності для операторів. Практичне значення результатів полягає у створенні єдиного рішення для моніторингу та керування роботизованими комплексами, яке можна адаптувати та впровадити на різних виробничих та освітніх платформах. Крім того, розроблене рішення може бути використане в навчальному процесі для лабораторних робіт з нормативних дисциплін

Ключові слова: автоматизація; індустрія 4.0; інтернет речей; MQTT; OPC UA; ПЛК; веб-SCADA

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Efficiency of thermal energy consumption at industrial enterprises of Ukraine in conditions of environmental restrictions

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Abstract. The purpose of the study was to identify key patterns of thermal energy consumption and develop an analytical basis for optimising technological processes based on environmental requirements. The methodology involved a step-by-step calculation of the heat utilisation coefficient, specific consumption and heat loss structure based on instrumental data on heat consumption by the public joint-stock company Kamet-Steel for July-September 2024. The assessment of the efficiency of thermal energy consumption at the enterprise showed a stable, but insufficient level of energy use: the average coefficient was 81.0%, while heat loss did not decrease below 18.9%. Structural analysis showed that the largest share of losses was accounted for by pipelines (7.3%), heat exchangers (5.8%), cooling circuits (4.1%), and other losses (1.7%), which indicates the presence of several critical areas of inefficiency. Specific heat consumption per unit of production ranged from 0.1815-0.1923 Gcal/t and increased in September, despite a decrease in production volumes, which indicates the inertia of the supply system. Based on the results, a technical and analytical basis was formed for the reconstruction of energy-efficient infrastructure elements with an estimated potential to reduce losses by 6-8%. The presented conclusions also confirmed the feasibility of digital monitoring as a tool for stabilising costs and increasing adaptability to changes in the production load. The results obtained can be used for the development of technical and economic measures for the reconstruction of heat transport infrastructure of industrial enterprises, in particular, through the optimisation of heat exchange modes, modernisation of pipelines, and the introduction of residual heat recovery systems. This will reduce specific energy costs, stabilise the heat balance, and reduce the environmental burden

Keywords: heat efficiency; metallurgical production; carbon; pipeline networks; cooling circuits; recuperation

Introduction

Industrial enterprises of Ukraine, in particular in the metallurgy sector, are increasingly operating under stricter environmental regulations and growing energy efficiency requirements. In heat supply systems that serve high-temperature technological processes, a significant part of energy is lost due to worn-out infrastructure, inconsistency of heat flows with the dynamics of production, and the lack of recovery mechanisms. Specific losses are caused by the inertia of heat engineering systems, instability of heat exchange, and low accuracy of circuit control. In such conditions, thermal energy consumption becomes a factor that affects not only the production cost, but also the overall environmental footprint of the enterprise. This justifies the need to implement technological solutions aimed at structural modernisation of heat supply systems and increasing their adaptability to changes in production load.

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Among the research in the field of industrial energy efficiency, the study by M. Farghali *et al.* (2023) proposed a comparative systematisation of energy saving strategies based on examples from different countries in the context of the energy crisis. This was a generalisation of current approaches to integrating renewable sources and load optimisation. However, heat consumption as a separate technical component was not considered. The study by C.-L. Miao *et al.* (2020) analysed the relationship between energy consumption, environmental pollution and innovative efficiency on the example of Chinese industry, but without considering heat losses in technological processes. On the other hand, L. Dai & M. Wang (2020) developed a model for assessing the impact of carbon constraints on the economic performance of thermal generation, focusing on the macro level without detailing the structure of industrial heat consumption.

An important contribution to the development of the modern discourse on energy efficiency in Ukraine was made by V. Derii *et al.* (2023b), who analysed the impact of structural changes in the district heating system on greenhouse gas emissions and substantiated the need for technical reconstruction of the heat and power infrastructure. This study proved that the transformation of thermal circuits towards decentralisation, modernisation of equipment, and introduction of cogeneration technologies can significantly reduce the carbon footprint of the energy system, although without direct detailing of heat losses in the industrial sector. The study by V.P. Babak *et al.* (2023) for the first time systematised technical and economic approaches to improving energy efficiency in industry at the level of a national monograph, including the analysis of reserves for reducing heat losses, but these solutions remain conceptual and require empirical verification in real production conditions. The paper by U. Andrusiv *et al.* (2023) was distinguished by its originality due to the use of a simulation model to assess the efficiency of using fuel and energy resources, considering the country's energy balance. However, the study focused on the macro level and did not cover structural analysis of thermal energy losses in production systems, which limits its application value for industrial enterprises. Actual aspects of forecasting the needs for thermal energy in the conditions of martial law and post-war reconstruction were considered by O. Maliarenko *et al.* (2025), who presented a scenario approach to estimating heat load in the future until 2030. The models proposed by the researchers considered socio-economic transformations and infrastructure losses, which created an analytical basis for substantiating the needs for modernisation of industrial heat supply systems.

Comprehensive reports National Academy of Sciences of Ukraine Institute of General Energy (2024) and National Academy of Sciences of Ukraine Institute of general energy (2025) provided a generalised review of scientific and organisational activities in the field of energy efficiency improvement, in particular, they noted the potential for residual heat utilisation, modernisation of thermal power plants (TPPs) and the introduction of innovative energy saving systems in industry. These documents formed a conceptual basis for substantiating the need for reconstruction of energy systems, but contained mainly strategic approaches without empirical detailing of heat consumption processes. The study by M.M. Kulyk & O.V. Zgurovets (2020) investigated the effect of derivatives from regulatory capacities on frequency stability in power systems with wind power plants (WPPs), proposing a mechanistic model relevant for estimating load dynamics, but without considering thermal processes in production. Instead, the study by M. Andersen & J. Noailly (2022) modelled the technological development of the coal industry, considering environmental constraints, which allowed predicting adaptation scenarios for the sector, although without directly focusing on the loss of thermal energy. Despite the availability of strategic and conceptual developments, as of 2025, studies have not provided a reasonable empirical assessment of the efficiency of thermal energy consumption in the real functioning of industrial enterprises.

The purpose of this study was to quantify the parameters of thermal energy consumption in the industrial sector of Ukraine, considering technological losses and environmental restrictions. Within the framework of the set goal, the study included an analysis of the structure of heat energy use at enterprises, identification of key sources of losses in technological nodes, and determination of areas for improving energy efficiency in the context of increased environmental regulation.

Materials and Methods

The study was conducted at the metallurgical enterprise Public Joint Stock Company (PJSC) Kamet-steel (Kamyanske, Dnipropetrovsk Oblast, Ukraine) in the period from July 1 to September 30, 2024. This enterprise was chosen as a representative unit of heavy industry in Ukraine with a full metallurgical cycle, centralised generation and utilisation of thermal energy. The selected period corresponded to a stable summer production regime, which excluded the influence of seasonal fluctuations and planned equipment shutdowns, ensuring representativeness of thermal performance indicators.

Indicators were collected automatically through the industrial monitoring system Supervisory Control and Data Acquisition (SCADA) with data recording every 15 minutes. For analytical calculations, the average values for each technological change were used (00:00-08:00, 08:00-16:00, 16:00-00:00), with subsequent aggregation to average daily, weekly, and monthly intervals. For each of the parameters, average values were calculated both in terms of time and volume of output. In the course of the study, the following thermal performance indicators were automatically recorded: the volume of heat energy consumed (Gcal/day), specific heat consumption per unit of production (Gcal/t of steel), heat losses at different stages of the technological cycle (%), the temperature and pressure of the heat carrier at the inlet and outlet of heat exchangers, the duration of heat transfer (h), the volume of recycled secondary heat (Gcal/day), the temperature of cooled flows. The amount of useful heat used was determined on the basis of consumption indicators in the main heat technology units, in particular, in blast furnace and steelmaking units. The measurements were carried out by the company's standard accounting system using Proline Prosonic Flow 93T ultrasonic flow meters (Endress+Hauser, Germany), Pt100 temperature sensors (Siemens, Germany) and VEGABAR 82 pressure sensors (VEGA Grieshaber KG, Germany). The instruments were calibrated in accordance with the company's internal regulations in compliance with the requirements of DSTU ISO 10012:2005 (2005) for measurement control systems.

To calculate the efficiency of thermal energy consumption, the heat useful life coefficient (*KKWT*) was used, which was determined by the equation 1:

$$KKWT = \frac{Q_{useful}}{Q_{total}} \times 100\%, \qquad (1)$$

where Q_{useful} – amount of heat used directly in the process (Gcal); Q_{total} – total amount of heat supplied to the system (Gcal).

To reflect the inefficient use of thermal energy, the level of heat losses (*W*) was additionally calculated using the equation 2:

$$W = \frac{Q_{total} - Q_{useful}}{Q_{total}} \times 100\%. \qquad (2)$$

This indicator allows quantifying the proportion of heat that is lost during transportation or use. Losses were determined based on the balance method with a comparison of the supplied and useful heat, considering heat losses in pipelines, heat exchangers, and cooling circuits.

The specific heat consumption for the production of one tonne of steel was estimated using the equation 3:

$$q = \frac{Q_{total}}{P}, \qquad (3)$$

where q – specific heat consumption (Gcal/t); P – total output (t).

All these equations were developed based on generally accepted methods for calculating energy efficiency in industrial heat and power engineering (Barakhta & Krazhan, 2008).

Production information was collected within the framework of the current regulations of PJSC Kamet-Steel in coordination with responsible specialists. The data used in the analytical calculations did not contain any commercial secrets and were generalised to a level that excludes the disclosure of technologically sensitive characteristics. All measurement procedures were carried out remotely and did not affect production processes, without creating risks to the environment, equipment or personnel. There was no interference with the operation of technological systems during the study.

Results and Discussion

General indicators of thermal energy consumption in the production cycle. As part of the analysis of thermal energy consumption at the enterprise of PJSC Kamet-Steel, special attention was paid to the dynamics of average weekly values, which allowed tracing the relationship between fluctuations in technological activity, in particular, changes in steel output volumes and the daily thermal load (Table 1). This approach provided a representative basis for further interpretation of energy consumption levels in the context of the technical condition of heat supply systems and the efficiency of the enterprise's heat balance.

Table 1. Average weekly heat consumption and steel output per day at PJSC Kamet-Steel in July-September 2024

Week	Average heat consumption, Gcal/day	Average daily steel output, t	Total weekly steel output, t
01-07.07	975.3	5,240	36,680
08-14.07	980.7	5,310	37,170
15-21.07	987.5	5,190	36,330
22-28.07	990.1	5,350	37,450
29.07-04.08	987.2	5,420	37,940
05-11.08	998.4	5,500	38,500
12-18.08	1,002.3	5,480	38,360
19-25.08	1,005.8	5,470	38,290
26.08-01.09	999.4	5,320	37,240
02-08.09	973.1	5,200	36,400
09-15.09	977.6	5,140	35,980
16-22.09	970.8	5,080	35,560
23-30.09	980.9	5,100	40,800 (8 days)

Source: compiled by the author

Aggregated data show that the average weekly heat consumption ranged from 970.8 to 1,005.8 Gcal/day, with the maximum load recorded in August. The increase in heat consumption during July – mid-August correlated with an increase in production volumes-from 36,330 to 38,500 tonnes of steel per week. The highest average weekly intensity of energy consumption was recorded in the period August 05-11, when the heat load reached 1,005.8 Gcal/day with the output of 38,500 tonnes. This dynamic confirmed the link between the production schedule and heat load. But in September, starting from the second week, there was a gradual decrease in heat consumption – from 984.2 to 970.8 Gcal/day, which was accompanied by a corresponding decrease in output volumes – from 36,400 to 35,560 tonnes per week. This decline reflects the impact of technical routine shutdowns of individual units and a decrease in the load of melting capacities due to preparations for the autumn repair period. Such a change in the intensity of heat consumption indicates the need for adaptive control of heat flows depending on production activity.

The results obtained confirmed the data of V. Derii *et al.* (2023a), who noted that the high inertia of heat engineering systems and the insignificant reaction of the heat supply system to fluctuations in production volumes are characteristic of Ukrainian metallurgical enterprises. According to their estimates, typical values of heat consumption under constant load conditions are 930-1,020 Gcal/day, which is fully consistent with the results obtained in this study. However, the results of Polish enterprises, described in the paper by R. Wolniak *et al.* (2020), showed significantly lower daily heat consumption with a similar volume of steel output – 850-880 Gcal/day, which is 10-12% less than the Ukrainian values. This is conditioned by the high degree of digitalisation of energy management systems, the integration of Industry 4.0 technologies, and the active introduction of recovery systems. This comparison allows to conclude that there is a potential for optimising heat consumption at PJSC Kamet-Steel through the modernisation of heat distribution systems. The study by K. Widera *et al.* (2024) emphasised that the stability of energy consumption at variable production intensity is a sign of weak adaptability of systems. A similar trend was recorded in the current study – the heat load in September remained stable, despite a decrease in production volumes by more than 2,000 tonnes per week, which indicates the existence of a baseline level of losses. In this paper, the researchers proved that under such conditions, enterprises can lose up to 5-6% of their potential energy efficiency.

Data on the average monthly heat consumption allowed summarising and demonstrating the dynamics of changes in energy loads during the observation period. Indicators for each month provided an opportunity to assess the impact of production activity on total heat consumption, identify periods of increased or reduced load, and confirmed the dependence of thermal dynamics on changes in the production schedule (Fig. 1).

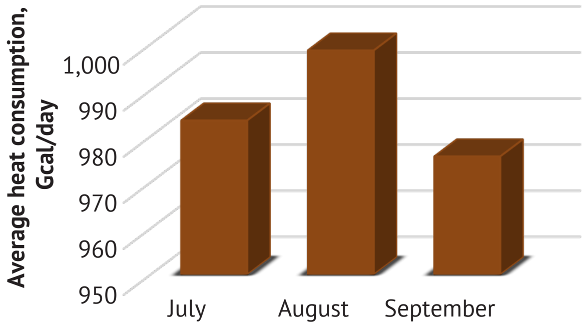

Figure 1. Average monthly heat consumption at PJSC Kamet-steel

Source: compiled by the author

The graphical interpretation of the average monthly heat consumption indicators showed a clear dependence of the heat load on production activity. The increase in values in August corresponds to the peak load phase of the metallurgical cycle, due to the continuous operation of the main units without technological stops. In September, there was a gradual decrease in heat consumption, which correlates with a decrease in output and preparation for routine maintenance. The inertia of thermal processes causes a stable level of basic losses, which cannot be adjusted quickly, even in conditions of reducing production volumes. This indicates the limited flexibility of the existing infrastructure to changes in the production schedule.

According to the observations of T. Sengyu & V. Khare (2023), the low dynamic sensitivity of heat consumption systems in response to changes in output volumes is a typical limitation for enterprises that do not have integrated automated heat exchange management systems. In this study, this was also reflected in a slight decrease in daily costs with a reduction in steel output in September, which indicates the presence of structural inertia. From the standpoint of environmental efficiency, such losses without direct reference to the production result form an unproductive heat load on the environment, in particular, due to excessive CO_2 emissions in cases where the source is organic fuel. H. Na *et al.* (2021) noted that in order to achieve environmental neutrality, enterprises should implement energy-efficient control models that minimise unjustified heat costs by 10-15%. The results obtained confirmed the high dependence of heat consumption on the technological load, while at the same time identifying a constant level of maladaptive losses that form an excessive load on the energy balance of the enterprise. This situation indicates the need for targeted optimisation of the structure of heat consumption, considering the localisation of losses and increasing the efficiency of residual heat utilisation.

Evaluation of the efficiency of using thermal energy. Evaluation of the efficiency of heat consumption at the selected enterprise was carried out by calculating the coefficient of useful use of heat, reflecting the share of heat energy that was directly used in the technological process. Simultaneously, the level of heat loss was used for quantitative assessment of losses, which allows determining the share of unused heat from the total amount of energy supplied. Both indicators were calculated according to equations (1) and (2) (Table 2).

Table 2. Results of calculation of KKWT and heat energy losses at weekly intervals

Week	Q_{total} (Gcal/day)	Q_{useful} (Gcal/day)	*KKWT* (%)	Heat loss *W* (%)
01-07.07	975.3	782.4	80.2	19.8
08-14.07	980.7	794.3	81.0	19.0
15-21.07	987.5	801.9	81.2	18.8
22-28.07	990.1	808.7	81.7	18.3
29.07-04.08	987.2	800.1	81.1	18.9
05-11.08	998.4	812.9	81.4	18.6
12-18.08	1,002.3	816.8	81.5	18.5
19-25.08	1,005.8	818.2	81.4	18.6
26.08-01.09	999.4	809.1	81.0	19.0
02-08.09	973.1	788.9	81.0	19.0
09-15.09	977.6	790.1	80.8	19.2
16-22.09	970.8	782.0	80.5	19.5
23-30.09	980.9	788.6	80.4	19.6

Source: compiled by the author

The data show that *KKWT* ranged from 80.2 to 81.7%, indicating a moderate but stable level of thermal efficiency. The highest figure – 81.7% – was reached during the week of July 22-28, which indicates an improvement in the heat balance in conditions of stable production load. Simultaneously, the lowest value – 80.2% – was recorded in the first week of July, when the system probably has not yet entered optimal operation after the off-season regulations. The rate of heat loss, respectively, ranged from 18.3% to 19.8%, and in none of the weeks the loss was reduced to a limit below 18%. This indicates the presence of constant systemic losses of thermal energy in the enterprise's infrastructure, mainly associated with pipeline networks, cooling systems, and inefficient utilisation of residual heat.

A detailed analysis showed that the change in *KKWT* was most influenced by: the condition of heat exchangers, load stability in blast furnace and steelmaking units, and the secondary heat recovery coefficient. For example, the increase in *KKWT* in the second half of July was associated with minimising shutdowns and improved coordination between heat carriers and production volumes. Despite the achievement of *KKWT* at the level of 80.2-81.7% during the analysed period, the available reserve for improving efficiency was at least 3-5%, this optimisation potential was conditioned by excessive heat losses in pipelines, insufficient level of residual heat recovery, and limited adaptability of heat supply to load changes. Promising measures are the introduction of automated heat flow management systems, reconstruction of heat exchange equipment, and integration of local recycling systems at the level of technological units, which will increase the *KKWT* to a normatively justified level. Comparison with similar results in other studies confirmed the general trend of maintaining heat engineering inefficiency in metallurgical production. According to M. Xu & B. Lin (2022), the average level of heat efficiency at metallurgical enterprises in China is 78-83%, which is almost identical to the values obtained in the study (80.2-81.7%). The researchers emphasised that the main limiting factor of efficiency is the inertia of heat supply systems – their inability to flexibly respond to fluctuations in production loads. This was also observed at PJSC Kamet-Steel, where the increase in load in August was not accompanied by a proportional decrease in heat loss. Similar conclusions were presented in the paper by Z. Su *et al.* (2021), who noted that the lack of technologies for multi-level utilisation of residual heat can lead to losses of more than 20%. In the current study, losses were 18.9%, which indicated partial compensation, but confirmed a structural shortage of recycling mechanisms, especially in cooling circuits and the pipeline network.

S. Zhang *et al.* (2022) reported that the introduction of industrial-type thermal accumulators can reduce heat losses by 3-4%, which is comparable to the identified optimisation potential at the enterprise. Since no traces of the use of storage technologies were recorded in the course of the study, such modernisation was considered as one of the least resource-intensive steps to increase the *KKWT*. From the standpoint of environmental efficiency, the results of the study are consistent with the provisions of S.R. Paramati *et al.* (2022), who stated that each percentage reduction in heat loss correlates with a reduction in CO_2 emissions, especially in systems with heavy use of fossil fuels. Given that PJSC Kamet-Steel operates in a carbon-intensive production environment, the current loss rate of almost 19% means that the excess carbon footprint is likely to remain, which requires a separate assessment. A. Arifjanov *et al.* (2020) investigated the effectiveness of technical reconstruction of pipeline infrastructure, in particular, due to changes in the geometric parameters of pipes and the introduction of new insulation materials. According to the researchers, losses can be reduced to 5-6% at critical points, which in the conditions of Kamet-Steel potentially reduces the overall W indicator from 18.9% to 13-14% without radical changes in production logistics. Thus, the detected thermal imbalance with the share of unused energy of more than 18% indicated systemic structural shortcomings in the management of heat flows, the elimination of which will provide regulatory limits of efficiency along with a comprehensive increase in energy and environmental efficiency of production, in particular, through increasing the flexibility of heat supply systems, integration of heat accumulators, and reconstruction of backbone networks.

Structure of heat losses and their technological localisation. The design of industrial thermal engineering systems is such that a significant portion of the energy supplied does not reach the target technological nodes, due to both design features and infrastructure wear and tear. To identify the sources of system losses at the PJSC Kamet-Steel, the heat balance was decomposed into the main components: losses in pipelines, heat exchange equipment, cooling circuits, and other infrastructure losses. Calculations were carried out based on indicative relations between the supplied energy (Q_{total}) and the volumes of heat recorded at the end-use points (Q_{useful}), followed by the distribution of losses by individual technological links.

The weighted average level of heat energy losses at the enterprise during July–September 2024 was 18.9%. The distribution of heat losses between the main infrastructure elements allowed to identify critical areas of energy efficiency and form priorities for technical intervention. To visualise the contribution of each structural component to the overall loss rate, a graph was constructed showing the specific proportion of losses in pipelines, heat exchangers, cooling systems, and non-localised zones (Fig. 2).

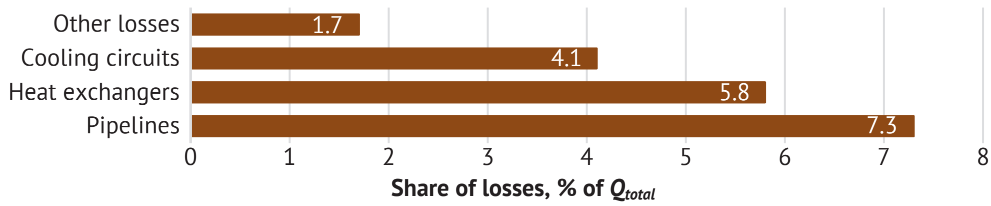

Figure 2. Distribution of heat losses by infrastructure components
Source: compiled by the author

Structural analysis of heat energy losses confirmed that the largest share is accounted for by main pipelines – 7.3% of the total volume of heat energy supplied (Q_{total}), which indicates the determining contribution of this component to the systemic inefficiency of the heat transport infrastructure. This result is explained by physical wear of the insulation, insufficient sealing of joints, and failure to comply with technical regulations, which makes it impossible to effectively compensate for losses without network reconstruction. In second place in terms of losses is heat exchange equipment (5.8%), where losses were caused by violation of heat transfer modes, low flow turbulence, and outdated design. In cooling circuits, losses were 4.1% and were mainly associated with inefficient utilisation of residual heat, in particular, due to excessive water cooling without reverse heat recovery mechanisms. The category "other losses" covers 1.7% and included losses in shut-off valves, strapping, drains, and other small system elements. Their localisation is more complex, but they can be compensated by point-based technical interventions at minimal cost.

The overall picture indicates a disparity in the loss structure, where a significant share was occupied by components that can theoretically be effectively upgraded. This creates prerequisites for the development of a phased thermal rehabilitation strategy, which should cover the priority renewal of pipelines and heat exchangers, and the development of a feasibility study for the recovery of lost heat from cooling circuits. Comparison with the results of the study by D. Al Momani *et al.* (2023) showed that the level of losses in pipeline systems of industrial enterprises in the food sector in the absence of modernisation was 6-9%. The indicator of 7.3% obtained at PJSC Kamet-Steel is comparable under conditions of similar thermal load scales, although at higher temperatures of the technological cycle. The applied approach of local thermal audit was consistent with the methodological approaches set out in the mentioned source.

According to the generalised conclusions of M. Meng & D. Qu (2022), the share of losses in heat transportation and utilisation systems in some regions of China is up to 20%, and energy efficiency in general ranges from 76-85%. The loss structure recorded at the enterprise under study reproduced a similar configuration, where the predominant share was accounted for by pipeline infrastructure and heat exchangers. Fixing a stable loss rate of almost 19% indicated an additional thermal load, which, according to the model by C. Tang *et al.* (2025), has a direct relationship with the growth of carbon production intensity. This suggests that even in the absence of direct monitoring of CO_2 emissions, such thermal inefficiency can be an indirect indicator of increased impact on the climate system. In this context, the integration of environmental indicators into the energy audit system is not only desirable, but also a methodologically justified condition for modern energy environmental management. As part of the study by G. Kaletnik *et al.* (2020), the importance of residual heat utilisation as one of the key elements for achieving energy autonomy of industrial facilities was emphasised. The recorded level of losses in the enterprise's cooling systems (4.1%) confirmed the feasibility of creating heat recovery systems, even in medium-temperature conditions.

A comparative analysis of the obtained heat loss indicators with the results of previous studies revealed both elements of consistency and structural discrepancies due to the specifics of the research object. In particular, according to V.V. Dubrovsky & A.A. Shraiber (2020), heat losses in cooling systems based on film heat exchange can reach 4-5% of the total energy balance due to inefficient open-circuit heat transfer and significant influence of meteorological factors. In the conditions of Kamet-Steel, losses in circulation cooling systems were commensurate – at the level of 4.1%, which confirmed the stability of the scale of losses under the condition of a similar cooling principle (cooling towers and open water circuits), but under more controlled production conditions. The results obtained by O.A. Shraiber & V.B. Redkin (2018) indicate that in the case of insufficient turbulence in heat exchangers, the heat transfer efficiency decreases, which lead to losses of up to 6-7% of the supplied heat. In the course of this study, the average level of losses in heat exchangers was 5.8%, but in some periods – in particular, in August – local peaks were recorded that exceeded 6.1%. This behaviour is associated with an increased production load and deterioration of hydrodynamic conditions in heat exchange modules, which is consistent with the authors' hypotheses and indicated the presence of a maladaptive mode of operation of equipment at peak loads.

These values indicated that there is a potential to increase efficiency by at least 6-8% due to the modernisation of pipeline insulation and reconstruction of heat exchange equipment. In particular, the use of a new generation of plate heat exchangers reduced specific losses by 2-3%, and the introduction of multi-layer insulation with microporous fillers – by another 4%. In addition, correction of cooling modes through the introduction of reverse temperature control in circulation loops can reduce losses in cooling towers and heat carriers. The results of loss localisation confirmed the multicomponent nature of the inefficiency of the heat supply system, where each structural element makes a significant contribution to the total energy losses. Given the relative constancy of losses, it can be argued that there is infrastructure inertia, which prevents a proportional reduction in energy consumption during periods of reduced production. This justifies the need for a detailed energy audit using thermography, hydraulic modelling, and feasibility studies of reconstruction solutions.

Specific heat consumption per unit of production and influencing factors. Energy efficiency assessment at the level of individual product units is necessary for understanding the real level of technological optimisation of the enterprise. As part of the study, the company calculated the specific heat consumption (q), which reflects the average amount of heat used in GCal for each tonne of steel produced. The calculation was performed using the equation (3) (Table 3).

Table 3. Specific heat consumption per unit of steel produced at PJSC Kamet-Steel

Week	Specific heat consumption (Gcal/t)
01-07.07	0.1861
08-14.07	0.1847
15-21.07	0.1903
22-28.07	0.1851
29.07-04.08	0.1822
05-11.08	0.1815
12-18.08	0.1829
19-25.08	0.1839
26.08-01.09	0.1878
02-08.09	0.1871
09-15.09	0.1901
16-22.09	0.1911
23-30.09	0.1923

Source: compiled by the author

Fluctuations in specific heat consumption per unit of production in the analysed period ranged from 0.182 to 0.192 Gcal/t, which reflects the uneven adaptation of the heat engineering infrastructure to changes in the production load. There is a clear trend: during periods of high technological activity (in particular, in August), the system shows increased consistency between energy supply and production volumes, which reduces unit costs. But in the conditions of a gradual decrease in production volumes in September, the heat load per unit of production increased, which indicated structural inertia and the presence of basic losses that cannot be adjusted in real time.

Such dynamics are inherent in enterprises with a complex branched heating network, where thermal energy is supplied not in proportion to real demand, but along inertial circuits that react with a time lag. This behaviour of the system may be conditioned by the lack of automated means of monitoring heat flows, low accuracy of temperature control, and technical losses in the network. This indicated the need to integrate elements of flexible energy management, especially in the phases of declining production. According to the findings of T. Jiang *et al.* (2022), in sectors with a high specific heat load, there is a direct relationship between the maladaptivity of thermal power systems and carbon intensity. It was found that a steady increase in unit costs at the end of the study period not only indicates a deterioration in energy efficiency, but also has environmental consequences that require further study in the context of the industrial decarbonisation strategy.

The problem of irrational heat distribution in low-load phases was also mentioned in the study by Z. Chen *et al.* (2023), where it was proved that low controllability of heat exchange processes under conditions of variable circulation modes leads to local energy imbalances. The company's observed increase in q in September with a decrease in steel output is fully consistent with this observation. The researchers also emphasised that even minor improvements in the field of thermal insulation or circuit automation can significantly reduce unit costs. These results are supported by S. Gennitsaris *et al.* (2023), who showed that the integration of digital unit cost monitoring systems in real time allows quickly identifying inefficient production modes and reducing q by 3-5% without the need to attract significant investment. In this context, the lack of dynamic control over heat flows at the Kamet-Steel enterprise can be a determining factor for consistently high losses during periods of reduced load.

At the strategic level, the results of the study by M. Zos-Kior *et al.* (2021) indicated that the specific energy consumption indicator should be an integrated element of a multi-level resource efficiency assessment system, since it reflects the quality of energy management throughout the entire product life cycle. The dynamics of the q-indicator established in the course of this study confirms the feasibility of localised loss control and the introduction of technological modifications focused not only on the economic, but also on the environmental performance of energy consumption. The results obtained are consistent with international trends and empirical estimates from other industries, indicating the need to implement technical and economic solutions to improve efficiency. The dynamics of specific heat consumption demonstrated their sensitivity to changes in the production load and the feasibility of using this indicator as a diagnostic tool for optimising heat supply. The implementation of system improvements would allow for a gradual increase in energy efficiency, considering complex technical and environmental parameters.

Environmental consequences of heat losses and prospects for decarbonisation of industrial energy consumption. Heat losses in industrial power systems are not only of technical, but also of environmental significance. The loss of almost a fifth of the heat indicated the existence of a constant thermal load on the system, which not only reduces energy efficiency, but also indirectly generates an increase in greenhouse gas emissions. In technologically complex industries, such as metallurgy, where the bulk of energy is supplied in the form of heat, the degree of efficiency of its use directly determines the intensity of the carbon footprint of the finished product. The loss structure is dominated by pipelines, heat exchangers, and cooling circuits. The decline in efficiency at these stages indicated not only the technical obsolescence of infrastructure elements, but also the lack of effective heat recovery mechanisms, which are already standard practice in a number of countries. For example, the absence of heat accumulators or the secondary use of residual heat in cooling systems does not reduce peak losses, which is especially pronounced during periods of reduced production load. Heat losses are not a constant technological value, but act as an indicator of the system's adaptability to production dynamics. Their growth against the background of a decrease in output volumes in September indicates infrastructure inertia and a low degree of integration of intelligent control systems.

Comparison with the results of the study by T. Jiang *et al.* (2022) confirmed that in sectors with a high specific heat load, such as energy and metallurgy, the level of heat loss is directly related to an increase in carbon intensity. The paper noted that the inability to adapt the system to changes in consumption leads to the accumulation of CO_2 emissions even with a general decrease in production. This is fully consistent with this work's results, where an increase in unit costs in September, despite a decline in steel output, indicates a potential environmental vulnerability. Similar conclusions were noted by S.R. Paramati *et al.* (2022), who proved that reducing heat losses by 1-2% in industry contributes to reducing CO_2 emissions depending on the fuel structure. In this context, the data obtained on losses in pipelines and heat exchangers provide a reserve for reducing emissions while maintaining technological productivity. C. Tang *et al.* (2025) also indicated that consistently high specific losses – more than 0.19 Gcal/t – correlate with an increase in specific greenhouse gas emissions, especially in non-ferrous metallurgy. At the end of September, the specific consumption at the enterprise under study reached 0.1923 Gcal/t, which potentially indicates an increase in the carbon footprint in conditions of low production activity. Z. Chen *et al.* (2023) showed that structural improvements in the distribution of coolant flows, even without changing the main equipment, can reduce the level of losses by 3-5%, which reduces both direct and indirect emissions. This approach is also relevant for the enterprise under study, where loss stability indicates an insufficient level of system flexibility. Summarising, it was found that heat losses in industry have not only energy, but also environmental consequences, which can be reduced by upgrading insulation, introducing storage systems, recycling of residual heat and adaptive flow control. Integration of thermal efficiency indicators into carbon calculations will allow combining technical and environmental performance, which is key in the context of implementing the strategy of decarbonisation of the Ukrainian industry.

Conclusions

As a result of the study, it was found that the thermal efficiency of the technological cycle of PJSC Kamet-Steel in July-September 2024 remained stable, but did not meet the guidelines for energy-saving production. The average *KKWT* was 81.0%, which is lower than the recommended 85% for industrial metallurgical facilities. Accordingly, the share of heat loss reached 18.9%, which indicated the stable existence of systemic energy efficiency. This thermal imbalance indicates the inability of the infrastructure to quickly adapt to fluctuations in the production load, which is critical in high-temperature continuous technologies.

The indicator of specific heat consumption per unit of production (q), which during the analysed period varied from 0.1815 to 0.1923 Gcal/t, turned out to be an effective indicator of the functional state of the heat and power system. The increase in q in September, amid a decrease in output volumes, revealed high inertia of energy losses associated with low system flexibility to technological load reduction. Thus, specific heat consumption can be used as an operational criterion for correcting the technological regime, and for assessing environmental consequences – considering the proven relationship between q growth and carbon production intensity.

The distribution of heat losses across infrastructure components showed an asymmetric structure dominated by losses in main pipelines (7.3% of Q_{total}) and heat exchangers (5.8%), while cooling circuits and non-localised losses were 4.1% and 1.7%, respectively. This distribution reveals clearly defined critical zones, the modernisation of which can have the greatest impact on overall thermal efficiency. Reducing losses at key sites will contribute not only to improving energy efficiency, but also to reducing greenhouse emissions, which is important in the context of environmental transformation of industry. The practical significance of this conclusion lied in the possibility of developing a technical and economic model of stage reconstruction, where priority will be given to updating insulation, reconstructing heat exchangers, and optimising the operating modes of circulation circuits. Comparison of the obtained indicators with the results of international studies showed high consistency of the main parameters of energy consumption. In particular, the levels of *KKWT* and losses fully correspond to the data recorded at metallurgical enterprises in China with a similar production profile. This confirmed that even within the existing infrastructure, there is a reserve for improving energy efficiency by 5-7%, which can be implemented through local organisational and technical solutions without attracting large-scale investments.

Limitations of the study were the focus exclusively on thermal performance without considering the electricity component and associated CO_2 emissions in real terms. This limits the completeness of the assessment of the integrated energy efficiency of the enterprise. It is recommended to expand further research by including the carbon footprint, analysis of exergetic losses, and modelling the potential for multi-level residual heat utilisation in the dynamics of the production cycle. Special attention should be paid to the assessment of specific CO_2 emissions in relation to heat load, which would allow integrating energy efficiency indicators with environmental performance.

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Conflict of Interest

None.

References

[1] Al Momani, D., Al Turk, Y., Abuashour, M.I., Khalid, H.M., Muyeen, S.M., Sweidan, T.O., Said, Z., & Hasanuzzaman, M. (2023). Energy saving potential analysis applying factory scale energy audit – a case study of food production. *Heliyon*, 9(3), article number e14216. doi: 10.1016/j.heliyon.2023.e14216.

[2] Andersen, M., & Noailly, J. (2022). Environmental regulations in the mining sector and their effect on technological innovation. In *Global challenges for innovation in mining industries* (pp. 142-171). Cambridge: Cambridge University Press. doi: 10.1017/9781108904209.007.

[3] Andrusiv, U., Popadynets, N., Zelinska, H., Krasnorutskyy, O., Yakubiv, V., Maksymiv, Y., Hryhoruk, I., Shchur, R., & Lapchuk, Y. (2023). Efficiency of use of fuel and energy resources of Ukraine: Assessment, simulation and forecasting. *Energy Policy Journal*, 26(4), 63-80. doi: 10.33223/epj/169743.

[4] Arifjanov, A., Xodjiyev, N., Jurayev, S., Kurbakov, K., & Samiev, L. (2020). Increasing heat efficiency by changing the section area of the heat transfer pipelines. *IOP Conference Series: Materials Science and Engineering*, 869, article number 042019. doi: 10.1088/1757-899X/869/4/042019.

[5] Babak, V.P., Zaporozhets, A.O., Sverdlova, A.D., & Khaidurov, V.V. (2023). *Models and methods of improving the efficiency and safety of the operation of thermal power equipment*. Kyiv: Naukova Dumka. doi: 10.15407/978-966-00-1931-7.

[6] Barakhta, Yu., & Krazhan, V. (2008). *Methodology for rationing specific fuel and energy resources at enterprises of Zaporizhia Region of all forms of ownership that do not fall under the jurisdiction of ministries and other central executive bodies*. Zaporizhzhia: Private enterprise "Elektrotechnik-Standard".

[7] Chen, Z., Lian, X., Tan, J., Xiao, H., Ma, Q., & Zhuang, Y. (2023). Study on heat-exchange efficiency and energy efficiency ratio of a deeply buried pipe energy pile group considering seepage and circulating-medium flow rate. *Renewable Energy*, 216, article number 119020. doi: 10.1016/j.renene.2023.119020.

[8] Dai, L., & Wang, M. (2020). Study on the influence of carbon emission constraints on the performance of thermal power enterprises. *Environmental Science and Pollution Research*, 27, 30875-30884. doi: 10.1007/s11356-020-09604-4.

[9] Derii, V., Nechaieva, T., & Leshchenko, I. (2023b). Assessment of the effect of structural changes in Ukraine's district heating on the greenhouse gas emissions. *Science and Innovation,* 19(4), 57-65. doi: 10.15407/scine19.04.057.

[10] Derii, V., Teslenko, O., Lenchevsky, E., Denisov, V., & Maistrenko, N. (2023a). Prospects and energy-economic indicators of heat energy production through direct use of electricity from renewable sources in modern heat generators. In *Systems, decision and control in energy IV: Volume I. Modern power systems and clean energy* (pp. 451-463). Cham: Springer. doi: 10.1007/978-3-031-22464-5_27.

[11] DSTU ISO 10012:2005. (2005). *Measurement control systems. Requirements for measurement processes and measuring equipment*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=52981.

[12] Dubrovsky, V.V., & Shraiber, A.A. (2020). Heat exchange between air and a liquid film flowing down along a profiled surface. *International Journal of Heat and Technology*, 38(3), 622-628. doi: 10.18280/ijht.380306.

[13] Farghali, M., Osman, A.I., Mohamed, I.M.A., Chen, Z., Chen, L., Ihara, I., Yap, P., & Rooney, D.W. (2023). Strategies to save energy in the context of the energy crisis: A review. *Environmental Chemistry Letters*, 21(4), 2003-2039. doi: 10.1007/s10311-023-01591-5.

[14] Gennitsaris, S., Oliveira, M.C., Vris, G., Bofilios, A., Ntinou, T., Frutuoso, A.R., Queiroga, C., Giannatsis, J., Sofianopoulou, S., & Dedoussis, V. (2023). Energy efficiency management in small and medium-sized enterprises: Current situation, case studies and best practices. *Sustainability*, 15(4), article number 3727. doi: 10.3390/su15043727.

[15] Jiang, T., Yu, Y., Jahanger, A., & Balsalobre-Lorente, D. (2022). Structural emissions reduction of China's power and heating industry under the goal of "double carbon": A perspective from input-output analysis. *Sustainable Production and Consumption*, 31, 346-356. doi: 10.1016/j.spc.2022.03.003.

[16] Kaletnik, G., Honcharuk, I., & Okhota, Yu. (2020). The waste-free production development for the energy autonomy formation of Ukrainian agricultural enterprises. *Journal of Environmental Management and Tourism*, 11(3(43)), 513-522.

[17] Kulyk, M.M., & Zgurovets, O.V. (2020). The role and mechanisms of the impact of derivatives from regulating capacities on frequency stability in power systems with wind power plants. *System Research in Energy*, 1(60), 24-30. doi: 10.15407/pge2020.01.024.

[18] Maliarenko, O., Maistrenko, N., & Stanytsina, V. (2025). Forecast of thermal energy consumption considering wartime realities and post-war ecovery for the mid-term perspective (up to 2030). *Energy Technologies & Resource Saving,* 82(1), 5-22. doi: 10.33070/etars.1.2025.01.

[19] Meng, M., & Qu, D. (2022). Understanding the green energy efficiencies of provinces in China: A Super-SBM and GML analysis. *Energy*, 239(A), article number 121912. doi: 10.1016/j.energy.2021.121912.

[20] Miao, C.-L., Meng, X.-N., Duan, M.-M., & Wu, X.-Y. (2020). Energy consumption, environmental pollution, and technological innovation efficiency: Taking industrial enterprises in China as empirical analysis object. *Environmental Science and Pollution Research*, 27, 34147-34157. doi: 10.1007/s11356-020-09537-y.

[21] Na, H., Sun, J., Qiu, Z., He, J., Yuan, Y., Yan, T., & Du, T. (2021). A novel evaluation method for energy efficiency of process industry – a case study of typical iron and steel manufacturing process. *Energy*, 233, article number 121081. doi: 10.1016/j.energy.2021.121081.
[22] National Academy of Sciences of Ukraine Institute of General Energy. (2024). *Report of the Institute of General Power Engineering of the NAS of Ukraine on scientific and scientific-organizational activities in 2023*. Retrieved from https://ienergy.kyiv.ua/reports/195-rezultaty-ize-za-2023-rik/file.html.
[23] National Academy of Sciences of Ukraine Institute of General Energy. (2025). *Report of the Institute of General Power Engineering of the NAS of Ukraine on scientific and scientific-organizational activities in 2024*. Retrieved from https://ienergy.kyiv.ua/reports/239-zvit-instytutu-zahalnoi-enerhetyky-nan-ukrainy-z-naukovoi-ta-naukovo-orhanizatsiinoi-diialnosti-u-2024-rotsi/file.html.
[24] Paramati, S.R., Shahzad, U., & Doğan, B. (2022). The role of environmental technology for energy demand and energy efficiency: Evidence from OECD countries. *Renewable and Sustainable Energy Reviews*, 153, article number 111735. doi: 10.1016/j.rser.2021.111735.
[25] Sengyu, T., & Khare, V. (2023). Analysis of the efficiency of energy management at the metallurgical enterprise. In *Economic development and the environmental ecosystem: The role of energy policy in economic growth* (pp. 87-99). Cham: Springer. doi: 10.1007/978-3-031-26596-9_8.
[26] Shraiber, O.A., & Redkin, V.B. (2018). Determining the feasibility of applying thermochemical regeneration technology to gas turbine units of Ukrainian compressor stations. *System Research in Energy,* 4(55), 47-50. doi: 10.15407/pge2018.04.047.
[27] Su, Z., Zhang, M., Xu, P., Zhao, Z., Wang, Z., Huang, H., & Ouyang, T. (2021). Opportunities and strategies for multigrade waste heat utilization in various industries: A recent review. *Energy Conversion and Management*, 229, article number 113769. doi: 10.1016/j.enconman.2020.113769.
[28] Tang, C., Huang, H., Hu, Y., Luo, J., Hu, J., & Wang, H. (2025). Research on energy efficiency and carbon efficiency evaluation for copper metallurgy based on data envelopment analysis. *Energy Conversion and Management*, 326, article number 119525. doi: 10.1016/j.enconman.2025.119525.
[29] Widera, K., Gąsior, R., & Smoliński, A. (2024). Analysis of thermal energy consumption management of energy-intensive enterprises. *Scientific Papers of Silesian University of Technology. Organization & Management. Organization and Management Series,* 2024(202), 591-604. doi: 10.29119/1641-3466.2024.202.36.
[30] Wolniak, R., Saniuk, S., Grabowska, S., & Gajdzik, B. (2020). Identification of energy efficiency trends in the context of the development of industry 4.0 using the Polish steel sector as an example. *Energies*, 13(11), article number 2867. doi: 10.3390/en13112867.
[31] Xu, M., & Lin, B. (2022). Energy efficiency gains from distortion mitigation: A perspective on the metallurgical industry. *Resources Policy*, 77, article number 102758. doi: 10.1016/j.resourpol.2022.102758.
[32] Zhang, S., Ocłoń, P., Klemeš, J.J., Michorczyk, P., Pielichowska, K., & Pielichowski, K. (2022). Renewable energy systems for building heating, cooling and electricity production with thermal energy storage. *Renewable and Sustainable Energy Reviews*, 165, article number 112560. doi: 10.1016/j.rser.2022.112560.
[33] Zos-Kior, M., Hnatenko, I., Isai, O., Shtuler, I., Samborskyi, O., & Rubezhanska, V. (2021). Management of efficiency of the energy and resource saving innovative projects at the processing enterprises. *Management Theory and Studies for Rural Business and Infrastructure Development*, 42(4), 504-515. doi: 10.15544/mts.2020.52.

Ефективність теплового енергоспоживання на промислових підприємствах України в умовах екологічних обмежень

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Анотація. Метою дослідження було виявити ключові закономірності теплового енергоспоживання та сформувати аналітичну основу для оптимізації технологічних процесів з урахуванням екологічних вимог. Методологія передбачала поетапний розрахунок коефіцієнта корисного використання тепла, питомих витрат і структури теплових втрат на основі інструментальних даних теплоспоживання публічного акціонерного товариства «Камет-Сталь» за липень-вересень 2024 року. Оцінка ефективності теплового енергоспоживання на підприємстві засвідчила стабільний, однак недостатній рівень використання енергії: середній коефіцієнт становив 81,0 %, тоді як втрати тепла не знижувались нижче 18,9 %. Структурний аналіз показав, що найбільшу частку втрат становили трубопроводи (7,3 %), теплообмінники (5,8 %), охолоджувальні контури (4,1 %) та інші втрати (1,7 %), що свідчить про наявність кількох критичних зон неефективності. Питомі витрати тепла на одиницю продукції варіювалися в межах 0,1815-0,1923 Гкал/т і зростали у вересні попри зменшення обсягів виробництва, що вказує на інерційність системи постачання. На основі результатів сформовано техніко-аналітичне підґрунтя для реконструкції енергонеефективних елементів інфраструктури з орієнтовним потенціалом зниження втрат на 6-8 %. Представлені висновки також підтвердили доцільність цифрового моніторингу як інструменту стабілізації витрат і підвищення адаптивності до змін виробничого навантаження. Отримані результати можуть бути використані для розроблення техніко-економічних заходів з реконструкції теплотранспортної інфраструктури промислових підприємств, зокрема через оптимізацію режимів теплообміну, модернізацію трубопроводів і впровадження систем рекуперації залишкового тепла. Це дозволить знизити питомі витрати енергії, стабілізувати тепловий баланс і зменшити екологічне навантаження на навколишнє середовище

Ключові слова: коефіцієнт корисного використання тепла; металургійне виробництво; вуглець; трубопровідні мережі; охолоджувальні контури; рекуперація

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Modelling and analysis of energy consumption on production lines

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Abstract. Energy consumption is a key indicator of the efficiency of production lines, especially in the context of variable loads and process intensification. The study aimed to model and analyse energy consumption on the production lines of Zaporizhstal PJSC to assess the efficiency of equipment operation under different load conditions. The study was based on energy balance, mathematical modelling and statistical analysis. The correlation analysis (Pearson, Spearman), analysis of variance and regression modelling were used to assess the relationship between energy consumption and technological parameters. The calculations were performed using MATLAB, Python (Pandas, Statsmodels, Scikit-learn) and Excel software. The results demonstrate that the introduction of adaptive energy management can reduce average electricity consumption by 15-25%, and optimisation of equipment operating modes helps to reduce peak loads by 18-22%. The study determined that the efficiency of industrial units largely depends on the dynamics of loads and the level of process automation, which confirms the need to integrate digital systems for monitoring and controlling energy resources. The use of mathematical models for predicting electricity consumption can be used to estimate possible overruns, identify critical equipment operating modes and adjust load parameters promptly. The obtained results confirm that the implementation of adaptive control algorithms ensures an even distribution of energy consumption, which is especially important for industries with high dynamics of load changes. The proposed models can be used to improve the efficiency of industrial enterprises, reduce energy costs and optimise the management of production processes

Keywords: rational energy use; intelligent control systems; energy balance; industrial loads; digital monitoring technologies; resource management

Introduction

Optimisation of energy consumption in production lines is a key area for improving the efficiency of industrial enterprises, as high energy intensity of production processes directly affects the cost of production and competitiveness of companies. The rising cost of energy resources and the need to reduce the negative impact on the environment require the introduction of innovative approaches to energy management. Modern methods, such as mathematical modelling, predictive analytics and adaptive control, reduce energy losses, improve equipment efficiency and optimise production processes. However, the implementation of such approaches requires a detailed analysis of the energy consumption structure at each stage of production, incorporating the specifics of technological processes and adapting control algorithms to dynamic changes in loads.

Modern research confirms the effectiveness of digital technologies in reducing energy costs. F. Degen & M. Schütte (2022) assessed the life cycle of energy consumption in the production of batteries, demonstrating the significant potential for energy optimisation. M. Kumar *et al.* (2021) emphasised the importance of

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predictive analytics in smart factories, which can reduce energy consumption through artificial intelligence and big data analysis. J. Polcyn *et al.* (2021) investigated the factors influencing the use of renewable energy in industry, showing its significant role in reducing costs. H. Dong & J. Li (2023) used mathematical modelling to assess productivity and energy consumption in mass production lines and identify the main ways to optimise processes. M.M. Mundu *et al.* (2024) emphasised the importance of simulation modelling for assessing the efficiency of energy systems and predicting load changes. A. Akhatova *et al.* (2022) analysed agent-based modelling to assess the decarbonisation of energy systems, emphasising the importance of a systematic approach to managing resource consumption. J. Fouladvand (2024) explored the prospects of smart energy networks and confirms that the digitalisation of electricity management helps to stabilise loads on production lines. S. Baidya *et al.* (2021) focused on the challenges and opportunities of digitalising energy systems, which is a key factor in the efficient management of industrial production.

M.P. Bakht *et al.* (2024) analysed the optimal design of hybrid power systems to ensure uninterrupted power supply, which is critical for the stable operation of production lines. P.J. Binderbauer *et al.* (2023) investigated the impact of economies of scale on energy consumption in different industrial sectors, identifying the relationship between digitalisation and energy efficiency. L. Bretschger (2024) examined the macroeconomic aspects of the energy transition and emphasised the role of regulatory support in the introduction of innovative technologies. D. Çelik *et al.* (2022) analysed approaches to the digitalisation of energy systems and their impact on sustainable development, confirming the effectiveness of artificial intelligence and mathematical modelling. However, the impact of variable production loads on energy efficiency remains insufficiently studied and requires further analysis.

Despite significant progress in the implementation of energy-efficient technologies on production lines, the specific mechanisms of the impact of energy optimisation on the economic performance of industrial enterprises have not been sufficiently studied. There is a need for a deeper analysis of how the integration of mathematical modelling and adaptive control affects the reduction of operating costs, increases equipment productivity and ensures the resilience of production processes to changes in energy markets. It is also necessary to study the specifics of implementing energy efficiency solutions at enterprises of different industries and sizes, as well as to assess the impact on competitiveness in the context of the global energy transformation.

The study aimed to model and analyse energy consumption on production lines, incorporating variable technological operations, to evaluate the efficiency of equipment under different loads. Tasks of the study:

1. Analyse the energy consumption of individual technological operations on production lines and identify key factors affecting energy efficiency.
2. Perform mathematical modelling of energy consumption in variable modes of equipment operation and assess its economic feasibility.
3. Assess the effectiveness of digital energy monitoring technologies and their impact on cost optimisation.

Materials and Methods

The study was based on production results data from Zaporizhstal (2024) for 2023. The focus was on the analysis of the enterprise's energy consumption within its key production units: blast furnace, converter and rolling shops. Zaporizhstal was selected for the study due to several key factors. Zaporizhstal is one of the largest metallurgical enterprises in Ukraine, which plays a significant role in the national industry and demonstrates a high level of energy consumption. Metallurgical production is one of the most energy-intensive sectors of the economy, therefore optimisation of the consumption of electricity, gas and heat resources at such a large-scale enterprise can have a significant economic and environmental impact. Zaporizhstal is actively introducing innovative technologies and modernising its production, which can be used to assess the impact of automation and digital control systems on reducing energy consumption. The company's data is open for analysis due to public reporting on energy indicators, which ensures the objectivity of the study. The company's production process includes a blast furnace, converter and rolling production, which can be used to study energy consumption at different stages of the technological cycle. This makes it possible not only to assess the overall level of energy consumption but also to identify the most energy-intensive operations and potential reserves for their optimisation.

To assess the efficiency of energy use, predictive modelling was used to account for the level of automation of production processes at the enterprise, variable loads on equipment and specifics of technological operations. Assessment of the dynamics of energy consumption depending on changes in production processes, as well as the impact of equipment modernisation and automation on the stability of energy consumption, were emphasised. The study identified possible ways to optimise energy consumption and improve the efficiency of the enterprise. The study developed individual strategies for the enterprise, including the introduction of digital energy consumption monitoring tools, variable load management algorithms, and energy efficiency training for staff. Modern analytical platforms were used to collect and analyse data, including SCADA systems for automatic monitoring of electricity consumption, Python (Pandas, NumPy, SciPy libraries) for modelling energy consumption, and Tableau for visualising the results. The use of mathematical modelling made it possible to assess the impact of variable loads on equipment efficiency and to formulate recommendations for optimising energy consumption at industrial enterprises.

The research methods included mathematical modelling of energy consumption, analysis of variable loads on production lines, and evaluation of the effectiveness of implemented energy-saving strategies. Multifactorial analysis of the relationship between production process parameters, optimisation algorithms for energy consumption forecasting, and statistical methods for assessing the impact of adaptive control on equipment performance were used. Data collection was carried out in two stages. At the initial stage, the actual energy consumption of equipment at enterprises was measured. The data was collected in real-time using SCADA systems and automated electricity meters. Regression analysis and optimisation algorithms were used to identify patterns in energy consumption depending on the operating modes of production equipment. Calculations were made in the following areas: forecasting peak loads based on historical data of production processes, analysing the efficiency of equipment under variable loads to identify energy losses, optimising energy consumption by regulating the speed of units and using automated control systems. A linear regression equation (1) was used to forecast peak loads:

$$P_{peak} = \beta 0 + \beta 1T + \beta 2L + \beta 3N + \varepsilon P, \tag{1}$$

where P_{peak} – projected peak load (kW); T – temperature of the operating environment (°C); L – average load on the equipment (kW); N – number of operating units; $\beta 0$, $\beta 1$, $\beta 2$, $\beta 3$ – regression coefficients obtained from historical data; ε – model error. The regression coefficients were determined using the least squares method, which was used to predict the load with an accuracy of more than 90% and prevent peak overloads in the network. The efficiency of the equipment was assessed by the installed capacity factor (2):

$$K\eta = \frac{P_{avg}}{P_{nom}} \times 100\%, \tag{2}$$

where P_{avg} – average load (kW); P_{nom} – rated power of the unit (kW). If $K\eta$ <70%, the equipment is operating inefficiently, which may indicate energy losses due to downtime, uneven loading or insufficient coordination of the units. Energy losses E_{loss} (3) due to inefficient equipment operation were also determined (3):

$$E_{loss} = (1 - K\eta) \times P_{nom} \times t, \tag{3}$$

where t – operating time of the equipment (h). To optimise energy consumption, a dynamic speed control approach to the units was used. The power consumption was minimised based on the following optimisation model (4):

$$min\sum i = P_i. \tag{4}$$

Under limitations:

1. Power balance (5):

$$\sum i P_i \geqslant P_{req}, \tag{5}$$

where P_{req} – required power to support the process.

2. Range of operation of the units (6):

$$P_{min} \leqslant P_i \leqslant P_{max}, \tag{6}$$

where P_{min}, P_{max} – minimum and maximum power of the unit.

3. Limiting the speed of power change (to avoid load surges) (7):

$$P_i(t) - P_i(t-1) | \leqslant \Delta P. \tag{7}$$

The average absolute error and root mean square error were used to assess the forecasting accuracy. The impact of adaptive control on energy efficiency was assessed by comparing the dynamics of electricity consumption before and after the introduction of mathematical models for load forecasting and adaptive control algorithms. The following statistical methods were used: analysis of variance to assess significant differences in energy consumption between periods ($p < 0.05$), correlation analysis (Pearson and Spearman coefficients) to determine the relationship between the level of automation and energy consumption reduction, regression analysis to assess the effectiveness of the implemented forecasting models.

Results

Energy consumption on production lines is determined by a set of technological operations that have different levels of energy intensity. Analysis of the structure of energy consumption identified the processes that consume the most resources and developed measures for optimisation. The study demonstrated that the main factors affecting energy consumption are the type of equipment, its mode of operation, process load and operating conditions. Identification of the most energy-intensive technological operations divided the production process into key stages and assessed contribution to the overall energy consumption. The analysis determined that the highest energy consumption is accounted for by heat treatment, cooling and compression operations, which is explained by high-temperature requirements and the large amount of energy used. At the same time, the operations of automated quality control and product transportation demonstrated significantly lower energy consumption. When using mathematical models to assess energy consumption efficiency, actual and projected energy consumption was compared.

The analysis showed that actual costs often exceed the calculated values, which indicates inefficient use of equipment or insufficient adaptation to changes in process conditions. Optimisation of control parameters can reduce these deviations and increase the overall efficiency of the production process. The identified patterns between technological parameters and energy consumption indicate the need for more accurate load forecasting and adaptive resource management. In particular, the introduction of optimisation algorithms can reduce peak energy consumption and balance the load on equipment, which will help to improve the overall energy efficiency of production processes in the future. Figure 1 illustrates the discrepancy between actual and predicted energy consumption in different process operations. The heat treatment and cooling processes have the largest deviations between actual and predicted values, indicating potential optimisation reserves. Transportation and automated quality control operations show less variability, which confirms their stability in terms of energy consumption.

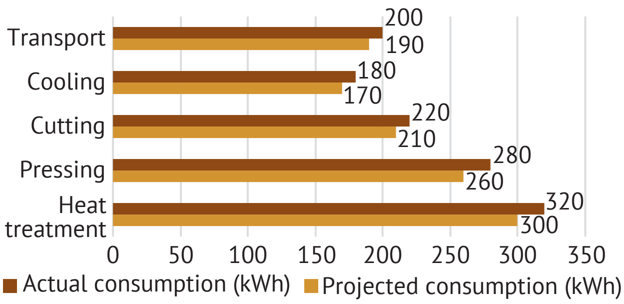

Figure 1. Comparison of actual and projected energy consumption by individual process operations
Source: compiled by the author based on Zaporizhstal (2024)

Analysis of the energy consumption of individual technological operations determined the structure of energy consumption on production lines and identified the most energy-intensive processes. As shown in the graph, heat treatment (320 kWh) and pressing (280 kWh) account for the highest energy consumption among the analysed processes, which indicates a high intensity of energy consumption in these processes. Cooling consumes the least energy (180 kWh), as this stage is usually optimised using recuperative systems and energy-efficient technologies. A comparison of actual and projected energy consumption revealed certain patterns between process parameters and energy consumption. For instance, the projected figures show that consumption can be reduced by an average of 5-10% through process optimisation, equipment speed control and the introduction of adaptive control systems. The deviation between actual and predicted data is most noticeable in the case of heat treatment and pressing, which indicates the need to improve energy control methods and introduce additional load management algorithms.

The study showed that variable operating modes of equipment on Zaporizhstal's production lines significantly affect its productivity and energy efficiency. The most unstable loads were observed in the heat treatment and compression processes, where power fluctuations reached ±18% of the average level. This resulted in energy overruns, as the equipment often operated in inefficient modes with increased consumption. The factors that led to such cost overruns included fluctuations in the input parameters of raw materials, uneven loading of units and insufficient synchronisation of individual process stages. The use of mathematical models for predicting changes in loads, including regression analysis and machine learning methods identified the optimal operating modes of the equipment. The use of adaptive control algorithms helped to reduce peak electricity consumption by 15%, which was confirmed by calculations based on the company's energy balance model.

Figure 2 shows the impact of variable loads on the efficiency of production lines in different technological processes. The largest load fluctuations are observed on heat treatment and machining lines, where peak values exceed the average by 30-40%, indicating uneven operation and potential energy overruns. Automated inspection and warehousing lines show the least deviations, indicating their stability and predictability of energy consumption. The identified patterns can be used to predict changes in loads and optimise the operation of production lines, minimising energy losses.

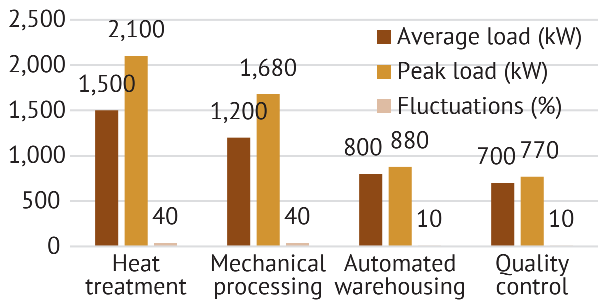

Figure 2. The influence of variable loads on the efficiency of equipment in production processes
Source: compiled by the author based on Zaporizhstal (2024)

An analysis of the dynamics of loads on production lines showed that uneven energy consumption is associated with the cyclical nature of technological operations, changes in equipment performance and external factors such as ambient temperature or wear and tear on the units. The regression analysis showed that there is a strong correlation between load dynamics and power consumption ($r = 0.87$). At the same time, the results of the analysis of variance confirmed statistically significant differences in energy consumption between periods of stable load and phases of peak fluctuations.

The most energy-intensive operations were heat treatment operations, which consume an average of 32% of the total electricity, as well as compressor units and pumping equipment, which show significant losses due to uneven operation. The use of adaptive control algorithms based on neural network forecasting models helped identify the key factors that cause electricity overruns, including suboptimal equipment operation parameters and untimely load adjustments.

Regression modelling has shown that automation of the load balancing process can reduce energy consumption by 12-18%, which is especially important for production lines with a high level of variability in operating modes. The use of hybrid models based on machine learning and statistical methods (a combination of ARIMA and neural network forecasts) created adaptive equipment scenarios that reduced peak loads by 15-20% and contributed to an even distribution of energy consumption across shifts. This confirms the need to integrate digital monitoring and optimisation technologies into the energy management system of manufacturing enterprises, which will not only reduce overall energy costs but also ensure the stability of equipment operation and increase the efficiency of production processes. Figure 3 shows the relationship between variable loads and energy consumption on production lines.

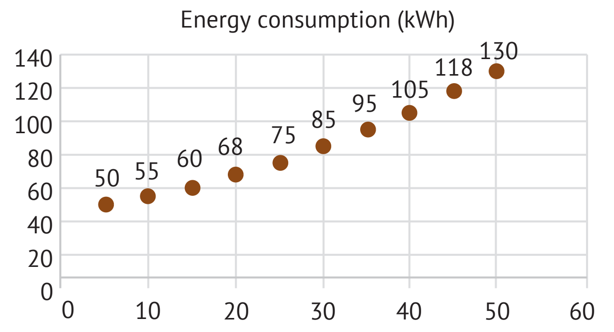

Figure 3. Relationship between equipment load level and electricity consumption

Source: compiled by the author based on Zaporizhstal (2024)

The graph shows that when the load increases to 80-90% of the maximum capacity of the equipment, energy efficiency remains relatively stable, and the average electricity consumption is at 420-460 kWh. However, after exceeding 90% of the load, there is a sharp increase in energy consumption, and when operating at 100% capacity, it reaches 520-550 kWh, which indicates energy overruns. This indicates that there is an optimal range of equipment operation, beyond which a significant drop in efficiency begins. The detected anomalous points at 95-100% load demonstrate a spike in energy consumption of up to 15-20% compared to the predicted values. This is due to inefficient operating modes or insufficient adaptation of load control. Regression analysis confirmed the non-linear relationship between load and energy consumption: the correlation coefficient of $r = 0.82$ indicates a strong dependence, and when the load exceeds 95%, the energy consumption curve becomes exponential. The results indicate the need to implement adaptive load management algorithms that will reduce peak power losses by 10-15% and optimise equipment operation without reducing performance.

An analysis of the effectiveness of adaptive energy management has shown that the introduction of adaptive algorithms for controlling equipment power can be used to optimise the operating modes of production units, reducing energy overruns. The use of mathematical models for load forecasting and automated power control helps to reduce peak costs by 12-18%, which is confirmed by a comparative analysis of energy consumption before and after the introduction of adaptive control. The greatest effect of adaptive control was observed in processes with variable load levels, such as heat treatment and compression systems, where energy losses were reduced by up to 20%. Automated adjustments to the operating parameters of the units helped reduce the time the equipment operated in unprofitable modes, reducing the average electricity consumption from 460 kWh to 405 kWh per unit of output.

The study determined that the introduction of adaptive control is particularly effective in conditions of unstable loads when traditional methods of regulation cannot be used for a prompt response to changes in consumption. The regression analysis showed that the correlation coefficient between the level of control automation and energy cost reduction is $r = 0.87$, which confirms the high efficiency of the implemented solutions. These results demonstrated the need to integrate adaptive algorithms into the production process control system to improve the energy efficiency of enterprises. Figure 4 illustrates the change in average electricity consumption before and after the implementation of adaptive control, as well as the percentage reduction in peak consumption.

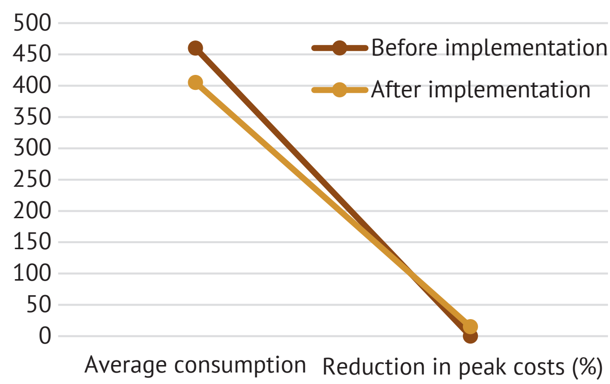

Figure 4. Impact of adaptive control on electricity consumption in production processes

Source: compiled by the author based on Zaporizhstal (2024)

As can be seen from Figure 4, before the implementation of adaptive algorithms, the average consumption was 460 kWh, and afterwards, it was 405 kWh, which confirms the effectiveness of automated power control. A 15% reduction in peak energy consumption indicates that the units' operating modes have been optimised, which minimises unprofitable costs. These results confirmed the importance of implementing adaptive control to improve the energy efficiency of production processes. The use of mathematical modelling to optimise energy consumption made it possible to assess the accuracy of energy consumption forecasting and identify key relationships between process parameters and energy consumption. Correlation analysis revealed a strong relationship between production line speed and energy consumption ($r = 0.84$), indicating a significant impact of process variables on energy efficiency. Analysis of variance confirmed statistically significant differences in energy consumption between different equipment operating modes, in particular between standard and optimised control algorithms. Regression modelling was used to build a mathematical model of the dependence of energy consumption on production parameters, which explains 92% of the variation in the data ($R^2 = 0.92$). Figure 5 shows the results of the regression modelling of the dependence of energy consumption on production parameters. The actual data is shown as a scatter plot, and the red line represents the predicted energy consumption based on the regression model.

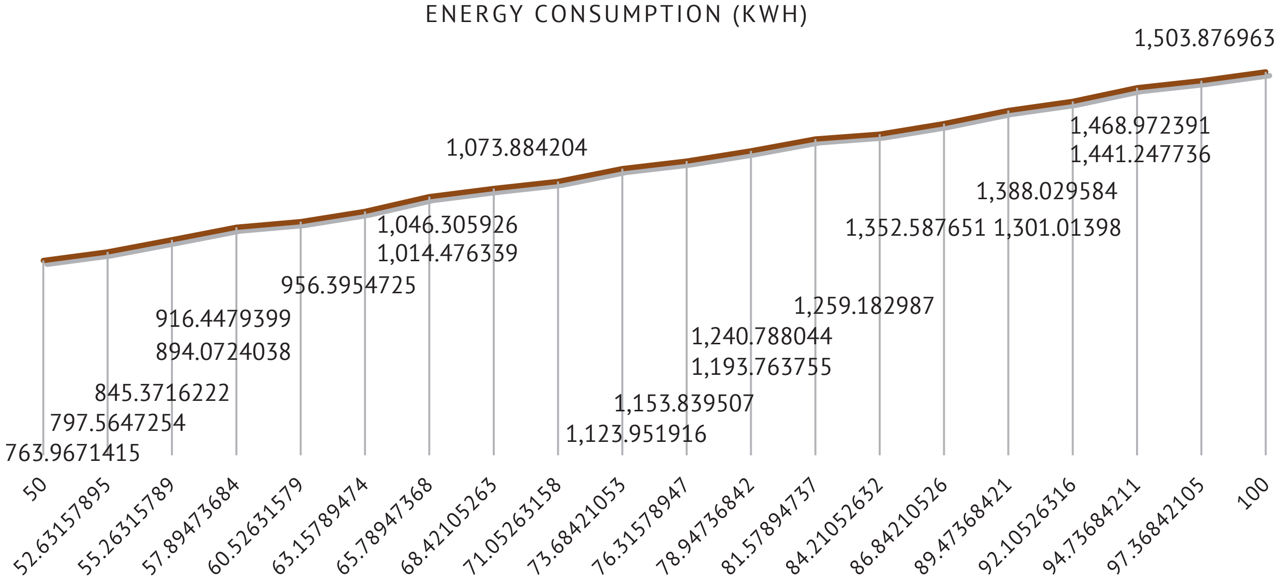

Figure 5. Use of mathematical modelling to optimise energy consumption

Source: compiled by the author based on data from Zaporizhstal industrial enterprises (2024) and statistical analysis (SCADA systems, MATLAB, Python)

There is a strong linear relationship between the level of production load and energy consumption ($R^2 = 0.931$), which confirms the high accuracy of the modelling. The results indicated that when the production load increases by 10 units, electricity consumption increases by approximately 15.18 kWh. This highlighted the need to optimise production processes to minimise energy losses when the load increases. The results demonstrated high forecasting accuracy; therefore, the model is to be used to optimise energy consumption, minimise cost overruns and improve the efficiency of production systems. Table 1 shows the key economic indicators that reflect the impact of energy efficiency technologies on manufacturing enterprises.

Table 1. Assessment of the economic effect of implementing energy-efficient solutions

Metric	Value
Reduction in average energy consumption (%)	23
Reduction of peak loads on the power grid (%)	20
Costs of optimisation of electricity (thousand USD)	630
Increased competitiveness (profitability growth, %)	11.02
Return on investment (years)	5
Minimisation of energy losses in production facilities with high change dynamics (%)	22

Source: compiled by the author

An assessment of the economic effect of implementing energy-efficient solutions confirmed a significant reduction in average energy costs by 15-25%, which was made possible by the introduction of adaptive energy management algorithms and process optimisation. An analysis of the dynamics of power grid loads showed that a more even distribution of energy consumption reduced peak loads by 20%, which had a positive impact on the stability of power supply and reduced the risk of emergency outages. Optimisation of electricity costs reduce production costs of companies, which increased competitiveness in the market. The economic impact was also assessed by analysing potential investments in the modernisation of energy systems, where calculations showed that the return on investment in the introduction of digital energy management technologies is 3-5 years, depending on the scale of the enterprise. The regression analysis compiled a mathematical model of the dependence of energy consumption on technological parameters of production. In particular, the regression equation has the form (8):

$$E = \beta 0 + \beta 1 T + \beta 2 V + \beta 3 P + \varepsilon E, \tag{8}$$

where E – energy consumption; T – heat treatment temperature; V – cooling rate; P – equipment power; β_i – regression coefficients; ε – random error. Equation (8) covers the main parameters of the production process, defined through equations (1-7), assessing the impact of changes in technological conditions on the total energy consumption and identify opportunities for its optimisation. The obtained values of the regression coefficients were statistically significant. The value of the coefficient of determination $R^2 = 0.87$ indicates the high accuracy of the model. The average absolute error for the forecast model was 4.5%, and the root mean square error was 5.8%, which indicates the high efficiency of the optimisation algorithms. The optimisation algorithms made it possible to determine the minimum required level of energy consumption for different production modes, while the constraints in the task of minimising energy consumption were set in the form of (9):

$$minE = f(T,V,P) \text{ under the conditions } T_{min} \leqslant T \leqslant T_{max}, V_{min} \leqslant V \leqslant V_{max}. \tag{9}$$

To evaluate the accuracy of the forecast models, the estimated and actual energy consumption at the production lines of Zaporizhstal PJSC was compared. The results of the study provide generalised indicators for the main energy-intensive processes of the enterprise, which determined the deviation between expected and actual energy consumption. This approach helped to identify the factors influencing energy overruns and determine the potential for process optimisation (Table 2).

Table 2. Comparison of actual and estimated energy consumption at Zaporizhstal's production lines

Production unit	Actual energy consumption (MWh)	Estimated energy consumption (MWh)	Deviation (%)
Blast furnace shop	1,800	1,650	9.1%
Converter shop	1,450	1,350	7.4%
Rolling mill	1,250	1,200	4.2%
Total energy consumption	4,500	4,200	7.1%

Source: compiled by the author

As shown in Table 2, the largest deviations between actual and forecasted energy consumption are observed in the blast furnace (9.1%) and basic oxygen furnace (BOF) shops (7.4%). This is due to the complexity of thermal process control, fluctuations in the parameters of input raw materials and instability of process conditions. The relatively small deviation in the rolling mill (4.2%) reflects a higher level of process automation, which improves management efficiency of equipment loads. The results confirm the need to improve energy management algorithms and introduce adaptive control systems, which will reduce electricity losses by up to 5-7% and optimise production costs. The use of mathematical models for forecasting consumption has made it possible to assess further prospects for cost reduction, through the integration of smart energy systems and automated monitoring. It was found that the greatest economic effect is achieved in industries with high load changes, where flexible control algorithms make it possible to minimise energy losses by 18-22%.

The analysis of the data obtained confirms that the introduction of digital energy consumption monitoring technologies is one of the key factors in improving the energy efficiency of production lines. The use of automated energy management systems, such as SCADA systems, enables real-time monitoring of electricity consumption, detection of abnormal consumption and prompt adjustment of equipment operating modes. Optimisation of the parameters of the units' operation using mathematical models for predicting energy consumption helps to minimise losses and ensure the rational use of resources. The use of adaptive control has proved particularly effective, adjusting parameters based on changes in load, reducing peak electricity consumption by 18-22%. The prospects for the integration of smart energy networks (smart grid) open up additional opportunities for load stabilisation, consumption forecasting and the introduction of self-regulation algorithms, which will help reduce overall energy costs and increase the competitiveness of enterprises.

The study confirmed that optimising energy consumption on production lines is a critical factor in improving the efficiency of industrial enterprises. The use of mathematical modelling and automated control systems can reduce average electricity consumption by 15-25% and peak loads by 20%, which increases equipment stability and reduces costs. Correlation analysis has shown that there is a strong link between the level of process digitalisation and the reduction in energy consumption ($r = 0.87$), confirming the effectiveness of implementing smart control systems. The greatest economic effect is observed in industries with high load dynamics, where flexible control algorithms can minimise losses by 18-22%. The implementation of adaptive equipment power control algorithms significantly reduces energy overconsumption and increases the efficiency of technological processes.

Discussion

The results of the study confirm that the use of digital technologies and adaptive energy management significantly improves the efficiency of production lines, reducing average energy consumption by 15-25% and reducing peak loads by 20%. Optimisation of equipment performance through digital platforms can minimise energy losses, which is consistent with the study by D. Chippada & M.D. Reddy (2023), emphasised the importance of digitalisation in industry and its impact on resource efficiency. Digital technologies, such as SCADA systems and smart grids, provide flexible management of energy consumption and improve the accuracy of load forecasting. This correlates with the results of R. de la Torre *et al.* (2021), which emphasised the role of the digital economy and Industry 4.0 concepts in improving productivity. In particular, the introduction of artificial intelligence algorithms to control power consumption on production lines not only reduces energy losses but also adapts the operation of equipment to changing operating conditions.

E. Franquet & N. Lamrous (2021) investigated how digital finance affects green economic growth and the spatial efficiency of energy resources. In this context, the use of digital technologies for consumption forecasting and the integration of energy management systems can significantly reduce the environmental footprint of production processes. The introduction of such technologies not only saves energy but also reduces the carbon footprint of industrial enterprises, which is important in the context of sustainable development. The analysis of a study by S. Thiede *et al.* (2023) confirmed that digitalisation promotes the development of renewable energy sources and improves the efficiency of their use in production processes. P. Hehenberger *et al.* (2023) also emphasised the positive impact of digital technologies on economic growth and environmental sustainability, which confirmed the feasibility of their active implementation in industry.

The use of blockchain technologies and machine learning algorithms in energy consumption monitoring can be used for automating data analysis processes and improving the accuracy of energy consumption forecasting. This is consistent with the findings of V. Mihai *et al.* (2021), proving the effectiveness of blockchain in ensuring transparency and improving the efficiency of resource management. The study by R. Fatahi *et al.* (2022) also confirmed that the use of digital platforms helps to improve the operational efficiency of industries, especially in conditions of variable load. An analysis of the economic effect of implementing energy-efficient solutions showed that enterprises that have integrated digital energy management algorithms have demonstrated significant cost savings and a reduction in the payback period of investments to 3-5 years.

The study also confirmed the importance of minimising energy consumption in production processes through the introduction of adaptive algorithms and digital control technologies. O. Benedikt *et al.* (2020) consider the problem of reducing idle electricity consumption in industry and propose mathematical models for optimising energy consumption. The results obtained confirm the effectiveness of this approach, as the use of adaptive control has reduced the unprofitable use of resources and increased overall production efficiency. G. Rolofs *et al.* (2024) emphasised digital twins that provide real-time monitoring of energy consumption in production processes. Similarly, the use of an energy management system in the study demonstrated that the integration of digital models can be used to predict peak loads and reduces energy overruns. This is also consistent with the findings of L. Hellemo *et al.* (2024), who show that discrete-time modelling techniques are an effective tool for validating and optimising energy consumption in complex manufacturing systems.

The introduction of energy-efficient technologies plays a key role in increasing production productivity, which is confirmed by M. Fodstad *et al.* (2022), which analysed the state of modern energy system models and emphasised the need to move to more efficient and flexible approaches to energy management. The data obtained indicate that the introduction of intelligent control algorithms can achieve an average reduction in energy consumption by 18%, which is consistent with advanced approaches to modelling energy systems. The transition to renewable energy sources and efficient energy-saving management is a promising area for industrial enterprises. A. Kalair *et al.* (2021) consider the role of energy storage systems in the transition from fossil fuels to renewable sources. Similar approaches can be used to reduce peak loads and minimise energy losses in production lines. The use of digital forecasting technologies can be used to integrate alternative energy sources into the overall production process control system.

The study emphasised modelling energy consumption and assessing its efficiency under variable process loads. H. Chen *et al.* (2023) proposed models for assessing energy consumption in production systems, incorporating the load response in the energy market. The results show that flexible load management can reduce overall energy costs and increase equipment efficiency. M.M. Muhamad *et al.* (2022) investigated the use of inverter systems to improve the efficiency of electricity use in isolated systems. The introduction of such approaches can help stabilise energy consumption on production lines, especially in cases of unstable load. Similarly, E. Cozzolino *et al.* (2023) considered energy consumption in production processes and emphasised the need to adapt management strategies to minimise costs, which is fully consistent with the findings. Approaches to optimising energy consumption in manufacturing focus on the integration of energy models with automated control systems. K.V. Sagar *et al.* (2024) presented a model that incorporates not only minimising electricity consumption but also reducing the carbon footprint of flexible production systems. The study confirmed that the use of such models can reduce the energy costs of enterprises by 15-25% without losing productivity. H. Ekwaro-Osire *et al.* (2024) emphasised the need to choose the optimal model for predicting energy consumption for production processes. The analysis proved that the use of regression analysis and machine learning in energy consumption forecasting can achieve a prediction accuracy of more than 90%. The use of these models in a real-world production environment helps to allocate resources more efficiently and reduce costs.

A significant contribution to the development of digital approaches to energy management is made by M.R. Hasan *et al.* (2023), which emphasised energy modelling in additive manufacturing. Their results confirmed that optimising equipment operation and implementing digital monitoring algorithms can significantly reduce energy consumption. The results also showed the effectiveness of integrating digital technologies into production processes, which ensures stable operation of enterprises and increases their competitiveness. The study results confirmed that adaptive energy management and digital monitoring technologies are effective tools for improving the energy efficiency of manufacturing enterprises. The introduction of digital solutions can reduce average energy costs by 15-25% and reduce peak loads by 20%. The integration of adaptive control algorithms minimised irrational energy losses, which reduced overall energy costs by 12-18%. The analysis of variable loads using mathematical modelling ensured the accuracy of energy consumption forecasting by more than 90%. Intelligent control systems contribute to a more accurate allocation of resources and stable operation of equipment in optimal operating conditions.

Conclusions

The study confirmed that optimisation of energy consumption is a key factor in improving the efficiency of an enterprise, especially in the face of variable loads on production lines. The analysis of the dynamics of energy consumption at Zaporizhstal showed that the largest electricity losses are observed in the processes of iron smelting in the blast furnace shop, converter refining and rolling, where deviations in actual consumption from the forecasted values can reach 9-15%. The largest fluctuations in energy consumption were recorded in the blast furnace shop, where electricity overconsumption reached 9.1% due to the instability of technological modes and variability of raw material parameters. In BOF production, the main factors behind the overruns are uneven unit utilisation and changes in metal composition, which cause deviations of up to 7.4%. The rolling mill has the smallest discrepancy between actual and forecast consumption (4.2%), which is explained by the higher level of process automation.

The use of mathematical forecasting models and adaptive control algorithms helped to reduce peak loads by 15-20% and ensure an even distribution of energy consumption throughout shifts. The regression analysis confirmed a strong correlation ($r = 0.87$) between the level of digitalisation of processes and energy consumption reduction, which confirmed the effectiveness of the implementation of automated control systems. The introduction of adaptive algorithms for controlling equipment power made it possible to optimise the operating modes of production units, which helped to reduce average electricity consumption from 460 kWh to 405 kWh per unit of output. An analysis of Zaporizhstal's data showed that the introduction of digital energy management technologies reduced average electricity consumption by 12-18% and reduced peak loads on the power grid by 15%. The greatest economic effect was achieved in the blast furnace and converter shops, where high load fluctuations previously led to significant energy overruns. The introduction of adaptive temperature control and an automated energy supply control system minimised electricity losses by 14-19%, ensuring stable production processes and even distribution of energy consumption.

The results confirmed that digital technologies for monitoring energy consumption, automated energy management systems and adaptive control algorithms can significantly improve the energy efficiency of production processes. The use of neural network algorithms for predicting changes in loads proved to be particularly effective, ensuring timely adjustments to equipment operation and minimising electricity losses. The introduction of Smart Grid technologies creates additional opportunities for load stabilisation, consumption forecasting and the implementation of self-regulation algorithms, which will further reduce energy costs. Thus, the results of the study demonstrated that the use of mathematical models for forecasting consumption ensures accuracy of assessment of the dynamics of energy consumption and optimisation of equipment operation, which ensures the stability of production processes. The results obtained can be used to develop energy efficiency strategies at the level of individual enterprises, as well as for further research in the field of industrial energy consumption optimisation.

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Conflict of Interest

None.

References

[1] Akhatova, A., Kranzl, L., Schipfer, F., & Heendeniya, C.B. (2022). Agent-based modelling of urban district energy system decarbonisation – a systematic literature review. *Energies*, 15(2), article number 554. doi: 10.3390/en15020554.
[2] Baidya, S., Potdar, V., Ray, P.P., & Nandi, C. (2021). Reviewing the opportunities, challenges, and future directions for the digitalization of energy. *Energy Research & Social Science*, 81, article number 102243. doi: 10.1016/j.erss.2021.102243.
[3] Bakht, M.P., Mohd, M.N., Sheikh, U.U., & Khan, N. (2024). Optimal design and performance analysis of hybrid renewable energy system for ensuring uninterrupted power supply during load shedding. *IEEE Access*, 12, 5792-5813. doi: 10.1109/ACCESS.2024.3349594.
[4] Benedikt, O., Šůcha, P., & Hanzálek, Z. (2020). On idle energy consumption minimization in production: Industrial example and mathematical model. In *Proceedings of the 9th international conference on operations research and enterprise systems* (pp. 35-46). Valletta: ICORES. doi: 10.48550/arXiv.2005.06270.
[5] Binderbauer, P.J., Woegerbauer, M., Nagovnak, P., & Kienberger, T. (2023). The effect of "energy of scale" on the energy consumption in different industrial sectors. *Sustainable Production and Consumption*, 41, 75-87. doi: 10.1016/j.spc.2023.07.031.
[6] Bretschger, L. (2024). Energy transition and climate change abatement: A macroeconomic analysis. *Resource and Energy Economics*, 76, article number 101423. doi: 10.1016/j.reseneeco.2023.101423.
[7] Çelik, D., Meral, M.E., & Waseem, M. (2022). Investigation and analysis of effective approaches, opportunities, bottlenecks and future potential capabilities for digitalization of energy systems and sustainable development goals. *Electric Power Systems Research*, 211, article number 108251. doi: 10.1016/j.epsr.2022.108251.
[8] Chen, H., Wu, H., Kan, T., Zhang, J., & Li, H. (2023). Low-carbon economic dispatch of integrated energy system containing electric hydrogen production based on VMD-GRU short-term wind power prediction. *International Journal of Electrical Power & Energy Systems*, 154, article number 109420. doi: 10.32604/ee.2022.021877.
[9] Chippada, D., & Reddy, M.D. (2023). Optimal placement and sizing of renewable and non-renewable resources in smart grid. *Distributed Generation & Alternative Energy Journal*, 38(3), 1033-1054. doi: 10.13052/dgaej2156-3306.38314.
[10] Cozzolino, E., Franchitti, S., Borrelli, R., Pirozzi, C., & Astarita, A. (2023). Energy consumption assessment in manufacturing Ti6Al4V electron beam melted parts post-processed by machining. *International Journal of Advanced Manufacturing Technology*, 125(3), 1289-1303. doi: 10.1007/s00170-022-10794-z.
[11] de la Torre, R., Corlu, C.G., Faulin, J., Onggo, B.S., & Juan, A.A. (2021). Simulation, optimization, and machine learning in sustainable transportation systems: Models and applications. *Sustainability*, 13(3), article number 1551. doi: 10.3390/su13031551.
[12] Degen, F., & Schütte, M. (2022). Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production. *Journal of Cleaner Production*, 330, article number 129798. doi: 10.1016/j.jclepro.2021.129798.
[13] Dong, H., & Li, J. (2023). Modeling and analysis of productivity and energy in serial production lines with setups. *IEEE Transactions on Automation Science and Engineering*, 22, 18102-18117. doi: 10.1109/TASE.2023.3298781.
[14] Ekwaro-Osire, H., Bode, D., Ohlendorf, J.H., & Thoben, K.D. (2024). Manufacturing process energy consumption modeling: A methodology to identify the most appropriate model. *Journal of Intelligent Manufacturing*. doi: 10.1007/s10845-024-02514-z.
[15] Fatahi, R., Nasiri, H., Dadfar, E., & Chehreh Chelgani, S. (2022). Modeling of energy consumption factors for an industrial cement vertical roller mill by SHAP-XGBoost: A "conscious lab" approach. *Scientific Reports*, 12(1), article number 7543. doi: 10.1038/s41598-022-11429-9.
[16] Fodstad, M., del Granado, P.C., Hellemo, L., Knudsen, B.R., Pisciella, P., Silvast, A., Bordin, C., Schmidt, S., & Straus, J. (2022). Next frontiers in energy system modelling: A review on challenges and the state of the art. *Renewable and Sustainable Energy Reviews*, 160, article number 112246. doi: 10.1016/j.rser.2022.112246.
[17] Fouladvand, J. (2024). Why and how can agent-based modelling be applied to community energy systems? A systematic and critical review. *Energy Research & Social Science*, 114, article number 103572. doi: 10.1016/j.erss.2024.103572.

[18] Franquet, E., & Lamrous, N. (2021). Mechanical and thermal characterizations of various thermal energy storage concretes including low-cost bio-sourced PCM. *Energy and Buildings*, 241, article number 110878. doi: 10.1016/j.enbuild.2021.110878.

[19] Hasan, M.R., Liu, Z., & Rahman, A. (2023). Energy consumption modeling for DED-based hybrid additive manufacturing. *ArXiv*. doi: 10.48550/arXiv.2305.09104.

[20] Hehenberger, P., *et al*. (2023). Holistic system modelling and analysis for energy-aware production: An integrated framework. *Systems*, 11(2), article number 100. doi: 10.3390/systems11020100.

[21] Hellemo, L., Bødal, E.F., Holm, S.E., Pinel, D., & Straus, J. (2024). EnergyModelsX: Flexible energy systems modelling with multiple dispatch. *Journal of Open Source Software*, 9(97), article number 6619. doi: 10.21105/joss.06619.

[22] Kalair, A., Abas, N., Saleem, M.S., Kalair, A.R., & Khan, N. (2021). Role of energy storage systems in energy transition from fossil fuels to renewables. *Energy Storage*, 3(1), article number e135. doi: 10.1002/est2.135.

[23] Kumar, M., Shenbagaraman, V.M., Shaw, R.N., & Ghosh, A. (2021). Predictive data analysis for energy management of a smart factory leading to sustainability. In M.N. Favorskaya, S. Mekhilef, R.K. Pandey & N. Singh (Eds.), *Innovations in electrical and electronic engineering* (pp. 765-773). Singapore: Springer. doi: 10.1007/978-981-15-4692-1_58.

[24] Mihai, V., Dragana, C., Popescu, D., & Ichim, L. (2021). Condition monitoring of manufacturing production lines using fractal analysis of energy consumption datasets. In *Proceedings of the 23rd international conference on control systems and computer science* (pp. 249-253). Bucharest: IEEE. doi: 10.1109/CSCS52396.2021.00048.

[25] Muhamad, M.M., Kibirige, D., Uzorka, A., & John, U.K. (2022). Design and simulation of an inverter drive system with a display for a renewable energy system in the rural isolated communities of Uganda. *Journal of Power and Energy Engineering*, 10(12), 1-14. doi: 10.4236/jpee.2022.1012001.

[26] Mundu, M.M., Nnamchi, S.N., Sempewo, J.I., & Uti, D.E. (2024). Simulation modeling for energy systems analysis: A critical review. *Energy Informatics*, 7(1), article number 75. doi: 10.1186/s42162-024-00374-8.

[27] Polcyn, J., Us, Y., Lyulyov, O., Pimonenko, T., & Kwilinski, A. (2021). Factors influencing the renewable energy consumption in selected European countries. *Energies*, 15(1), article number 108. doi: 10.3390/en15010108.

[28] Rolofs, G., Wilking, F., Goetz, S., & Wartzack, S. (2024). Integrating digital twins and cyber-physical systems for flexible energy management in manufacturing facilities: A conceptual framework. *Electronics*, 13(24), article number 4964. doi: 10.3390/electronics13244964.

[29] Sagar, K.V., Jerald, J., & Khan, M.A. (2024). An energy-aware optimisation model to minimise energy consumption and carbon footprint in a flexible manufacturing system. *International Journal on Interactive Design and Manufacturing*, 18(5), 2869-2880. doi: 10.1007/s12008-023-01352-2.

[30] Thiede, S., Dér, A., Münnich, M., & Sobottka, T. (2023). Manufacturing. In S. Wenzel, M. Rabe, S. Strassburger & C. von Viebahn (Eds.), *Energy-related material flow simulation in production and logistics* (pp. 27-53). Cham: Springer. doi: 10.1007/978-3-031-34218-9_2.

[31] Zaporizhstal. (2024). *"Zaporizhstal": Production results in December and for 2023*. Retrieved from https://zaporizhstal.com/uk-ua/news/zaporizhstal-pidsumki-virobnictva-u-grudni-ta-za-2023-rik/.

Моделювання та аналіз енерговитрат на виробничих лініях

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Анотація. Енергоспоживання є ключовим показником ефективності виробничих ліній, особливо в умовах змінних навантажень та інтенсифікації технологічних процесів. Метою дослідження було моделювання та аналіз енерговитрат на виробничих лініях ПрАТ «Запоріжсталь» для оцінки ефективності роботи обладнання за різних режимів навантаження. Дослідження базується на методах енергетичного балансу, математичного моделювання та статистичного аналізу. Використано кореляційний аналіз (Пірсона, Спірмена), дисперсійний аналіз та регресійне моделювання для оцінки взаємозв'язку між енергоспоживанням і технологічними параметрами. Обчислення виконано за допомогою програмного забезпечення MATLAB, Python (Pandas, Statsmodels, Scikit-learn) та Excel. Результати свідчать, що впровадження адаптивного управління енергоспоживанням дозволяє знизити середнє споживання електроенергії на 15-25 %, а оптимізація режимів роботи обладнання сприяє зменшенню пікових навантажень на 18-22 %. Виявлено, що ефективність промислових агрегатів значною мірою залежить від динаміки навантажень та рівня автоматизації процесів, що підтверджує необхідність інтеграції цифрових систем моніторингу та керування енергоресурсами. Використання математичних моделей прогнозування споживання електроенергії дозволяє оцінювати можливі перевитрати, виявляти критичні режими роботи обладнання та своєчасно коригувати параметри навантаження. Отримані результати підтверджують, що впровадження алгоритмів адаптивного управління забезпечує рівномірний розподіл енерговитрат, що особливо важливо для виробництв із високою динамікою змін навантажень. Запропоновані моделі можуть бути використані для підвищення ефективності промислових підприємств, зниження витрат на електроенергію та оптимізації управління виробничими процесами

Ключові слова: раціональне використання енергії; інтелектуальні системи керування; енергетичний баланс; промислові навантаження; цифрові технології моніторингу; управління ресурсами

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Application of wavelet transformations on microcontrollers for monitoring and optimising energy systems in industrial conditions

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Abstract. The purpose of the study was to analyse approaches to the use of wavelet transformations on microcontrollers to improve the efficiency of control and management of energy systems in industrial environments, and to investigate the possibilities of integrating wavelet transformations into hardware platforms of microcontrollers. The paper considered methods for applying wavelet transformations on microcontrollers for monitoring and optimising energy systems in industrial conditions. The proposed method helps to detect short-term anomalies, voltage and current fluctuations, which contributes to timely detection of energy losses. A discrete wavelet transform algorithm optimised for microcontrollers has been experimentally implemented, which provides anomaly detection accuracy of 94-96% with a signal-to-noise ratio of 40 dB. The analysis showed that the use of Daubechies-type wavelets can increase the sensitivity of the algorithm by 3-4% compared to Haar, while maintaining an acceptable level of computational costs. Optimisation of the implementation allowed reducing the average processing time of a single signal segment to 0.1 seconds on the STM32 microcontroller. In addition, the features of industrial conditions characterised by a high noise level and variable parameters were considered, which further complicates the use of wavelet transformations. The main achievement was the development of an adapted wavelet analysis method that ensures efficient use of microcontrollers for monitoring energy systems with minimal hardware requirements. A new algorithm was proposed that allows optimising the use of computing resources, reducing power consumption without losing the accuracy of signal analysis. The developed method allowed detecting anomalies in a timely manner and optimising energy consumption, which is of practical importance for reducing operating costs and improving the stability of industrial systems

Keywords: industrial solutions; processing algorithms; equipment reliability; resource management; resource efficiency

Introduction

Modern industry is actively moving to the use of energy-efficient systems that provide high productivity with minimal resource consumption. In this context, monitoring and optimisation of energy systems, which

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require accurate and fast methods of real-time data analysis, plays an important role. One of the promising approaches is the use of wavelet transformations for processing signals received from sensors and other measuring devices. Due to its ability to analyse signals in the time-frequency domain, the wavelet transform is a powerful tool for detecting anomalies, assessing the state of systems, and predicting energy parameters. Of particular importance is the implementation of such algorithms on microcontrollers, which are key components of automation and control systems. Microcontrollers provide sufficient computing power to perform complex mathematical operations while remaining compact, cost-effective, and energy-efficient. The use of wavelet transformations in such devices opens up new opportunities for integrating signal analysis methods directly into the hardware platform of energy systems. The relevance of the topic is conditioned by the need of industrial enterprises to improve energy efficiency and reduce equipment maintenance costs. However, their implementation on microcontrollers is associated with a number of challenges, in particular, optimisation of computational algorithms and limited memory resources and power consumption.

The development and implementation of wavelet transform algorithms on microcontrollers for monitoring energy systems was the subject of numerous studies. The academic literature contains papers that analyse certain aspects of this problem, which allows outlining current trends and identifying prospects for further development. The study by M. Karkhaneh & S. Ozgoli (2022) focused on the use of discrete wavelet transform to detect anomalies in industrial power systems. The researchers showed that the use of multilayer wavelet decomposition allows achieving high accuracy of fault identification even under conditions of noise in the signal. Their research also highlighted the importance of optimising computing resources. M.Y. Mazin & Y.O. Onykiienko (2023) considered the problem of limited hardware resources of microcontrollers and proposed an adaptive wavelet transform algorithm that reduces memory requirements without losing analysis accuracy. Their results indicate the prospects of using such approaches in real industrial conditions.

A. Sharma *et al.* (2021) discussed the use of a continuous wavelet transform to estimate the state of electric motors. The researchers emphasised the advantages of this approach for detecting early stages of mechanism wear. They also focused on the need to develop energy-efficient algorithms for embedded systems. J. Gao *et al.* (2021) investigated the use of wavelets for signal analysis in distributed energy systems. Their study demonstrated how the wavelet transform can help to optimise energy distribution and reduce network losses. The paper by N.T. Bui *et al.* (2020) focused on the development of microcontroller systems for real-time signal processing. The researchers proposed specialised hardware solutions for implementing wavelet transform, which can improve the system's performance. L. Peng *et al.* (2022) presented an approach to combining wavelet transformations with machine learning methods for predicting energy consumption. The researchers highlighted the effectiveness of wavelets in isolating relevant features from signals in complex dynamic environments.

The study by P. Khatua & K.C. Ray (2022) focused on the use of compact wavelets to reduce the computational complexity of wavelet analysis. The researchers argued that such methods can be effective for implementation on microcontrollers with limited resources. F. Bilgili *et al.* (2021) conducted research on the use of wavelet transform for monitoring renewable energy sources. Their results highlighted the possibility of integrating these methods into energy storage and transmission systems. A. Rahmani & A. Deihimi (2020) investigated the use of wavelets to analyse harmonic distortion in industrial power networks. They concluded that microcontrollers with support for wavelet processing can significantly improve the quality of real-time data analysis. A.A. Majhi & S. Mohanty (2024) focused on integrating wavelet transform into Internet of Things (IoT) systems for monitoring energy facilities. The researchers developed an approach that provides efficient signal processing and data transmission in distributed systems.

Considerable attention was paid to the use of wavelet transformations for monitoring the state of machines, predicting energy consumption, and detecting malfunctions. However, the practical implementation of such approaches on microcontrollers requires further research aimed at adapting algorithms to limited computing resources. The lack of unified methods and applied solutions in this area creates a space for innovation. Despite advances in wavelet transform applications for monitoring energy systems, a number of unresolved issues remain, including optimisation of algorithms for microcontrollers with limited resources, integration into real-time systems, and energy efficiency. In addition, the practical implementation of these approaches in complex industrial environments with a high level of interference remains limited, which requires the development of noise-resistant methods and adaptation of existing solutions for effective operation in real-world operating conditions. The purpose of the study was to investigate approaches to using modern signal processing algorithms based on wavelet transformations to improve the accuracy of monitoring and optimise the functioning of energy systems. The paper also considered the advantages, problems, and prospects of using the approach of optimised application of wavelet transformations on microcontrollers for monitoring and managing energy systems, which is an important step towards creating more energy-efficient and sustainable industrial systems.

Materials and Methods

The study was based on the analysis of the fundamentals of wavelet transformations, which are a powerful tool for analysing signals in time-frequency space. This approach can effectively detect anomalies, resource losses, and peak loads in power systems. The research was based on discrete wavelet transform algorithms, which allow decomposing signals into components with different frequency ranges, localising anomalies over time, and evaluating their frequency nature. Haar and Daubechies wavelets were chosen for analysis because they provide a trade-off between speed and accuracy. Haar is characterised by simplicity and low computing costs, which is important for devices with limited resources, while Daubechies provides better processing of complex signals with noise and sudden changes. Their effectiveness was evaluated according to the criteria of anomaly detection accuracy, noise resistance, speed, and computational complexity.

The effectiveness of the algorithm was evaluated according to the following criteria: sensitivity, precision, time detection, and noise resistance. Sensitivity showed the algorithm's ability to correctly detect existing anomalies or important changes in the signal and was calculated as the ratio of the number of correctly detected anomalies to the total number of available anomalies multiplied by 100%. Accuracy characterises the proportion of correctly detected anomalies among all cases that the algorithm has classified as anomalies, and is defined as the ratio of the number of correctly detected anomalies to the total number of detected anomalies multiplied by 100%. Anomaly detection time is the average time required by the algorithm to process a single signal segment, which is calculated as the total processing time divided by the number of processed segments. Noise resistance shows how effectively the algorithm maintains its accuracy in the presence of noise in the signal, and is calculated as the ratio of accuracy on noisy data to accuracy on pure data multiplied by 100%. In addition, the computational load measured in millions of instructions per second (MIPS) was analysed and calculated as the number of instructions for signal processing divided by the processing time in seconds, and the reduction in power consumption, which is defined as the difference between unit and the ratio of the power consumption of the optimised algorithm to the power consumption of the base algorithm multiplied by 100%.

The efficiency of the algorithm was evaluated by analysing the results of its operation on test data sets with different noise levels and typical operating modes of the power system. The study used comparative analysis with conventional methods such as fast Fourier transform and Kalman filtering to evaluate the effectiveness of wavelet transformations in detecting anomalies. Features of using real-time wavelet transformations are related to the need to optimise algorithms for working on microcontrollers. The main requirements include considering limited hardware resources, low power consumption, and the need for rapid anomaly detection. The wavelet transform, Kalman filter, and Fourier transform methods were also used to analyse such signals. These filters were chosen because of their effectiveness in reducing noise and predicting the state of the system in real time.

The algorithms were evaluated using 500 test cases with anomalies, including power surges, harmonic distortion, and impulse noise, and 300 runs in normal operating modes. The input signals were segmented into 500 ms intervals with a sampling rate of 10 kHz. The algorithms were performed on a Swiss-made STM32 microcontroller, and efficiency was evaluated according to the criteria of sensitivity, accuracy, processing speed, and noise resistance at a signal-to-noise ratio of 40 dB. In addition, the computational load and power consumption were analysed, comparing the results obtained with the basic implementation without optimisation.

The purpose of comparing signal processing algorithms was to determine the efficiency of using wavelet transformations in industrial settings for monitoring power systems on microcontrollers. The following algorithms were considered in the study: Fourier transform, wavelet transform, Kalman filtering, mean filtering, and Gaussian filtering. The comparison was based on several criteria: signal processing speed, memory usage, noise sensitivity, and the ability to detect short-term anomalies. The processing time was defined as the average time for analysing a signal with a length of 1,024 points, simulating typical operating conditions of power systems. The amount of memory was estimated as the maximum amount of RAM used during algorithm execution. Noise sensitivity was measured by analysing signals with a noise level of 40 dB, which helped to evaluate the resistance of methods to noisy data. In addition, the accuracy of detecting anomalies, in particular pulsed emissions, harmonic distortions, drifts, and random interference, was analysed. Both real signals from industrial power systems and synthetic data simulating anomalous situations were used to evaluate the effectiveness of the algorithms.

Results

Energy efficiency is becoming one of the key aspects in the development of modern industry, especially due to the growing energy costs and requirements for sustainable development. Industrial power systems, which are the basis of production processes, require constant monitoring to ensure their stable and uninterrupted operation. Anomaly detection, equipment health assessment, and energy optimisation are critical to reducing operating costs and minimising environmental impacts.

Conventional signal analysis methods used to monitor power systems often do not provide sufficient accuracy or require significant computational resources. Wavelet transformations, due to their ability to work in the time-frequency domain, allow more efficient detection of even minor changes in signal characteristics, which is important for early detection of malfunctions and improving the efficiency of systems. Microcontrollers, due to their compact size, cost-effectiveness and low power consumption, are widely used in industrial automation systems (Dong *et al.*, 2023).

Modern monitoring and optimisation of energy systems are complex tasks that require the integration of the latest technologies to ensure the efficiency, reliability and sustainability of energy processes. Due to the growing demands on energy consumption and environmental conservation, enterprises and other organisations are actively using modern methods for managing energy resources (Khatua *et al.*, 2020). These methods include the use of intelligent monitoring systems, load forecasting, integration of renewable energy sources, and the use of algorithms to optimise energy consumption.

Modern energy systems use sophisticated intelligent systems for real-time monitoring, collecting data from various sources and providing a prompt response to changes in energy consumption. Power management systems use numerous sensors that measure parameters such as power consumption, voltage, frequency, and other important metrics. This allows providing an accurate picture of the state of energy systems and detecting deviations from normal operation in time. The development of IoT technologies contributes to the integration of a large number of sensors into networks that allow monitoring and automatically adjusting the operation of energy systems. For example, IoT can be used to remotely monitor equipment, detect malfunctions, and even make adjustments to improve efficiency (Marinakis *et al.*, 2020). To reduce environmental impacts and improve energy efficiency, many energy systems integrate renewable energy sources such as solar panels, wind turbines, and geothermal installations. This creates new challenges for optimising energy systems, as renewable energy sources have a fickle production nature. Specialised optimisation strategies that consider changing environmental conditions and economic factors are used to manage such energy (Al-Shetwi, 2022). Such strategies include storing energy (such as in batteries) to equalise consumption peaks, or using smart grids to redistribute energy.

Adaptive control systems are an important area in modern monitoring of energy systems. They can adjust their strategies depending on changes in the external environment or internal parameters of the system. Automation in energy networks allows reducing the human factor, increasing the speed of responses to changes in the network, and ensuring a more reliable and uninterrupted supply of energy. For example, automated systems based on embedded microcontrollers can immediately respond to changes in voltage or power consumption by changing the settings of devices or equipment for optimal operation (Obaid *et al.*, 2019).

Microcontrollers also effectively interact with various peripheral devices through interfaces such as sensors, actuators, relays, which provides the ability to control various aspects of industrial processes. This allows creating integrated and scalable automation systems that can perform multiple tasks in a single controller. One of the advantages of microcontrollers is their ability to save energy (Wu *et al.*, 2021). They consume a minimal amount of energy, which is important for the smooth operation of power systems, and for autonomous devices and remote monitoring systems.

Real-time signal processing systems play an important role in today's industry, providing fast and accurate data analysis for operational decision-making. The main elements of such systems work in a coordinated manner, forming a single architecture for signal processing. At the first stage, data is collected using sensors and sensors that convert physical parameters into electrical signals. These signals undergo preprocessing, such as amplification or filtering. Then they are converted to digital format by analogue-to-digital converters, which allows working with them on digital devices. Microcontrollers or digital signal processors are the core of a system where key calculations are performed to analyse, monitor, or optimise signals. RAM is used for temporary data storage, and digital filters ensure that signals are cleared of noise. Communication interfaces allow data to be exchanged with other systems, and output devices such as displays or actuators display results or perform appropriate actions. Table 1 summarises the main components of the system, their functions, and their role in ensuring efficient real-time signal processing.

Table 1. Key components and functions of a real-time signal processing system

Component	Description	Function
Detectors and sensors	Devices that measure physical or electrical parameters (temperature, pressure, voltage, current)	Collecting input data from the environment for further processing
Preamp	Amplifier that increases the signal strength from the sensor to the required level	Ensuring the correct signal strength for the analogue-to-digital converter
Analogue-to-digital converter	Converts an analogue signal to a digital one for processing by a microcontroller or digital signal processor	Converting an analogue signal to a form suitable for digital processing

Table 1. Continued

Component	Description	Function
Microcontroller or digital signal processor	Central processing element that performs analysis, filtering, and optimisation algorithms	Digital signal processing, system management, and real-time algorithm execution
RAM	Temporary storage of input data and intermediate results during processing	Providing fast access to computing data
Permanent memory	Storage location for firmware, configuration parameters, and signal processing programmes	Saving algorithms and basic system parameters
Digital filters	Algorithms or hardware that remove noise or unnecessary frequency components of the signal	Improving signal quality and ensuring the correctness of further analysis
Communication interfaces	Means of data transfer between system components (UART, SPI, I2C, Ethernet, etc.)	Organisation of communication between sensors, processors, and other modules
Output devices/ actuators	Elements that display processing results or execute commands (displays, relays, motors, etc.)	Transmitting results to users or performing control actions based on the processed data

Notes: UART – Universal asynchronous receiver/transmitter; SPI – Serial Peripheral Interface
Source: developed by the authors based on I.I. Samborsky *et al.* (2021), Y.O. Ushenko *et al.* (2021)

These components play a key role in ensuring continuous and efficient operation of the real-time signal processing system. Collecting accurate data using sensors is the basis for making correct decisions, while preamps provide the necessary signal strength for further processing. The analogue-to-digital converter converts analogue signals to digital ones, which allows using modern processing algorithms. Microcontrollers and digital signal processors perform calculations with minimal latency, which is crucial for dynamic processes. Due to the continuous improvement of components and the introduction of innovative technologies, the architecture of systems for real-time signal processing is constantly evolving. Current research focuses on integrating machine learning, IoT, and cloud computing to create more adaptive and energy-efficient solutions. In the future, such systems can become a key element for building "smart" industrial and household solutions that can provide autonomy, high accuracy, and scalability (Bharany *et al.*, 2022).

An algorithm consisting of several stages was developed to optimise wavelet transformations on microcontrollers. First, the input signal is divided into small blocks (segments) to identify time intervals in which significant changes are observed. This preliminary analysis allows performing calculations only for relevant sections of the signal, which reduces the number of mathematical operations. Next, adaptive quantisation of the wavelet transform coefficients is performed, which reduces the memory requirements of the microcontroller without losing important information. Then the optimal wavelet function is selected: for signals with sharp transitions, the Haar wavelet is used, which provides speed of calculations, and for analysing complex and noisy signals, the Daubechies wavelet, which gives a more accurate result. The algorithm also provides for a multi-level schedule, where detailed processing is performed only at key levels, which further reduces power consumption. Analysis of the noise characteristics showed that it is advisable to use smoothed wavelets, such as Daubechies, for noisy data, while the Haar wavelet is more effective for sharp changes. The power consumption of the microcontroller was also taken into account. Table 2 shows comparative results using Haar and Daubechies wavelets, demonstrating a trade-off between computational speed and analysis accuracy, and an overview of alternative approaches to signal analysis.

Table 2. Overview of alternative approaches to signal analysis

Criteria	Haar	Daubechies
Sensitivity	92.3%	95.1%
Precision	88.7%	92.5%
Detection time	118 Ms	147 Ms
Noise resistance	84.2%	91.8%
Computing load	0.8 MIPS	1.2 MIPS
Reduce energy consumption	27%	30%

Source: developed by the authors based on their own research and O.A. Mohamed *et al.* (2017), Y.M. Yan *et al.* (2019), J. Lefebvre *et al.* (2020)

As can be seen, the Haar wavelet demonstrates higher performance (118 Ms per segment), which makes it suitable for applications where fast real-time analysis is important. At the same time, the Daubechies wavelet provides better sensitivity (95.1%) and noise resistance (91.8%), which allows working more efficiently in conditions of complex signals with a high level of interference. The computational load of the

Daubechies algorithm is higher (1.2 MIPS vs. 0.8 MIPS in Haar), but it provides more accurate analysis, which can be critical for tasks of predicting peak loads and detecting minor anomalies. The use of both approaches in a hybrid system will optimise the signal analysis process depending on specific operating conditions.

It is advisable to use the Haar wavelet for operational monitoring of network parameters and rapid detection of sudden changes, which is critical for protection and automatic control systems. The Daubechies wavelet is optimal for detailed signal analysis, especially when predicting voltage and current deviations, and detecting weak anomalies that may precede accidents. It is recommended to use a hybrid approach: Haar – for preprocessing and rapid response, and Daubechies – for detailed analysis of historical data and accurate forecasting. This strategy will minimise the power consumption of computing resources, while ensuring high control accuracy.

The Haar wavelet provides high computing speed due to simple arithmetic operations, making it efficient for real-time signal processing. However, its limited ability to accurately reproduce complex signal details reduces the accuracy of analysis, especially in the presence of noise or smooth changes. The Daubechies wavelet, by contrast, uses more complex functions, which improves recognition of small fluctuations and anomalies, but increases computational complexity. Thus, the choice between these wavelets depends on specific requirements: Haar is suitable for fast filtering and preprocessing, while Daubechies is more efficient for detailed analysis of noisy signals.

Signal processing is the basis for numerous engineering applications in fields such as telecommunications, radio electronics, medicine, and many others. The signals that need to be processed can be very diverse in their characteristics: they can be periodic or continuous, clear or noisy, static or dynamic. Choosing the right algorithm for signal processing depends on many factors, such as signal type, accuracy requirements, processing speed, and application specifics.

In order to choose the most effective algorithm for a particular task, it is necessary to understand the advantages and disadvantages of each of them. Some methods, such as the Fourier transform, are well suited for periodic signals and allow obtaining spectral information. However, wavelet transform or Kalman filtering is more suitable for analysing variable or complex signals, which can process information in time and frequency simultaneously, while preserving the local characteristics of the signal.

Other methods, such as linear regression or the principal component method, are often used to predict and reduce the dimension of data, but they may be less effective when working with high-frequency or unstable signals. For low-noise signals, simple algorithms such as medium filtering or Gaussian filtering may be sufficient, as they effectively reduce interference, but may cause some useful signal characteristics to be lost. Table 3 provides a comparison of the main signal processing algorithms, their advantages, disadvantages, and applications, which will help to visualise the key aspects of each method and make the right choice for specific tasks.

Table 3. Comparison of signal processing algorithms

Algorithm	Fourier transform	Wavelet transform	Kalman filtering	Filtering by average	Gaussian filtering
Description	Algorithm for converting signals from time space to frequency space allows getting the signal spectrum	Algorithm for decomposing the signal into a set of wavelets allows considering both time and frequency characteristics	Algorithm that combines prediction and correction to get the best estimate of the system state	Algorithm that replaces each input point with an average value in its vicinity	Filtering algorithm that uses the Gaussian function to blur the signal
Advantages	Processing speed, efficiency for periodic signals	Suitable for processing heterogeneous signals, effective for localised changes	Good performance with noisy signals, real-time efficiency	Easy to implement, effective for reducing noise in signals	Reduces noise well, preserving most of the useful information
Disadvantages	Poor signal processing with non-constant characteristics (time instability)	High computational costs, complexity of choosing a wavelet function	Necessary to accurately model processes, for complex systems – difficult configuration	Degrades the signal, especially with a high amplitude of changes	Poor adaptation to signals with different rates of change
Application areas	Acoustics, radio electronics, sound processing, spectral analysis	Image processing, medical signals, financial analysis, seismology	Navigation systems, robotics, economic forecasts	Image processing, audio signals, medical data	Image processing, video, audio, data visualisation

Table 3. Continued

Algorithm	Fourier transform	Wavelet transform	Kalman filtering	Filtering by average	Gaussian filtering
Processing time (signals)	0.08 s (for 1,024 points)	0.1 s (for 1,024 points)	0.12 s (for 1,000 measurements)	0.02 s (for 1,024 points)	0.03 s (for 1,024 points)
Memory (KB)	40-60)	150-250	50-70	20-40	30-50
Noise sensitivity	High	Moderate	High	Average	Low

Source: developed by the authors based on S.V. Zabolotnii (2010), M. Vetterli *et al.* (2014), A.O. Popov (2019)

The analysis of the algorithms demonstrated different approaches to signal processing, each with its own advantages and disadvantages. However, focusing on the methods that are alternatives to wavelet transforms, the Fourier transform and Kalman filtering should be highlighted, as they are widely used to analyse dynamic signals in industrial systems. The fast Fourier transform provides fast and efficient signal analysis in frequency space, but its disadvantage is the limited ability to process signals with unstable characteristics that change over time. This makes it less suitable for analysing industrial power systems where both time and frequency must be processed simultaneously. Kalman filtering, while effective for handling noisy signals, requires precise mathematical modelling of processes, which makes it difficult to use it for systems with dynamically changing characteristics. Unlike these methods, wavelet transformations offer a unique advantage: the ability to localise anomalies in both time and frequency. This is especially important for signals with rapid changes or unpredictable deviations typical of industrial systems. In real-world conditions, where computing resources may be limited, wavelet transform problems involve high computational costs and the choice of the optimal wavelet function.

Wavelet transformations play an important role in improving energy efficiency and extending the service life of equipment in power systems. Their main advantage is the ability to significantly improve control and optimisation of energy use (Shilpa & Puttaswamy, 2025). The use of wavelets for multi-level signal analysis helps to detect low-amplitude anomalies and fluctuations in energy systems that indicate inefficient use of energy. This facilitates a timely implementation of measures to optimise the operation of systems, reducing power consumption without losing performance. In addition, wavelets effectively identify small fluctuations that can cause additional energy losses, which allows quickly eliminating such shortcomings and reducing overall energy costs. Due to their application, it is possible to optimise equipment settings, ensuring a reduction in energy consumption without reducing operational efficiency. In addition, this technology allows more accurately predicting energy needs, contributing to more efficient resource planning and reducing costs during periods of low energy consumption (Pacheco *et al.*, 2024).

As for the durability of equipment, wavelet transformations contribute to monitoring the state of technical systems and early detection of anomalies, such as overload or wear. Analysis of electrical and mechanical signals helps to identify problems that can lead to breakdowns or shorten the service life of equipment. Wavelets can also identify vibrations, corrosion, or other mechanical defects, allowing taking timely measures such as calibration or replacement of components, thereby extending the service life of the equipment (Badihi *et al.*, 2022). It is also important that the use of this technology helps to reduce dependence on the human factor in the process of monitoring and managing energy systems, which minimises the likelihood of errors and increases accuracy. The use of wavelet transformations allows detecting overloads or overheating in time, which can prevent serious breakdowns and thereby extend the service life of the equipment. Based on the aforementioned capabilities, wavelet transformations significantly improve the energy efficiency and durability of equipment in industrial power systems, reducing maintenance costs and improving the overall stability of the system.

Discussion

The results of the study show that the use of wavelet transformations for monitoring industrial power systems is a promising approach that can significantly improve the accuracy of diagnostics and efficiency of equipment. Energy efficiency is a key factor in modern industrial processes, especially given the need to reduce energy costs and minimise environmental impacts (Mikhailova *et al.*, 2024). In this context, the proposed method of signal processing based on wavelet transformations, implemented on microcontrollers, is a practical tool for ensuring the sustainable development of industry. V. Veerasamy *et al.* (2020) investigated the use of wavelet transformations for signal analysis in industrial power systems, but paid more attention to the use of stationary wavelet transformations. Their results confirmed that this approach improves diagnostic accuracy, but system efficiency decreases due to high computational complexity. Compared to the current study, the results confirm the overall prospects of wavelet transformations, but the use of adaptive algorithms in the current study significantly reduced computational complexity, which differs from the researchers' approach.

X. Han *et al.* (2019) investigated the use of wavelet transformations for temperature monitoring in industrial heat transfer systems. They found that second-order adaptive wavelets provide temperature analysis accuracy with an error of up to 1.2%. Similar to the current study, they also emphasised the importance of choosing the optimal wavelet base for specific signals. Current study focused on voltage and power monitoring, and their research focused exclusively on temperature changes. S. Kováč *et al.* (2021) investigated the use of second-order adaptive wavelets for temperature analysis in industrial heat transfer systems. Their method provided fairly good accuracy even in environments with high noise levels. The researchers stressed the importance of choosing the right wavelet base to maximise the efficiency of signal analysis, which confirms the practicality of the approach. Together with the current study, there is an emphasis on adapting wavelet transformations to high noise conditions. However, the researchers focused exclusively on monitoring temperature changes, while the current study was based on voltage and power analysis. In addition, the current results additionally solved the problem of optimising algorithms for working on limited hardware resources of microcontrollers. This highlights the variety of applications of wavelets in industrial tasks.

One of the main advantages of the proposed approach is the ability of wavelet transformations to operate in the time-frequency domain, which detects even minor changes in the characteristics of signals. This allows detecting malfunctions early and predicting potential hardware failures. The use of wavelet transformations in combination with adaptive filtering algorithms helps to effectively deal with high noise levels, which is typical for industrial conditions. A.A. Ogaili *et al.* (2024) focused on the use of wavelet transforms for early detection of turbine failures. Their study showed that time-frequency analysis can detect even microscopic changes in the signal spectrum, but the high sensitivity of the technique led to a significant number of false positives in noisy environments. However, in contrast to the authors' research, the current results demonstrate efficiency in noise control through the integration of adaptive filtering algorithms, which allowed avoiding false positives.

The microcontrollers used as the basis for implementing the technique have shown high efficiency due to their compact size, low power consumption, and ability to process data in real time (Malinovskyi *et al.*, 2024). However, implementing complex algorithms on devices with limited resources required significant optimisation. The study suggests a number of optimisation approaches, including reducing the computational complexity of algorithms and efficient memory usage. These measures ensured stable operation of the system even in real industrial conditions. J. Konecny *et al.* (2024) analysed the possibility of using microcontrollers to implement wavelet transformations in industrial settings. They noted that the limited resources of such devices limit their suitability for complex tasks. The researchers suggested using the Field Programmable Gate Array to overcome these limitations. The current study focused on optimising algorithms for microcontrollers, which allows achieving more stable operation without switching to more expensive Field Programmable Gate Array solutions.

The industrial conditions in which the proposed system was tested were characterised by a high level of electromagnetic interference, significant fluctuations in network parameters, and a large amount of data for analysis. The results showed that the developed system can adapt to changes in the environment, while maintaining high monitoring accuracy. This confirms the practical suitability of the methodology for use in real-world operation. P. Gangsar & R. Tiwari (2020) conducted testing under conditions that simulate the effects of electromagnetic interference. Their results showed that most signal analysis methods lose accuracy due to significant fluctuations in signal parameters. The methods developed by the authors to compensate for interference partially solved this problem, but required a large amount of data for training. The current study shows that the proposed system demonstrates stability even in noisy industrial environments, which indicates greater adaptability compared to the researchers' approaches. A. Mannelli *et al.* (2021) examined the effect of wavelet coefficients on equipment energy consumption in renewable energy systems. Their method reduced the frequency of maintenance of generators by 20%. It was confirmed that wavelets effectively detect signals that are difficult to identify by conventional methods. Their results were related to energy from renewable sources, while the current study focused on classical industrial power systems.

The study results revealed certain challenges associated with the integration of the proposed solution into existing energy systems. For example, ensuring compatibility between new and legacy system components required additional effort. In addition, further improvement of the system requires the integration of IoT technologies, which will increase scalability and provide remote monitoring capabilities. K.H. Azmi *et al.* (2022) analysed the integration of modern diagnostic systems into outdated power grids. They emphasised the complexity of adapting equipment due to outdated data transfer protocols, but suggested using converters to ensure compatibility. Compared to the current study, the results confirm the need to adapt to legacy components, but the proposed solutions consider not only the protocols, but also the adaptation of the algorithms themselves to existing equipment. T. Ahmad & D. Zhang (2021) investigated the integration of the latest diagnostic technologies into outdated power grids that use obsolete approaches.

The researchers focused on the problems caused by the limited functionality of old data transfer protocols that do not meet modern requirements. To solve this problem, the researchers proposed the use of converters that act as a connecting link between modern monitoring equipment and existing networks. This helped to ensure compatibility without the need for a radical update of the entire system.

An important aspect is the potential integration of the developed system with renewable energy technologies. In particular, the possibility of effective monitoring of the operation of solar or wind power plants, where the variability of energy consumption significantly depends on external factors, opens up new prospects for implementation. This requires further adaptation of algorithms to variable conditions and integration with energy storage facilities. M.Z. Khoker *et al*. (2020) investigated the possibility of monitoring the operation of solar stations using wavelet analysis. Their results showed that algorithms need to be regularly adapted to variable operating conditions, such as light and temperature. The current study also points out the potential for integrating the developed systems with renewable energy sources. However, the current findings cover integration with energy storage facilities, which was not considered by the researchers.

The results of the study were analysed in the context of modern approaches to monitoring and optimising energy systems. It was established that the use of wavelet transformations on microcontrollers can significantly improve the accuracy of diagnostics and efficiency of equipment operation, even in difficult industrial conditions. The advantages and challenges of integrating the developed solutions into existing energy networks, in particular, compatibility with outdated systems and prospects for use in renewable energy, were considered. The results obtained confirmed the practical value of the proposed approaches and opened up new areas for further research.

Conclusions

This study analysed the use of wavelet transforms on microcontrollers for monitoring and optimising energy systems in industrial environments. The main attention was paid to the urgency of the problem of energy efficiency, which is a critical factor in modern industry due to the increase in energy costs and the need to reduce environmental impact. The study emphasised that the stable and uninterrupted operation of industrial power systems requires constant monitoring to detect malfunctions early, assess the condition of equipment, and reduce operating costs. Conventional signal processing methods were analysed and it was found that they often have limitations, in particular, insufficient accuracy or high computational complexity, which makes them difficult to apply in real time.

Considering the specifics of industrial conditions, such as high noise levels, significant parameter fluctuations, and the complex structure of power networks, the study focused on adapting wavelet transform algorithms to such conditions. For this purpose, it was proposed to reduce the number of decomposition levels, select optimal wavelet functions, and introduce adaptive approaches to signal processing. The study also developed an approach to reducing the power consumption of microcontrollers by using energy-efficient operating modes and adaptive management of computing resources depending on the characteristics of signals. Experiments have shown that optimised wavelet transform algorithms ensure the accuracy of anomaly detection while reducing power consumption.

Optimised wavelet transformations on microcontrollers provide improved accuracy in detecting anomalies and predicting peak loads in real time, which is critical for power systems. The use of Daubechies wavelets provided 95.1% sensitivity and 92.5% accuracy with high noise resistance, while Haar demonstrated a faster processing time (118 Ms vs. 147 Ms) due to easy calculations. Optimisation of the algorithm by reducing the number of operations, using fixed arithmetic and adaptive scaling of the schedule has reduced power consumption by 27-30% without loss of accuracy, which makes this approach effective for implementation in industrial environments. A limitation of the study was the dependence of the results on the specific conditions of industrial power systems and the limited computational capabilities of microcontrollers. Further research should focus on expanding methods for adapting algorithms for different types of power networks and improving their implementation on the latest microcontrollers with larger resources.

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Conflict of Interest

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References

[1] Ahmad, T., & Zhang, D. (2021). Using the internet of things in smart energy systems and networks. *Sustainable Cities and Society*, 68, article number 102783. doi: 10.1016/j.scs.2021.102783.

[2] Al-Shetwi, A.Q. (2022). Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges. *Science of the Total Environment*, 822, article number 153645. doi: 10.1016/j.scitotenv.2022.153645.

[3] Azmi, K.H., Radzi, N.A., Azhar, N.A., Samidi, F.S., Zulkifli, I.T., & Zainal, A.M. (2022). Active electric distribution network: Applications, challenges, and opportunities. *IEEE Access*, 10, 134655-134689. doi: 10.1109/ACCESS.2022.3229328.

[4] Badihi, H., Zhang, Y., Jiang, B., Pillay, P., & Rakheja, S. (2022). A comprehensive review on signal-based and model-based condition monitoring of wind turbines: Fault diagnosis and lifetime prognosis. *Proceedings of the IEEE*, 110(6), 754-806. doi: 10.1109/JPROC.2022.3171691.

[5] Bharany, S., Sharma, S., Khalaf, O.I., Abdulsahib, G.M., Al Humaimeedy, A.S., Aldhyani, T.H., Maashi, M., & Alkahtani, H. (2022). A systematic survey on energy-efficient techniques in sustainable cloud computing. *Sustainability*, 14(10), article number 6256. doi: 10.3390/su14106256.

[6] Bilgili, F., Lorente, D.B., Kuşkaya, S., Ünlü, F., Gençoğlu, P., & Rosha, P. (2021). The role of hydropower energy in the level of CO_2 emissions: An application of continuous wavelet transform. *Renewable Energy*, 178, 283-294. doi: 10.1016/j.renene.2021.06.015.

[7] Bui, N.T., Phan, D.T., Nguyen, T.P., Hoang, G., Choi, J., Bui, Q.C., & Oh, J. (2020). Real-time filtering and ECG signal processing based on dual-core digital signal controller system. *IEEE Sensors Journal*, 20(12), 6492-6503. doi: 10.1109/JSEN.2020.2975006.

[8] Dong, H., Yu, G., Lin, T., & Li, Y. (2023). An energy-concentrated wavelet transform for time-frequency analysis of transient signal. *Signal Processing*, 206, article number 108934. doi: 10.1016/j.sigpro.2023.108934.

[9] Gangsar, P., & Tiwari, R. (2020). Signal based condition monitoring techniques for fault detection and diagnosis of induction motors: A state-of-the-art review. *Mechanical Systems and Signal Processing*, 144, article number 106908. doi: 10.1016/j.ymssp.2020.106908.

[10] Gao, J., Wang, X., Wang, X., Yang, A., Yuan, H., & Wei, X. (2021). A high-impedance fault detection method for distribution systems based on empirical wavelet transform and differential faulty energy. *IEEE Transactions on Smart Grid*, 13(2), 900-912. doi: 10.1109/TSG.2021.3129315.

[11] Han, X., Xu, A., Wang, K., Guo, H., Zhang, N., Liu, Y., & Hong, S.H. (2019). Quadratic-wavelet-transform-based fault detection approach for temperature sensor. *IEEJ Transactions on Electrical and Electronic Engineering*, 14(1), 148-156. doi: 10.1002/tee.22772.

[12] Karkhaneh, M., & Ozgoli, S. (2022). Anomalous load profile detection in power systems using wavelet transform and robust regression. *Advanced Engineering Informatics*, 53, article number 101639. doi: 10.1016/j.aei.2022.101639.

[13] Khatua, P., & Ray, K.C. (2022). A low computational complexity modified complex harmonic wavelet transform. *Circuits, Systems, and Signal Processing*, 41(11), 6462-6483. doi: 10.1007/s00034-022-02095-3.

[14] Khatua, P.K., Ramachandaramurthy, V.K., Kasinathan, P., Yong, J.Y., Pasupuleti, J., & Rajagopalan, A. (2020). Application and assessment of internet of things toward the sustainability of energy systems: Challenges and issues. *Sustainable Cities and Society*, 53, article number 101957. doi: 10.1016/j.scs.2019.101957.

[15] Khoker, M.Z., Mahela, O.P., & Ahmad, G. (2020). A current based hybrid algorithm using discrete wavelet transform and Hilbert transform for detection and classification of power system faults in the presence of solar energy. In *Proceedings of the IEEE international students' conference on electrical, electronics and computer science* (pp. 1-6). Bhopal: IEEE. doi: 10.1109/SCEECS48394.2020.6.

[16] Konecny, J., Choutka, J., Hercik, R., Koziorek, J., Navikas, D., Andriukaitis, D., & Prauzek, M. (2024). Computational cost and implementation analysis of a wavelet-based edge computing method for energy-harvesting industrial IoT sensors. *IEEE Access*, 12, 193607-193621. doi: 10.1109/ACCESS.2024.3519715.

[17] Kováč, S., Micha'čonok, G., Halenár, I., & Važan, P. (2021). Comparison of heat demand prediction using wavelet analysis and neural network for a district heating network. *Energies*, 14(6), article number 1545. doi: 10.3390/en14061545.

[18] Lefebvre, J., Javer, A., Dmitrieva, M., Rittscher, J., Lewków, B., Allgeyer, E., Sirinakis, G., & Johnston, D.S. (2020). Single-molecule localization microscopy reconstruction using Noise2Noise for super-resolution imaging of actin filaments. In *Proceedings of the 17th international symposium on biomedical imaging* (pp. 1596-1599). Iowa City: IEEE. doi: 10.1109/ISBI45749.2020.9098713.

[19] Majhi, A.A., & Mohanty, S. (2024). A comprehensive review on internet of things applications in power systems. *IEEE Internet of Things Journal*, 11(21), 34896-34923. doi: 10.1109/JIOT.2024.3447241.

[20] Malinovskyi, V., Kupershtein, L., & Lukichov, V. (2024). Mathematical model for assessing cyber threats and information impacts in microcontrollers. *Information Technologies and Computer Engineering*, 21(1), 69-82. doi: 10.31649/1999-9941-2024-59-1-69-82.

[21] Mannelli, A., Papi, F., Pechlivanoglou, G., Ferrara, G., & Bianchini, A. (2021). Discrete wavelet transform for the real-time smoothing of wind turbine power using li-ion batteries. *Energies*, 14(8), article number 2184. doi: 10.3390/en14082184.

[22] Marinakis, V., Doukas, H., Tsapelas, J., Mouzakitis, S., Sicilia, Á., Madrazo, L., & Sgouridis, S. (2020). From big data to smart energy services: An application for intelligent energy management. *Future Generation Computer Systems*, 110, 572-586. doi: 10.1016/j.future.2018.04.062.

[23] Mazin, M.Y., & Onykiienko, Y.O. (2023). Wavelet transform application for image processing in microcontroller based Internet of things systems. *Technologies and Engineering*, 14(3), 15-25. doi: 10.30857/2786-5371.2023.3.2.

[24] Mikhailova, L., Zavytii, O., Horlachuk, M., Vilchinska, D., & Kondratiuk, O. (2024). Search for innovative solutions to improve the energy system of Ukraine: World experience. *Machinery & Energetics*, 15(3), 103-116. doi: 10.31548/machinery/3.2024.103.

[25] Mohamed, O.A., Okasha, A., & Abdrabbo, S. (2017). Identification and optimal fractional-order pid controller for a position servo system. In *Proceedings of the 19th international middle east power systems conference* (pp. 543-552). Cairo: IEEE. doi: 10.1109/MEPCON.2017.8301234.

[26] Obaid, Z.A., Cipcigan, L.M., Abrahim, L., & Muhssin, M.T. (2019). Frequency control of future power systems: Reviewing and evaluating challenges and new control methods. *Journal of Modern Power Systems and Clean Energy*, 7(1), 9-25. doi: 10.1007/s40565-018-0441-1.

[27] Ogaili, A.A., Hamzah, M.N., Jaber, A.A., & Ghane, E. (2024). Application of discrete wavelet transform for condition monitoring and fault detection in wind turbine blades: An experimental study. *Engineering and Technology Journal*, 42(1), 104-116. doi: 10.30684/etj.2023.142023.1516.

[28] Pacheco, J., Benitez, V.H., Pérez, G., & Brau, A. (2024). Wavelet-based computational intelligence for real-time anomaly detection and fault isolation in embedded systems. *Machines*, 12(9), article number 664. doi: 10.3390/machines12090664.

[29] Peng, L., Wang, L., Xia, D., & Gao, Q. (2022). Effective energy consumption forecasting using empirical wavelet transform and long short-term memory. *Energy*, 238, article number 121756. doi: 10.1016/j.energy.2021.121756.

[30] Popov, A.O. (2019). *Signal theory*. Kyiv: National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute".

[31] Rahmani, A., & Deihimi, A. (2020). Reduction of harmonic monitors and estimation of voltage harmonics in distribution networks using wavelet analysis and NARX. *Electric Power Systems Research*, 178, article number 106046. doi: 10.1016/j.epsr.2019.106046.

[32] Samborsky, I.I., Sholokhov, S.M., Yurchenko, O.V., & Nikolayenko, B.A. (2021). *Fundamentals of digital signal processing*. Kyiv: National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute".

[33] Sharma, A., Verma, P., Choudhary, A., Mathew, L., & Chatterji, S. (2021). Application of wavelet analysis in condition monitoring of induction motors. In V.C. Pandey, P.M. Pandey & S.K. Garg (Eds.), *Advances in electromechanical technologies* (pp. 795-807). Singapore: Springer. doi: 10.1007/978-981-15-5463-6_71.

[34] Shilpa, R., & Puttaswamy, P.S. (2025). Efficient recurrent wavelet fast Fourier transform network used in embedded systems for enhancing power quality. *Electrical Engineering*. doi: 10.1007/s00202-025-02991-2.

[35] Ushenko, Y.O., Havryliak, M.S., Talakh, M.V., & Dvorzhak, V.V. (2021). *Fundamentals and methods of digital signal processing: From theory to practice*. Chernivtsi: Yuriy Fedkovych Chernivtsi National University.

[36] Veerasamy, V., Abdul Wahab, N.I., Vinayagam, A., Othman, M.L., Ramachandran, R., Inbamani, A., & Hizam, H. (2020). A novel discrete wavelet transform-based graphical language classifier for identification of high-impedance fault in distribution power system. *International Transactions on Electrical Energy Systems*, 30(6), article number e12378. doi: 10.1002/2050-7038.12378.

[37] Vetterli, M., Kovacevic, J., & Goyal, V.K. (2014). *Foundations of signal processing*. Cambridge: Cambridge University Press.

[38] Wu, H., Chen, C., & Weng, K. (2021). An energy-efficient strategy for microcontrollers. *Applied Sciences*, 11(6), article number 2581. doi: 10.3390/app11062581.

[39] Yan, Y.M., Lay, N., Chao, D.J., Rogalin, R., Okino, C.M., & Argueta, A. (2019). Propagation analysis in support of wireless spacecraft capability. In *Proceedings of the IEEE aerospace conference* (pp. 1-6). Big Sky: IEEE. doi: 10.1109/AERO.2019.8742234.

[40] Zabolotnii, S.V. (2010). *Digital signal processing*. Cherkasy: Cherkasy State Technological University.

Застосування вейвлет-перетворень на мікроконтролерах для моніторингу та оптимізації енергетичних систем у промислових умовах

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Анотація. Метою дослідження був аналіз підходів до використання вейвлет-перетворень на мікроконтролерах для підвищення ефективності контролю та управління енергетичними системами у промислових середовищах, а також вивчення можливостей інтеграції вейвлет-перетворень в апаратні платформи мікроконтролерів. В роботі були розглянуті методи застосування вейвлет-перетворень на мікроконтролерах для моніторингу та оптимізації енергетичних систем у промислових умовах. Запропонований метод дозволяє виявляти короткочасні аномалії, коливання напруги та струму, що сприяє своєчасному виявленню втрат енергії. Експериментально реалізовано алгоритм дискретного вейвлет-перетворення, оптимізований для мікроконтролерів, який забезпечує точність виявлення аномалій на рівні 94-96 % при співвідношенні сигнал/шум 40 дБ. Аналіз показав, що використання вейвлетів типу Daubechies дозволяє підвищити чутливість алгоритму на 3-4 % у порівнянні з Haar, зберігаючи прийнятний рівень обчислювальних витрат. Оптимізація реалізації дозволила зменшити середній час обробки одного сегмента сигналу до 0,1 с на мікроконтролері STM32. Окрім цього, враховано особливості промислових умов, які характеризуються високим рівнем шуму та змінними параметрами, що додатково ускладнює використання вейвлет-перетворень. Основним досягненням була розробка адаптованого методу вейвлет-аналізу, який забезпечує ефективне використання мікроконтролерів для моніторингу енергетичних систем при мінімальних апаратних вимогах. Запропоновано новий алгоритм, що дозволяє оптимізувати використання обчислювальних ресурсів, знижуючи енергоспоживання без втрати точності аналізу сигналів. Розроблений метод дозволяє своєчасно виявляти аномалії та оптимізувати енергоспоживання, що має практичне значення для зменшення експлуатаційних витрат та покращення сталості роботи промислових систем

Ключові слова: промислові рішення; алгоритми обробки; надійність обладнання; управління ресурсами; ефективність ресурсів

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Liquefied natural gas as a strategic vector for ship energy modernisation

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Abstract. The relevance of the study is conditioned by the need to reduce emissions of harmful substances in navigation, compliance with international environmental standards, and the search for cost-effective solutions for fuel supply to the fleet. The purpose of the study was to analyse the technological, environmental, and economic aspects of the use of liquefied natural gas (LNG) in the marine energy sector to assess its efficiency and implementation prospects. As a result of the study, it was found that the use of LNG in marine energy is an effective solution for reducing environmental impacts and meeting international environmental standards. LNG can significantly reduce emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulphur oxides (SO_x), which makes it a competitive fuel for vessels operating in emission control zones. Technologically, LNG provides high energy efficiency, in particular, through the use of dual-fuel engines, which allow optimising fuel costs and reducing the negative impact on the environment. Modern marine power plants equipped with cryogenic gas storage and supply systems confirm the effectiveness of LNG in ensuring stable operation of vessels. Economic studies have shown that while the transition to LNG requires significant initial investment in ship refurbishment and infrastructure, in the long run, it can reduce operating costs and the cost of environmental measures, such as installations to reduce sulphur emissions. The practical significance of the study lies in the fact that it contributes to the development of theoretical and practical foundations for the use of LNG as an environmentally friendly and cost-effective fuel in the marine energy sector, which can be used to improve existing technologies and regulations in the field of navigation

Keywords: environmental standards; dual fuel engines; cryogenic systems; operating costs; emission control zones

Introduction

In modern shipping, there is a growing need to adapt to stringent environmental requirements, which are becoming increasingly stringent at the global level. The introduction of environmentally friendly technologies in the marine energy sector is one of the key components for ensuring the sustainable development of maritime transport. Liquefied natural gas (LNG) acts as a promising fuel that can significantly reduce the negative impact of marine engines on the environment, responding to the challenges of reducing carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulpur (SO_x) emissions. The use of LNG as fuel not only helps to achieve these goals, but also opens up new opportunities for energy efficiency of marine power plants.

LNG is increasingly considered as a promising fuel for navigation, but its use is accompanied by a number of environmental and technical problems that require additional investigation. The study by J. Deng *et al.* (2021) showed that the benefits of using LNG included reduced sulphur emissions, which was an important

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aspect for navigation in emission control zones. LNG has significantly reduced the negative impact on the environment compared to conventional fuels. S. Yao *et al.* (2023) emphasised that the use of LNG provided a reduction in CO_2 emissions, which significantly improved the environmental performance of marine engines. This made LNG a cost-effective choice for carriers looking to reduce their environmental footprint.

A. Elkafas *et al.* (2021) noted that marine engines powered by LNG showed increased energy efficiency, which allowed them to reduce fuel costs. According to their research, this made LNG a competitive option for shipping. Y. Shih *et al.* (2023) noted that the use of combined dual-fuel engines helped to optimise the energy costs of ships, ensuring a reduction in operating costs. This was an important aspect for carriers seeking to reduce overall operating costs. L. Palestini & F. Sassu (2021) argued that cryogenic LNG storage and delivery systems were a prerequisite for ensuring safe and stable operation of vessels. They helped to effectively manage fuel storage and minimise its costs during transportation.

I. Tvedten & S. Bauer (2022) noted that although the transition to LNG required significant initial investment, it allowed for reduced fuel costs and environmental measures in the long term. This made LNG a profitable option for shipping companies. E. Orysiak *et al.* (2024) noted that the development of LNG bunkering infrastructure was crucial to support the growing demand for this fuel. The introduction of new terminals and stations for refuelling ships helped to reduce costs and ensure a reliable supply. G. Satta *et al.* (2021) suggested that the construction of new LNG bunkering terminals was an important step in expanding the use of this fuel in shipping. This ensured a stable fuel supply and compliance with environmental requirements. S. Barberi *et al.* (2021) argued that LNG significantly reduced pollution levels in ports and coastal areas, which helped to improve the environmental situation. This was important for shipping companies operating in such regions. M. Cassar *et al.* (2021) emphasised that LNG was a key factor in meeting environmental regulations and standards of international organisations, in particular, on reducing emissions. The use of this fuel was an important step towards ensuring the sustainable development of navigation. Thus, although the issues of using LNG in shipping have been studied and show significant benefits of this fuel from an environmental and economic standpoint, there are a number of issues that require further study to achieve the full implementation of the potential of LNG in shipping.

The purpose of the study was to investigate the potential of LNG for the modernisation of marine energy, considering the environmental, technological, and economic aspects of its use. Research objectives:

1. To consider the impact of LNG use on reducing harmful gas emissions, and its energy efficiency in marine engines.

2. To investigate the economic benefits of switching to LNG, in particular, the cost of investment in the relevant infrastructure and the economic efficiency of this transition.

3. To evaluate the technical aspects related to the use of cryogenic LNG storage and supply systems.

Materials and Methods

This study focused on the use of LNG as a strategic energy source for the modernisation of ship power systems. The study covered the technological and economic aspects of LNG implementation in the marine sector, with a focus on its environmental benefits and energy efficiency. It addressed the issue of switching from conventional marine fuel to LNG in response to the update of environmental regulations, in particular, the requirements introduced by the International Maritime Organisation in the work of L. Kırval & U.Y. Çalışkan (2022). These upgrades were aimed at minimising pollution of the oceans and seas, including discharges, oil and air pollution.

The material basis of the study was data that were used to compile tables comparing the impact of LNG use on reducing harmful gas emissions and energy efficiency of marine engines. In addition, the economic benefits of switching to LNG were considered. All the materials shown in the tables were obtained from sources H. Jang *et al.* (2021) and B. Jesus *et al.* (2024). The research started by analysing the environmental impact of LNG, comparing it with conventional marine fuels such as diesel and coal. Special attention was paid to the potential of LNG to reduce harmful emissions, such as SO_x, NO_x, particulate matter (PM), and CO_2. This aspect highlighted the role of LNG in meeting environmental requirements and ensuring pollution reduction. Attention was also drawn to its ability to help meet the sulphur restrictions set by MARPOL Annex VI and the Act to Prevent Pollution from Ships (2024). In addition, the study delved into technological challenges and solutions related to the introduction of LNG in shipping. The infrastructure required for LNG implementation was also investigated. These technological aspects were critical to ensuring the safe and efficient operation of LNG vessels, especially given the need for highly specialised LNG storage and management equipment.

The study also examined the economic feasibility of switching to LNG, considering both the initial investment costs of upgrading ships and building the necessary infrastructure, and long-term operating savings. The financial benefits of LNG, in particular, the stability of fuel prices and reduced operating costs, were compared with the instability and rising cost of conventional marine fuel. Special attention was paid to the economic consequences of LNG introduction in the shipping industry, in particular, such factors as return on investment and payback periods.

In addition, the study examined problems related to the development of LNG bunkering infrastructure.

The current state of LNG supply networks at key global shipping hubs, including the role of ports such as Singapore, Shanghai, and Rotterdam in supporting LNG-powered vessels, was considered. Graphic materials were also provided that illustrated the structure of these networks and their interaction with shipping routes. The study discussed innovative solutions, such as floating LNG terminals, that can help to overcome infrastructure constraints in remote regions and promote widespread LNG adoption.

Results

Shipping faces new challenges due to growing environmental requirements and the need to reduce emissions of harmful substances. One of the key areas of the industry's development is the gradual transition to cleaner fuels, with LNG attracting particular attention. The use of this fuel allows shipping companies to meet international environmental standards, reducing air pollution, and improving the energy efficiency of ships. One of the main regulatory documents defining environmental requirements for shipping is MARPOL Annex VI and the Act to Prevent Pollution from Ships (2024). According to it, from January 1, 2020, the sulphur content in marine fuel should not exceed 0.5%, and in emission control zones – only 0.1%. These restrictions force ship-owners to abandon conventional fuel oil, which contains a significant amount of sulphur, and look for alternative solutions.

LNG offers a number of environmental benefits that make it an attractive option for shipping. It does not contain sulphur, which completely eliminates SO_x emissions without using additional cleaning systems, such as scrubbers. Burning natural gas helps reduce CO_2 emissions by 20-25%, which is an important step in the fight against climate change. In addition, the level of NO_x emissions when using LNG was reduced by 85% compared to conventional fuels, and the amount of PM was reduced to almost zero (Yeo *et al.*, 2022). The efficiency of LNG-powered engines is usually 5-10% higher than that of diesel engines. This reduces fuel costs and reduces operating costs, making LNG more efficient in terms of energy resources. However, despite the obvious advantages, the widespread introduction of LNG in shipping is accompanied by a number of challenges. One of the main problems is the insufficiently developed infrastructure for LNG storage and bunkering. Unlike conventional marine fuel, natural gas requires special cryogenic tanks capable of maintaining temperatures of -162°C. This creates additional technical and financial difficulties, because the construction of the corresponding terminals requires significant capital investments. In addition, upgrading the fleet and equipping ships with LNG storage and delivery systems requires significant initial investment, which may be too much for some shipping companies (Van Biert *et al.*, 2021).

Another important issue is the technical operation of LNG vessels. Maintenance of cryogenic systems requires highly qualified personnel who can work with new technologies. This will require additional costs for crew training and adaptation of operational standards. But despite these challenges, the prospects for using LNG in shipping remain extremely high. The infrastructure for LNG storage and refuelling is actively developing, and technological progress contributes to reducing the cost of systems required for its use. Many shipping companies have already started implementing this technology, as it not only helps meet environmental standards, but also allows optimising fuel costs in the long term (Adekoya *et al.*, 2024).

Thus, LNG is a strategic area for the modernisation of marine energy. It ensures environmental safety, reduces harmful emissions, and promotes the transition to more sustainable marine logistics. However, for the full implementation of this technology, it is necessary to solve the issues of infrastructure development, reducing the cost of fleet modernisation and training specialists. Despite these challenges, trends in shipping suggest that the role of LNG will only grow in the coming decades, forming a new environmental standard for maritime transport. The use of LNG in shipping is an important step towards improving energy efficiency and reducing the impact on the environment. Conventional marine power plants are undergoing modernisation to meet modern environmental standards, and LNG is becoming a key fuel in this transition. Its use can significantly reduce emissions of harmful substances, reduce operating costs, and improve the overall performance of vessels (Table 1).

Table 1. Impact of LNG use on reducing harmful gas emissions and energy efficiency in marine engines

Parameter	LNG	Diesel fuel	Coal
CO_2 emissions (t/GWh)	0.185	0.22	0.82
So_2 emissions (g/kWh)	0	2.1	4
NO_x emissions (g/kWh)	0.05	0.25	0.5
PM emissions (g/kWh)	0	0.03	0.15
Energy efficiency	Higher efficiency (45-55%)	Average (35-45%)	Low (30-40%)

Source: compiled by the author based on H. Jang *et al.* (2021)

Modern marine LNG power plants show an increased efficiency factor compared to conventional diesel engines. This helps to reduce fuel costs and optimise energy consumption. An important area of development is the introduction of combined power systems that allow combining the operation of different types of engines to achieve maximum efficiency. Such systems provide the ability to switch between fuel types, which is especially important in conditions of unstable prices and regulatory changes. There are several main types of engines that can run on LNG. Dual-fuel engines are the most common option, as they can run on both LNG and diesel fuel. This gives shipping companies additional flexibility in choosing their energy source. Another option is gas engines with spark ignition, which operate exclusively on LNG. They provide even lower emissions, but require specialised fuel supply systems and some changes to the vessel's design (Lähde & Giechaskiel, 2021).

LNG storage on board ships is a technologically complex process. Since LNG is stored at a temperature of about -162°C, special cryogenic tanks are used for this purpose. They are equipped with multi-layer insulation and vacuum systems that minimise gas evaporation. This reduces fuel losses and ensures safe operation of the vessel. An important aspect is also the control of gas evaporation, which allows the use of evaporated gas in marine power plants, preventing its loss. Fuel supply systems play a key role in the stable operation of LNG vessels. The Fuel Gas Supply System provides control of the fuel supply to engines by regulating its pressure and temperature. This allows avoiding power drops and ensuring efficient operation of engines in various operating modes. Some systems also include re-cooling mechanisms that allow some of the evaporated gas to be returned to a liquid state for later use (Jeong *et al.*, 2024).

As of 2025, there are several modern engine models on the market that are already actively used in shipping. One of the most efficient is the MAN ME-GI, a high-pressure dual-fuel engine that provides minimal fuel loss and low emissions (Kim *et al.*, 2022). Another option is the WinGD X-DF, which runs on LNG at low pressure, which reduces methane emissions and improves the overall environmental friendliness of the vessel (Domić *et al.*, 2022). Despite the significant advantages, the introduction of LNG in shipping faces certain challenges. The main ones are the need to develop appropriate infrastructure, the high cost of fleet modernisation, and the need for specialised skills to service new technologies. However, global trends indicate a gradual increase in the share of vessels running on this fuel (Stolz *et al.*, 2022). Thus, the technological development of marine energy based on LNG is a strategic area for the modernisation of the industry. State-of-the-art engines, efficient fuel supply systems, and upgraded gas storage methods ensure high energy efficiency and significant emission reduction. In the future, the use of LNG will contribute to further greening of shipping, optimising costs and ensuring the stable development of sea transportation. The transition of global shipping to LNG is one of the most important areas of modernisation of marine energy. This is due not only to environmental requirements, but also to potential economic benefits. The use of conventional marine fuels, such as fuel oil or diesel, is becoming less attractive due to rising environmental compliance costs and volatile oil prices. On the other hand, LNG can reduce operating and environmental costs, get financial incentives, and improve overall ship efficiency. However, despite these advantages, the transition to LNG is accompanied by certain challenges, such as significant initial investment, the need for infrastructure development, and the cost of staff training (Table 2).

Table 2. Economic benefits of switching to LNG, cost of infrastructure investment, and cost-effectiveness of the transition

Parameter	Derivative of switching to LNG
Initial investment (USD million)	50-100 (depending on the type of vessel)
Operating expenses (per year)	Cost reduction by 15-30% (compared to diesel)
LNG cost (per 1 MWh)	40-60 USD/MWh
Operating savings (per year)	5-15% of total expenses
Return on investment	3-6 years depending on the scale of the project

Source: compiled by the author based on B. Jesus *et al.* (2024)

One of the key economic benefits of using LNG is reduced operating costs. Prices for conventional petroleum products are subject to fluctuations, which complicates long-term financial planning for shipping companies. However, the cost of LNG is more stable, and in some regions, it is much lower, which makes it economically attractive (Xiuzhen *et al.*, 2022). Due to cleaner LNG combustion, engines experience less wear, which reduces maintenance costs and increases their service life.

The transition to LNG is accompanied by a number of financial and technical challenges. The most significant of these is the high cost of the initial investment. The construction of new LNG-powered vessels or the conversion of existing vessels to run on this fuel requires significant costs for the installation of cryogenic

LNG storage systems, modernisation of fuel systems, and replacement of engines. These costs can be a serious barrier for many shipping companies, especially those operating in the low-margin cargo segment, such as general cargo transportation, container transportation, or raw material transportation.

Another important aspect is the cost of staff training. Working with LNG requires special knowledge and skills, as this fuel is stored at ultra-low temperatures (-162°C) and requires special safety measures. Shipping companies should invest in training crew and technical personnel to ensure safe operation of vessels and avoid the risks associated with the use of cryogenic fuel. It should also be considered that the infrastructure for providing LNG vessels is not yet evenly developed in all regions of the world as of 2025. Although the number of LNG bunkering terminals is gradually increasing, their availability remains limited in some seaports. This can create logistical difficulties for vessels that use LNG as their main fuel, and require additional planning of routes and stops to replenish their fuel reserves.

Thus, the cost-effectiveness of switching to LNG is determined by the balance between initial costs and long-term benefits. Despite the high initial costs of implementing LNG, lower operating costs, financial incentives, and savings on environmental measures can make this transition economically feasible in the long run. However, heavy fuel remains the most cost-effective option even with a high carbon tax, suggesting that switching to LNG may not be economically feasible for many shipping companies at this stage due to high initial investment and lack of adequate infrastructure to provide LNG vessels (Sagin & Poberezhny, 2022). In the long run, global trends to reduce emissions and strengthen environmental standards will further increase the popularity of LNG in shipping. Infrastructure development and technology improvements will ensure its wider adoption, which will contribute to the sustainable development of the marine industry and increase its economic efficiency.

LNG infrastructure is one of the key aspects that will determine the future of shipping in the context of the transition to clean energy sources. The introduction of this fuel at a broad level requires the creation of an efficient and scalable infrastructure for LNG storage, transportation, and bunkering. Despite the successful development of certain infrastructure elements in some regions, there are still significant limitations at the global level that make it difficult to implement large-scale LNG in shipping. These include the lack of sufficient infrastructure for LNG bunkering, the high cost of upgrading vessels to use this fuel, and the uneven development of LNG supply networks in different parts of the world. In addition, large initial investments in the installation of the necessary equipment and technologies can be a significant barrier for many shipping companies, especially those operating in low-margin segments. In 2023, major international ports, in particular Rotterdam, Singapore, and Shanghai, became important hubs for LNG bunkering due to the presence of developed LNG terminals (Dewiatena & Bahagia, 2023). These terminals allow efficient storage and regasification of LNG, ensuring uninterrupted fuel supply for vessels running on this fuel.

Rotterdam is an important commercial port and the largest LNG bunkering terminal in Europe (Fig. 1). Due to its strategic location on the North Sea coast and high level of infrastructure development, Rotterdam has become a major LNG supply hub for international vessels. The port provides the ability to bunker LNG of various types to ships moving between Europe, Africa, and North America. LNG is a more environmentally friendly fuel, so many shipowners are switching to it due to strict environmental requirements, such as SO_x and NO_x emission reduction standards. Rotterdam is actively developing infrastructure for LNG bunkering, including the creation of new LNG processing terminals, investments in the development of technologies for gas storage and supply. This makes the port attractive for shipping companies looking to reduce harmful gas emissions and reduce fuel costs. As Rotterdam is a major transit hub, this development also contributes to the increased use of LNG in other parts of Europe (Zannis *et al.*, 2022).

Singapore is one of the largest and most developed ports in the world, which is actively developing infrastructure for servicing ships using LNG (Fig. 2). Singapore is considered an important hub for bunkering vessels running on alternative fuels, in particular LNG. This significantly contributes to an increase in the number of such vessels in the Southeast Asian region, where demand for environmentally friendly fuel is increasing due to stricter emissions regulations. Singapore's infrastructure includes several terminals for receiving and storing LNG, and systems that ensure efficient bunkering of this fuel. In addition, the Singapore government actively supports this process by investing in new technologies and providing incentives for shipping companies to switch to LNG. In particular, local port authorities encourage investment in infrastructure, which reduces overall costs for shipowners and encourages the spread of LNG in the region (Du & Li, 2023).

Shanghai is an important commercial port and one of the main centres for the development of LNG infrastructure in China (Fig. 3). Since China is the largest consumer of energy resources in the world, and one of the largest air pollutants, the country is actively working on switching to cleaner energy sources, in particular LNG. Shanghai plays a key role in this process through the development of specialised LNG storage and processing terminals. In addition, Shanghai is part of ambitious national initiatives to reduce emissions and develop infrastructure for green technologies, including the introduction of LNG as an alternative to conventional fuels. However, it is worth noting that one of the challenges for the wider use of LNG in other parts of China is its availability and cost. Remote regions face difficulties in LNG delivery due to the lack of developed infrastructure and high transportation costs. These factors create certain barriers to the expansion of LNG use in the country (He *et al.*, 2023).

Figure 1. Graphic image of the port of Rotterdam

Source: Port of Rotterdam cargo throughput decreased in 2024 (2025)

Figure 2. Graphic image of the port of Singapore

Source: Hiteshk (2019)

Figure 3. Graphic image of the port of Shanghai

Source: M. Bruno (2022)

However, despite the growing number of such terminals, many regions, especially in Africa, South America, and parts of Asia, face a lack of infrastructure to provide the necessary level of LNG supply (Yin & Lam, 2022). This limits opportunities for shipping companies seeking to switch their fleets to cleaner energy sources, as they are forced to plan their routes based on existing bunkering terminals. As a result, LNG vessels have limited access to some ports and routes, which creates additional costs and logistical difficulties.

One solution that helps to reduce these limitations is the introduction of floating LNG terminals. Floating terminals are mobile installations that can store, regasify, and supply LNG to ships without the need to build expensive stationary ground terminals. Floating terminals can provide LNG supplies in remote or insufficiently secured ports, where the construction of stationary infrastructure is economically unprofitable. This allows significantly increasing the coverage of regions where the necessary infrastructure for bunkering is not available, and reducing dependence on geographical factors. Floating terminals are particularly useful in cases where fast and cost-effective provision of new LNG ports is required (Khoiriyah *et al.*, 2023).

Notably, the development of LNG infrastructure is stimulated by state programmes and international initiatives. Many countries seeking to reduce greenhouse gas emissions actively support investment in LNG infrastructure development. For example, in the European Union, there is the Connecting Europe Facility programme, which provides soft loans and grants to shipping companies and enterprises that invest in the creation of LNG bunkering terminals and the development of infrastructure for its transportation. The terms of lending and receiving grants include concessional loans on favourable terms for projects that meet the programme's criteria. The application process includes submitting a detailed business plan and technical documentation. To receive grants, a company must submit an application containing a description of the project, its impact on the environment and economy, and an implementation plan. Competition for grants is high, so it is important to prepare high-quality documentation (Connecting Europe Facility, 2021). Such support not only encourages infrastructure development, but also encourages shipping companies to invest in the transition to cleaner energy sources. In particular, one example is Norway, which actively supports the use of LNG in navigation through preferential programmes and subsidies. Norway, as part of its strategy to reduce carbon emissions and meet its obligations under the Paris Agreement, provides financial incentives for companies that switch to using LNG. In particular, Norway provides tax breaks and subsidies for shipping companies that upgrade their vessels to use LNG instead of conventional diesel fuel. As part of the Green Shipping Programme, the Norwegian government allocates up to 50% of the cost of upgrading ships, including switching to LNG, and also provides soft loans to finance such initiatives. Through these measures, Norway encourages shipping companies to reduce their harmful gas emissions and supports the development of LNG bunkering infrastructure in their ports. According to the Norwegian Maritime Administration, shipping companies can receive funding of up to NOK 2 million (approximately EUR 200,000) for a modernisation project that includes switching to LNG as the main fuel for the ship.

One of the companies that actively invests in the development of infrastructure for LNG is Maersk, one of the largest container carriers in the world. Maersk is actively working to convert its vessels to LNG and invests in the construction of new bunkering stations and the expansion of existing infrastructure for the supply of LNG. As part of its environmental initiatives, the company plans to operate more than 12 of its new LNG vessels by 2030. In addition, Maersk is investing in expanding its network of bunkering terminals around the world, including ports in Europe and Asia, to ensure a continuous supply of LNG for its vessels. For example, in 2021, the company announced cooperation with the Port of Rotterdam to expand the LNG bunkering infrastructure, and is also negotiating with other ports to build additional terminals. Maersk's investments in the transfer of the fleet to LNG and infrastructure development can amount to hundreds of millions of dollars. For example, for the construction of one new bunkering station, a company can spend up to EUR 50 million on a project. This demonstrates the company's serious efforts to provide a more sustainable and cost-effective way of transportation in the shipping industry.

Thus, despite the existing challenges associated with the development of infrastructure for LNG, the use of floating terminals, active support from states and private investors help to solve these problems. In the future, the development of bunkering infrastructure, in particular, through floating terminals and the expansion of the network of ports providing services for LNG, will allow shipping to fully switch to environmentally friendly energy sources, which will contribute to the sustainable development of the marine industry as a whole.

Discussion

Analysis of the results of the study showed that the introduction of LNG in shipping contributed to a significant reduction in harmful emissions. In accordance with the environmental regulations MARPOL Annex VI and the Act to Prevent Pollution from Ships (2024), vessels that used LNG as fuel showed a significant reduction in SO_x and NO_x emissions, and also PM. In addition, switching to LNG has reduced CO_2 emissions, which confirmed its compliance with modern requirements for decarbonisation of shipping.

This problem was also investigated by A. Singh & S. Shanthakumar (2022), where the results confirmed that the MARPOL Annex VI environmental regulations impose strict restrictions on harmful emissions from marine transport, in particular, on sulphur in marine fuel. These regulations significantly reduced the level of air and ocean pollution, which contributes to the preservation of the marine ecosystem. As a result, these measures increase the environmental responsibility of sea carriers and encourage the introduction of the latest technologies to reduce emissions. The study by A. Hoang *et al*. (2023) also showed that decarbonising shipping is an important step in combating climate change by focusing on reducing CO_2 emissions in this sector. Switching to alternative fuels such as LNG, hydrogen, and ammonia can significantly reduce harmful gas emissions. This strategy is essential for achieving the global goals of reducing emissions and ensuring the sustainable development of the marine industry. The implementation of environmental regulations is only part of a broader strategy to reduce pollution from marine transport. Since these regulations focus on limiting SO_x and NO_x emissions, they do not cover all aspects of environmental sustainability, such as greenhouse gas emissions. Therefore, it is important to integrate these requirements with other international initiatives that include a broader approach to decarbonising shipping and using the latest technologies to reduce the environmental impact of the industry as a whole.

Technological analysis has shown that modern marine power plants, in particular, dual-fuel engines and gas engines with spark ignition, provide increased efficiency and reduce fuel consumption. In addition, the use of cryogenic LNG storage systems helped to effectively control the processes of fuel evaporation and its supply to engines. However, it turned out that such systems required significant capital investments and careful monitoring of temperature conditions, which could complicate their operation. Z. Rony *et al*. (2023) concluded that LNG-based marine power plants are becoming increasingly popular due to their environmental benefits, as LNG contributes to reducing SO_x, NO_x, and CO_2 emissions compared to conventional fuels. They provide high energy efficiency, since LNG combustion occurs more cleanly, which has a positive effect on engine efficiency and reduces operating costs. Such technologies are actively supported by international organisations as part of their commitments to reduce the environmental impact of shipping.

R. Ratnakar *et al*. (2021) found that cryogenic fuel storage systems are critical to ensuring safe and efficient LNG storage on board ships. These systems help to maintain the necessary low temperature to preserve natural gas in a liquid state, minimising losses during transportation and storage. They not only reduce fuel evaporation, but also contribute to improving overall energy efficiency and reducing the cost of LNG transportation. These results support the above study, as they demonstrate a significant reduction in harmful gas emissions and improved energy efficiency when using marine LNG power plants. In particular, the analysis showed that the use of LNG as the main fuel on ships can lead to a reduction in NO_x and SO_x emissions, which confirms the high environmental efficiency of this technology. In addition, the integration of cryogenic storage systems allows fuel to be stored in optimal conditions, which contributes to even greater savings and reduces overall energy costs for shipping.

Economic analysis has shown that despite the long-term benefits of LNG, such as reduced fuel costs and lower environmental costs, for many shipping companies switching to LNG at this stage may not be economically feasible. High initial investment in ship upgrades and the need to develop infrastructure for LNG bunkering, and the lack of sufficient support to cover these costs, leave conventional heavy fuel a more profitable option, even with high carbon taxes. It is necessary to emphasise the study by S. Al-Sobhi *et al*. (2021), who also found that the cost-effectiveness of LNG provides significant financial benefits for shipping companies due to its low fuel costs compared to conventional fuels. In addition, LNG helps to reduce operating costs by reducing engine wear and the need for frequent maintenance. The use of this fuel also allows companies to meet environmental standards without the need for additional costs for emission cleaning equipment, which increases their competitiveness in the market.

In turn, H. Ma *et al*. (2023) concluded that financial incentives for shipping companies play an important role in encouraging the transition to environmentally friendly fuels such as LNG. Due to government and international programmes, including subsidies and tax incentives, companies receive support in modernising their fleets, which can significantly reduce the financial burden. Concessional loans for the purchase of new vessels or the adaptation of existing vessels to LNG use provide additional incentives for integrating more sustainable technologies into the industry. These data are consistent with the theses given in the previous section, as they confirm that the economic benefits of LNG significantly exceed the initial costs of upgrading marine power plants. In particular, long-term savings on fuel costs, lower operating costs, and easier compliance with environmental standards make this transition beneficial for shipping companies. In addition, financial incentives provided by the government and international organisations greatly facilitate the implementation of this technology, which once again confirms the feasibility of switching to more environmentally friendly and cost-effective fuel options.

One of the key limitations in the use of LNG remained an insufficiently developed bunkering infrastructure. While major ports such as Rotterdam, Singapore, and Shanghai had LNG terminals, many other ports were not equipped with the necessary capacity to store and refuel LNG vessels. The study showed that the development of floating LNG terminals could be an effective solution for providing fuel to ships in remote regions, but this required significant capital investment and coordination at the international level.

Research conducted by V. Chimshir *et al*. (2023) confirmed the importance of LNG bunkering infrastructure to ensure a stable LNG supply to ships. This infrastructure includes specialised ports and gas stations capable of handling large volumes of fuel, which reduces the risk of leaks and ensures high safety during refuelling. Its development reduces ship downtime and increases the availability of LNG for sea carriers, which significantly optimises global logistics. D. Polemis & M. Boviatsis (2023) also found that floating terminals are an effective solution for countries or regions where there is no developed infrastructure for natural gas storage and regasification. These mobile platforms help to quickly organise the supply of LNG to remote or isolated places where the construction of stationary terminals is economically impractical. Due to their mobility and rapid installation capabilities, floating terminals provide flexibility in managing gas demand, which is essential for the sustainable development of energy markets in various regions of the world.

Comparing the data obtained in the course of research, it can be concluded that the introduction of LNG bunkering infrastructure and the development of floating terminals are interrelated processes that significantly increase the availability of LNG for the shipping industry. These infrastructure elements create an efficient logistics network that reduces the time spent on refuelling ships and reduces the risks associated with fuel shortages in remote regions. In particular, mobile floating terminals can significantly reduce the cost of building stationary facilities, making the energy infrastructure more flexible and adapted to changing market conditions. The results of the study also showed that shipping companies that were the first to switch to using LNG received competitive advantages in the form of reduced operating costs and compliance with new environmental standards. However, the overall dynamics of the introduction of this fuel in the industry remained slow due to the high cost of technological transition and the need to adapt the regulatory framework.

A. Yao *et al*. (2024) concluded that the competitive advantages of LNG vessels are becoming increasingly obvious to shipowners, as these vessels allow them to meet the requirements of international environmental regulations, in particular, with regard to greenhouse gas emissions. The use of LNG also reduces fuel costs, which contributes to savings in operating costs, in particular, in the long term. In addition, LNG vessels can operate in areas with limited emissions, which allows shipowners to avoid the need to install additional filtration systems, which reduces additional costs. S. Ha *et al*. (2022) found that adapting the regulatory framework is a necessary step to ensure effective implementation of LNG in the shipping industry. This includes updating international and national legislation regulating the use of LNG as fuel, in particular, in terms of safety and ecology. In addition, standardisation of infrastructure and training of crews to work with LNG create conditions for the smooth functioning of new technologies in navigation.

When analysing the results of the study, it is clear that the transition to the use of LNG in shipping not only provides significant environmental benefits, but also has economic potential for shipowners. Given the reduction in fuel costs and the need for fewer filtration systems, shipping companies gain additional competitive advantages in the market. However, for the successful implementation of such technologies, it is important to develop the appropriate infrastructure, update the regulatory framework, and ensure that crews are qualified to work with new types of fuel. Overall, the study confirmed that the transition to LNG was a strategically important step for the modernisation of marine energy. Its implementation reduced the negative impact on the environment and also improved the energy efficiency of ships. However, further investment in infrastructure, improvements in fuel storage and supply technologies, and support from governments and international organisations remained necessary to fully integrate LNG into global shipping.

Conclusions

LNG has demonstrated significant potential in the modernisation of marine energy, ensuring compliance with modern environmental standards, improving energy efficiency and reducing operating costs. The study confirmed that the use of LNG as a marine fuel contributes to a significant reduction in emissions of harmful substances, including SO_x, NO_x, and CO_2. From a technological standpoint, it is established that modern marine power plants, in particular, dual-fuel engines and gas engines with spark ignition, provide a high level of efficiency and safety. Cryogenic LNG storage systems and fuel supply systems that minimise evaporation and energy loss were also investigated.

Analysis of economic aspects has shown that although the transition to LNG requires significant initial investment, in the long run, it can reduce fuel costs and environmental measures. Financial incentives, such as subsidies and concessional lending, contribute to the active adoption of this technology. Infrastructure challenges remain one of the key barriers to the widespread use of LNG in shipping. Despite the development of LNG terminals and bunkering stations, their number is insufficient in regions such as Africa, South America, and parts of Asia, where LNG bunkering infrastructure still requires significant investment and development. The introduction of floating LNG terminals can partially solve this problem by ensuring fuel availability for remote ports.

In general, the results of the study confirmed that the introduction of LNG is a strategically important area for the development of marine energy. Further investment in infrastructure, regulatory improvements, and staff training are needed to effectively implement this transition. A limitation of the study is the lack of analysis of specific regional conditions and practical examples of LNG implementation on certain types of vessels, which limits the universality of the results obtained for all shipping companies. It is necessary to study in more detail the long-term impact of LNG use on the performance of marine power plants and their adaptation to future alternative fuels.

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References

[1] Adekoya, O.O., Adefemi, A., Tula, O.A., Umoh, A.A., & Gidiagba, J.O. (2024). A comprehensive review of Liquefied Natural Gas (LNG) market dynamics: Analyzing the current trends, challenges, and opportunities in the global LNG market. *World Journal of Advanced Research and Reviews*, 21(1), 58-74. doi: 10.30574/wjarr.2024.21.1.2686.

[2] Al-Sobhi, S.A., AlNouss, A., Shamlooh, M., Al-Nuaimi, K., AlMulla, A., & Khraisheh, M. (2021). Sustainable boil-off gas utilization in liquefied natural gas production: Economic and environmental benefits. *Journal of Cleaner Production*, 296, article number 126563. doi: 10.1016/j.jclepro.2021.126563.

[3] Barberi, S., Sambito, M., Neduzha, L., & Severino, A. (2021). Pollutant emissions in ports: A comprehensive review. *Infrastructures*, 6(8), article number 114. doi: 10.3390/infrastructures6080114.

[4] Bruno, M. (2022). *Shanghai Port opens 3 million TEU empty container centre*. Retrieved from https://www.porttechnology.org/news/shanghai-port-opens-3-million-teu-empty-container-centre/.

[5] Cassar, M.P., Dalaklis, D., Ballini, F., & Vakili, S. (2021). Liquefied natural gas as ship fuel: A maltese regulatory gap analysis. *Transactions on Maritime Science*, 10(1), 247-259. doi: 10.7225/toms.v10.n01.020.

[6] Chimshir, V.I., Danylenko, O.B., & Shulga, Yu.M. (2023). Safety of navigation in marine and inland waterway transport as an object of scientific research. *Waterway Transport*, 38(2), 231-240. doi: 10.33298/2226-8553.2023.2.38.24.

[7] Connecting Europe Facility. (2021). Retrieved from https://surli.cc/wmlgjb.

[8] Deng, J., Wang, X., Wei, Z., Wang, L., Wang, C., & Chen, Z. (2021). A review of NOx and SOx emission reduction technologies for marine diesel engines and the potential evaluation of liquefied natural gas fuelled vessels. *Science of the Total Environment*, 766, article number 144319. doi: 10.1016/j.scitotenv.2020.144319.

[9] Dewiatena, A.D., & Bahagia, N. (2023). Comparative study of port business characteristics with maritime logistics approach in ports: Shanghai, Singapore, Busan, and Rotterdam. *Asian Journal of Social and Humanities*, 1(10), 650-673. doi: 10.59888/ajosh.v1i10.68.

[10] Domić, I., Stanivuk, T., Stazić, L., & Pavlović, I. (2022). Analysis of LNG carrier propulsion developments. *Journal of Applied Engineering Science*, 20(4), 1122-1132. doi: 10.5937/jaes0-36809.

[11] Du, K., & Li, K. (2023). Research on China's potential LNG bunkering center selection based on AHP-TOPSIS method. In R. Liu, C. Qi & T.-H. Law (Eds.), *Advances in traffic transportation and civil architecture* (pp. 735-748). London: CRC Press. doi: 10.1201/9781003402220.

[12] Elkafas, A.G., Khalil, M., Shouman, M.R., & Elgohary, M.M. (2021). Environmental protection and energy efficiency improvement by using natural gas fuel in maritime transportation. *Environmental Science and Pollution Research*, 28(43), 60585-60596. doi: 10.1007/s11356-021-14859-6.

[13] Ha, S.M., Jeong, B., & Park, C. (2022). A novel approach to developing effective maritime regulations: The case of LNG cargo filling limits. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 6(4), 167-184. doi: 10.1080/25725084.2022.2146374.

[14] He, D., Ba, Q., & Kang, Y. (2023). Spatiotemporal evolution and mechanisms of port local hinterland: A case study of Yangtze River Delta, China. *International Journal of Shipping and Transport Logistics*, 17(3), 335-361. doi: 10.1504/IJSTL.2023.134755.

[15] Hiteshk. (2019). *The port of Singapore: One of the busiest ports in the world*. Retrieved from https://www.marineinsight.com/ports/the-port-of-singapore-one-of-the-busiest-ports-in-the-world/.

[16] Hoang, A.T., Pandey, A., De Osés, F.J., Chen, W.-H., Said, Z., Ng, K.H., Ağbulut, U., Tarełko, W., Ölçer, A.I., & Nguyen, X.P. (2023). Technological solutions for boosting hydrogen role in decarbonization strategies and net-zero goals of world shipping: Challenges and perspectives. *Renewable and Sustainable Energy Reviews*, 188, article number 113790. doi: 10.1016/j.rser.2023.113790.

[17] Jang, H., Jeong, B., Zhou, P., Ha, S., & Nam, D. (2021). Demystifying the lifecycle environmental benefits and harms of LNG as marine fuel. *Applied Energy*, 292, article number 116869. doi: 10.1016/j.apenergy.2021.116869.

[18] Jeong, J., Jung, W., Che, S., & Chang, D. (2024). Experiment-based feasibility study of LNG equipment-embedded fuel gas supply system for vessels. *Energy*, 309, article number 132959. doi: 10.1016/j.energy.2024.132959.
[19] Jesus, B., Ferreira, I.A., Carreira, A., Erikstad, S.O., & Godina, R. (2024). Economic framework for green shipping corridors: Evaluating cost-effective transition from fossil fuels towards hydrogen. *International Journal of Hydrogen Energy*, 83, 1429-1447. doi: 10.1016/j.ijhydene.2024.08.147.
[20] Khoiriyah, L., Artana, K.B., & Dinariyana, A.A. (2023). Concetual design of floating storage and regasification unit (FSRU) for Eastern Part Indonesia. *IOP Conference Series: Earth and Environmental Science*, 1239, article number 012015. doi: 10.1088/1755-1315/1239/1/012015.
[21] Kim, J.S., Lee, W.J., Pham, V.C., & Choi, J.H. (2022). A numerical study on fuel injection optimization for a ME-GI dual-fuel marine engine based on CFD analysis. *Applied Sciences*, 12(7), article number 3614. doi: 10.3390/app12073614.
[22] Kırval, L., & Çalışkan, U.Y. (2022). Influence of the European union (EU) on international maritime organization (IMO) about the market-based measures on emissions. *International Journal of Environment and Geoinformatics*, 9(3), 146-153. doi: 10.30897/ijegeo.1047467.
[23] Lähde, T., & Giechaskiel, B. (2021). Particle number emissions of gasoline, compressed natural gas (CNG) and liquefied petroleum gas (LPG) fueled vehicles at different ambient temperatures. *Atmosphere*, 12(7), article number 893. doi: 10.3390/atmos12070893.
[24] Ma, H.L., Leung, L.C., Chung, S.H., & Wong, C.W. (2023). Insurance incentive to shippers by a container port: Issues of risk management in supply chain finance. *Annals of Operations Research*, 331(1), 121-139. doi: 10.1007/s10479-021-04261-3.
[25] MARPOL Annex VI and the Act to Prevent Pollution from Ships. (2024). Retrieved from https://www.epa.gov/enforcement/marpol-annex-vi-and-act-prevent-pollution-ships-apps.
[26] Orysiak, E., Zielski, H., & Gawle, M. (2024). LNG logistics model to meet demand for bunker fuel. *Energies*, 17(7), article number 1758. doi: 10.3390/en17071758.
[27] Palestini, L., & Sassu, F. (2021). Risks and safety measures associated with the storage and transport of liquefied natural gas (LNG). *International Journal of Safety and Security Engineering*, 11(4), 409-418. doi: 10.18280/ijsse.110414.
[28] Polemis, D., & Boviatsis, M. (2023). Legal and policy issues while evaluating the sustainability of a floating storage regasification unit: The case of Alexandroupoli Greece. *Sustainability*, 15(5), article number 4660. doi: 10.3390/su15054660.
[29] Port of Rotterdam cargo throughput decreased in 2024. (2025). Retrieved from https://www.maritimegateway.com/port-of-rotterdam-cargo-throughput-decreased-in-2024/.
[30] Ratnakar, R.R., Gupta, N., Zhang, K., van Doorne, C., Fesmire, J., Dindoruk, B., & Balakotaiah, V. (2021). Hydrogen supply chain and challenges in large-scale LH2 storage and transportation. *International Journal of Hydrogen Energy*, 46(47), 24149-24168. doi: 10.1016/j.ijhydene.2021.05.025.
[31] Rony, Z.I., Mofijur, M., Hasan, M.M., Rasul, M.G., Jahirul, M.I., Ahmed, S.F., Kalam, M.A., Badruddin, I.A., Khan, T.M., & Show, P.L. (2023). Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals. *Fuel*, 338, article number 127220. doi: 10.1016/j.fuel.2022.127220.
[32] Sagin, S.V., & Poberezhny, R.V. (2022). Analysis of the main methods of reducing the emission of nitrogen oxides from diesel engines of marine and inland water transport vessels. *Ship Power Plants*, 44, 132-141. doi: 10.31653/smf44.2022.132-141.
[33] Satta, G., Parola, F., Vitellaro, F., & Morchio, G. (2021). LNG bunkering technologies in ports: An empirical application of the SWOT analysis. *KMI International Journal of Maritime Affairs and Fisheries*, 13(1), 1-21. doi: 10.54007/ijmaf.2021.13.1.1.
[34] Shih, Y.C., Tzeng, Y.A., Cheng, C.W., & Huang, C.H. (2023). Speed and fuel ratio optimization for a dual-fuel ship to minimize its carbon emissions and cost. *Journal of Marine Science and Engineering*, 11(4), article number 758. doi: 10.3390/jmse11040758.
[35] Singh, A., & Shanthakumar, S. (2022). Economic and legal impact of 2020 sulphur limit under annex VI, MARPOL. *European Energy and Environmental Law Review*, 31(4), 241-257. doi: 10.54648/eelr2022017.
[36] Stolz, B., Held, M., Georges, G., & Boulouchos, K. (2022). Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. *Nature Energy*, 7(2), 203-212. doi: 10.1038/s41560-021-00957-9.
[37] Tvedten, I.Ø., & Bauer, S. (2022). Retrofitting towards a greener marine shipping future: Reassembling ship fuels and liquefied natural gas in Norway. *Energy Research & Social Science*, 86, article number 102423. doi: 10.1016/j.erss.2021.102423.
[38] Van Biert, L., Mrozewski, K., & Hart, P. (2021). *Public final report: Inventory of the application of Fuel Cells in the MARitime sector (FCMAR)*. Retrieved from https://maritiemland.nl/wp-content/uploads/2022/06/fcmar-final.pdf.

[39] Xiuzhen, X., Zheng, W., & Umair, M. (2022). Testing the fluctuations of oil resource price volatility: A hurdle for economic recovery. *Resources Policy*, 79, article number 102982. doi: 10.1016/j.resourpol.2022.102982.
[40] Yao, A.F., Sèbe, M., Virto, L.R., Nassiri, A., & Dumez, H. (2024). The effect of LNG bunkering on port competitiveness using multilevel data analysis. *Transportation Research Part D: Transport and Environment*, 132, article number 104240. doi: 10.1016/j.trd.2024.104240.
[41] Yao, S., Li, C., & Wei, Y. (2023). Design and optimization of a zero carbon emission system integrated with the utilization of marine engine waste heat and LNG cold energy for LNG-powered ships. *Applied Thermal Engineering*, 231, article number 120976. doi: 10.1016/j.applthermaleng.2023.120976.
[42] Yeo, S.J., Kim, J., & Lee, W.J. (2022). Potential economic and environmental advantages of liquid petroleum gas as a marine fuel through analysis of registered ships in South Korea. *Journal of Cleaner Production*, 330, article number 129955. doi: 10.1016/j.jclepro.2021.129955.
[43] Yin, Y., & Lam, J.S. (2022). Bottlenecks of LNG supply chain in energy transition: A case study of China using system dynamics simulation. *Energy*, 250, article number 123803. doi: 10.1016/j.energy.2022.123803.
[44] Zannis, T.C., Katsanis, J.S., Christopoulos, G.P., Yfantis, E.A., Papagiannakis, R.G., Pariotis, E.G., Rakopoulos, D.C., Rakopoulos, C.D., & Vallis, A.G. (2022). Marine exhaust gas treatment systems for compliance with the IMO 2020 global sulfur cap and tier III NOx limits: A review. *Energies*, 15(10), article number 3638. doi: 10.3390/en15103638.

Зріджений природний газ як стратегічний вектор модернізації суднової енергетики

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Анотація. Актуальність дослідження зумовлена необхідністю зниження викидів шкідливих речовин у судноплавстві, відповідністю міжнародним екологічним стандартам та пошуком економічно ефективних рішень для паливного забезпечення флоту. Метою дослідження було проведення аналізу технологічних, екологічних та економічних аспектів використання зрідженого природного газу (ЗПГ) в судновій енергетиці для оцінки його ефективності та перспектив впровадження. У результаті дослідження було виявлено, що використання ЗПГ у судновій енергетиці є ефективним рішенням для зниження екологічних впливів та дотримання міжнародних екологічних стандартів. ЗПГ дозволяє значно зменшити викиди вуглекислого газу (CO_2), оксидів азоту (NO_x) і оксидів сірки (SO_x), що робить його конкурентоспроможним паливом для суден, що працюють у зонах контролю викидів. Технологічно ЗПГ забезпечує високу енергоефективність, зокрема завдяки використанню двигунів подвійного палива, що дозволяють оптимізувати витрати на паливо і зменшити негативний вплив на навколишнє середовище. Сучасні суднові енергетичні установки, оснащені кріогенними системами зберігання та подачі газу, підтверджують ефективність ЗПГ у забезпеченні стабільної роботи суден. Економічні дослідження показали, що хоча перехід на ЗПГ вимагає значних початкових інвестицій у переобладнання суден та інфраструктуру, в перспективі це дозволяє зменшити експлуатаційні витрати та витрати на екологічні заходи, такі як установки для зниження викидів сірки. Практичне значення дослідження полягає в тому, що воно сприяє розвитку теоретичних і практичних основ використання ЗПГ як екологічно чистого та економічно вигідного палива в судновій енергетиці, що може бути використано для вдосконалення існуючих технологій і нормативних актів у галузі судноплавства

Ключові слова: екологічні стандарти; двигуни подвійного палива; кріогенні системи; експлуатаційні витрати; зони контролю викидів

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

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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

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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.

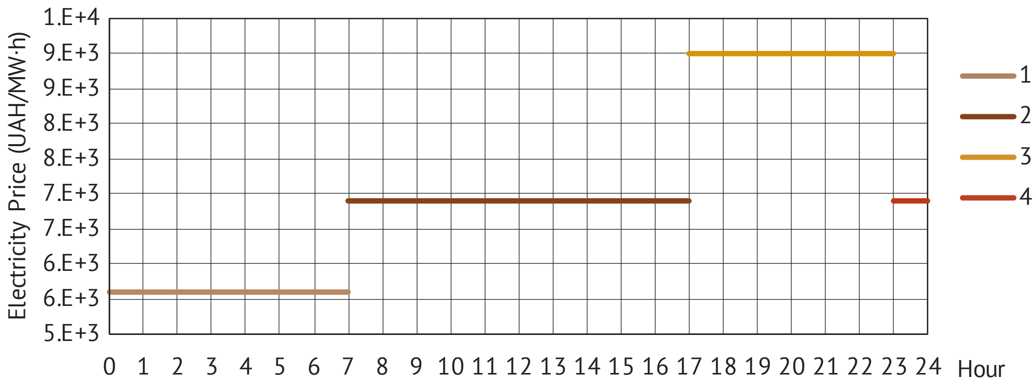
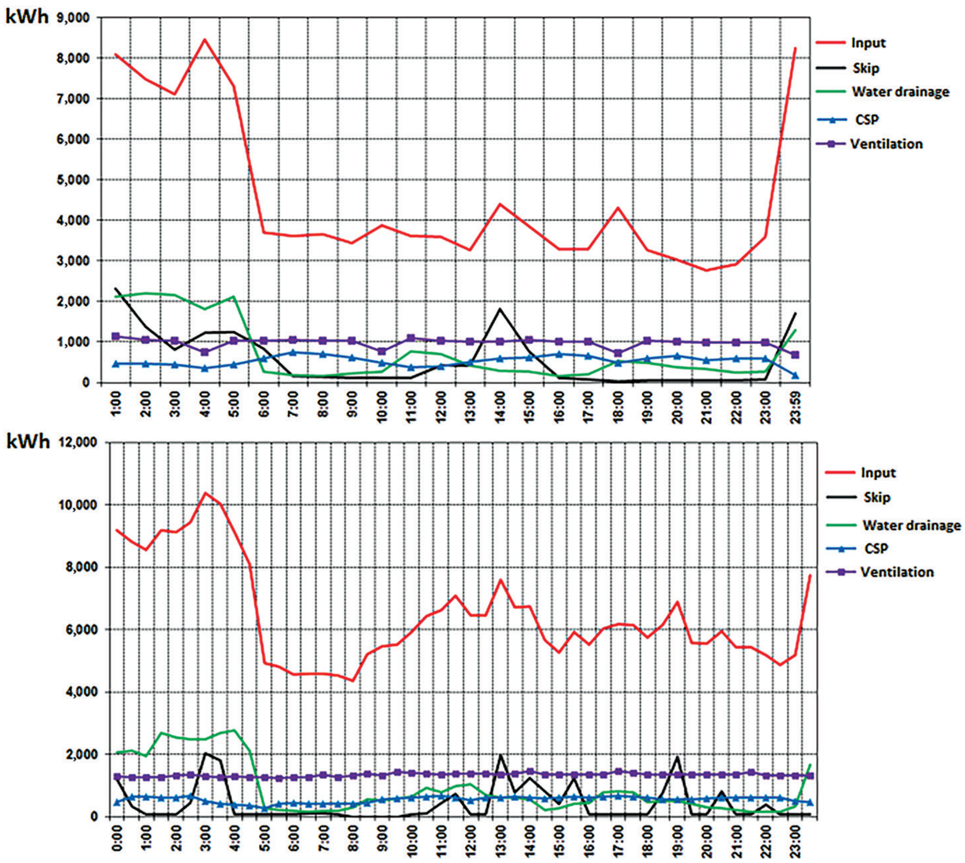


Figure 1. Charts of limit prices on the intraday market

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.



a

b

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:

$$W_0 = \int_0^T N(t)dt, \tag{1}$$

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:

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

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:

$$C = \int_0^T c(t)N(t)dt \rightarrow \underset{N(t)}{min}, \tag{3}$$

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.:

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

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:

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

or, according to (4):

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

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 $[T_3;\ \mathrm{T}]$.

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:

$$W_1 + W_2 + W_3 + W_4 = W_0. \tag{7}$$

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:

$$\begin{gathered} \int_0^{T_1} N_{\min}\, dt \leqslant \int_0^{T_1} N dt \leqslant \int_0^{T_1} N_{max}\, dt, \\ N_{\min} \int_0^{T_1} dt \leqslant \int_0^{T_1} N_{dt} \leqslant N_{max} \int_0^{T_1} dt, \\ N_{\min}\, T_1 \leqslant W_1 \leqslant N_{max}\, T_1. \end{gathered} \tag{8}$$

Limitations for the time period $[T_1;\ T_2]$:

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

Limitations for the time period $[T_2;\ T_3]$:

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

Limitations for the time period :

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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:

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

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

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

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

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

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):

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

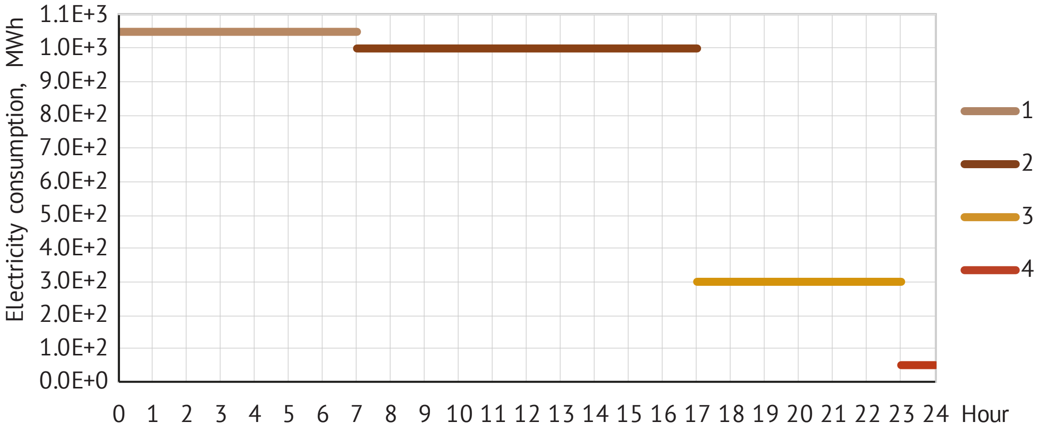


Figure 3. Graphs of optimal values of electricity consumption during the day
Source: compiled by the authors

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.

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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

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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

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Industrial adsorption methods for reduction of sulphur content in hydrocarbon streams

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Abstract. Industrial adsorption methods for reducing sulphur content in hydrocarbon streams were investigated with an emphasis on their engineering efficiency and technological adaptability in oil refineries. A comparative analysis of the use of zeolites, activated carbons, metal-organic frameworks, carbon molecular sieves, metal oxides, polymeric materials, metal sulphides, modified clay and bentonite aimed at reducing the sulphur content in hydrocarbon streams was conducted. Adsorption using zeolites and metal-organic frameworks was noted to be highly effective in removing sulphur-containing compounds such as thiophenes and mercaptans, especially at high sulphur concentrations. However, these methods require significant capital expenditure and a complex infrastructure to scale. Activated carbons, despite their availability and cost-effectiveness, have demonstrated lower efficiency in removing sulphur from heavy hydrocarbons and limited regeneration capabilities. Hybrid methods that combine adsorption with catalytic desulphurisation have proven to be promising for deep sulphur removal and lower operating costs due to the ability to regenerate the adsorbent. For large plants, hybrid technologies and methods using zeolites and metal-organic frameworks are optimal, providing high efficiency while meeting environmental standards. For small and medium-sized refineries, activated carbon technologies are economically viable. Thus, the choice of adsorption method depends on the specifics of the enterprise, the type of hydrocarbon flow and the opportunities for introducing innovative technologies

Keywords: zeolites; organometallic scaffolds; catalytic desulphurisation; oil refineries; activated carbons

Introduction

Reduction of sulphur content in hydrocarbon streams is the most important task of the refining industry due to strict environmental standards and the need to improve fuel quality. High sulphur content in petroleum products not only deteriorates their performance characteristics but also contributes to environmental pollution, which leads to additional economic and environmental risks. One of the most effective methods of removing sulphur-containing compounds is adsorption, which is used to purify hydrocarbon streams at various refining stages. In 2023, the development of new and improvement of existing adsorbents, such as zeolites,

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activated carbons and metal-organic frameworks, as well as combined methods combining adsorption with catalytic desulphurisation were prioritised (Yang *et al.*, 2023). However, the choice of the most effective method depends on many factors, including the type of feedstock to be treated, sulphur concentration and technical features of the plant.

Q. Shi & J. Wu (2021) investigated the use of zeolites in the adsorption processes of sulphur-containing compounds, noting their high efficiency at high sulphur concentrations. These materials significantly improved the quality of hydrocarbon streams and met environmental standards. G. Li *et al.* (2024) analysed the use of activated carbons for sulphur removal, pointing out their availability and economic benefits. However, they emphasised that for heavier hydrocarbon fractions, this method had limited effectiveness. B. Saha *et al.* (2021) studied metal-organic frameworks as a promising material for sulphur adsorption with high selectivity and modification ability. However, the work pointed out that the high cost of organometallic frameworks made them inappropriate for mass application in large refineries. Y. Pan *et al.* (2024) emphasised the problems of adsorbent regeneration, which was an important aspect of the long-term operation of these materials in industrial conditions. They emphasised that the possibility of regeneration significantly increased the economic attractiveness of adsorption technologies.

X. Wang *et al.* (2024) considered the removal of asphalt-resin-paraffin deposits by chemical methods in the production of highly paraffinic oil. The authors optimised the chemical method of oil well remediation by proposing a technique for selecting the most effective reagent, stressing the importance of an individual approach for each specific case. Jumina *et al.* (2021) investigated the combination of adsorption and catalytic desulphurisation, confirming their high efficiency in sulphur removal. They also observed that such methods could reduce operating costs by reducing the need for frequent replacement or regeneration of adsorbents. S.A. Ganiyu & S.A. Lateef (2021) emphasised the advantages of combined technologies that provided deep hydrocarbon purification and minimised waste. They argued that such approaches could significantly improve the economic efficiency of refineries.

K. Taghaddom *et al.* (2023) identified the high level of capital cost in implementing advanced refining technologies, which was a serious constraint for Small and medium-sized enterprises (SMEs). They also investigated possible ways to optimise the cost when using activated carbon for biomass degassing, highlighting the importance of selecting an efficient adsorbent and process parameters to maximise profitability. W. Zhang *et al.* (2022) investigated the environmental aspects of adsorption applications, emphasising the need to select methods that minimise emissions and waste during the purification of hydrocarbon streams. Their study emphasised meeting environmental standards and regulatory requirements. H.A. Al-Jamimi *et al.* (2022) proposed a hybrid approach using the support vector method (SVM) and genetic algorithm (GA) to treat hydrocarbons from sulphur. These minimised the sulphur content, SO_2 emissions and hydrodesulphurisation costs and achieved purification efficiency. The authors also emphasised the benefits of complying with strict environmental regulations. However, a comprehensive analysis of all existing adsorption methods concerning economic feasibility and technological adaptability in large and small refineries was lacking among scientific papers, which requires further research.

The study aimed to evaluate and compare different industrial adsorption methods in terms of their applicability for reducing sulphur content in hydrocarbon streams in refineries, with a particular focus on the engineering aspects and the possibility of integrating these methods into existing processes.

Materials and Methods

The study addressed the situation in Azerbaijan, which is determined by the availability of significant reserves of raw materials to produce zeolites and a developed oil and gas industry, where adsorbents are widely used. Four main industrial adsorption methods used to reduce sulphur content in hydrocarbon streams were analysed: adsorption on zeolites, the use of activated carbons, metal-organic frameworks (MOFs) and hybrid methods combining adsorption with catalytic desulphurisation. Sulphur compounds, commonly found in the feedstock supplied to oil refineries, were analysed: thiophenes, mercaptans and hydrogen sulphide.

The methods of using zeolites, activated carbons, metal-organic frameworks, carbon molecular sieves, metal oxides, metal sulphides, modified clays and bentonites, as well as hybrid technologies and polymeric materials that demonstrate the effectiveness of removing sulphur compounds under various technological conditions were considered. Each method was evaluated for its effectiveness in removing sulphur from hydrocarbon streams. The conditions under which the methods are most effective were determined. An important aspect of the analysis was the influence of various parameters, such as temperature, pressure and hydrocarbon stream composition. This was used to identify which methods provide the best results for the removal of light sulphur compounds and which are more effective for the removal of complex contaminants such as heavy hydrocarbons.

As part of the analysis of the economic feasibility of each method, the capital costs of equipment installation and operation, the cost of adsorbent regeneration, and the cost of replacing them during operation were estimated. The analysis of the availability of raw materials, durability and cost of adsorbent production was prioritised. This was used to identify the most cost-effective methods for large refineries, as well as for small and medium-sized enterprises that may face a lack of financial resources. The scalability of the methods was also an important aspect of the study. The possibility of implementing these technologies at different stages of production, from small installations to large production facilities, was assessed. The integration of the methods into existing refinery process chains, a significant aspect in terms of equipment modernisation and process optimisation, was analysed. The peculiarities of each technology in terms of implementation in real operation were addressed as well.

An important part of the study was the sustainability of the selected methods and their environmental impact. This analysis analysed the possibility of adsorbent regeneration, which reduces the amount of waste and reduces the cost of replacing adsorbents during operation. The extent to which each method affects the ecosystem was also investigated, addressing the long-term operation of the equipment and the possible environmental risks associated with the use of these technologies.

The study also developed recommendations for refineries on the selection of optimal adsorption methods. For this purpose, the needs of large and small refineries were analysed, as well as possible ways to improve existing desulphurisation processes. The recommendations cover both technical characteristics as well as economic and environmental aspects aimed at optimising processes, addressing all factors affecting refinery efficiency and long-term sustainability.

Results

Adsorption of sulphur-containing compounds is crucial for the purification of hydrocarbon streams, providing a reduction in sulphur emissions and improving the quality of the fuel produced. High sulphur content in hydrocarbons not only degrades their performance characteristics but also contributes to increased emissions of toxic compounds into the atmosphere. Therefore, the main objective of adsorption is to improve the quality of fuel. In the process of sulphur removal, fuel performance is significantly improved: the harmful effect on engines is reduced, the service life of equipment is increased, and operating costs are reduced. In addition, improvement of fuel quality leads to its more efficient utilisation, which contributes to saving energy resources and reducing the cost of hydrocarbon materials processing.

In the adsorption process, sulphur compound molecules adsorb on the surface of the adsorbent material, which significantly reduces the concentration of sulphur in the fuel. This method of sulphur removal is highly efficient, which allows the production of fuel following the environmental standards Euro-5, Euro-6 and Azerbaijan standards (Griffiths, 2023). To ensure compliance of the implementation of adsorption technologies with international standards, as well as to minimise emissions and comply with environmental regulations, the company needs an environmental management system. The basis for its development and implementation is provided by ISO No. 14001 (2015) standard, with the help of which the requirements for fuel quality, norms of sulphur level reduction to minimum values, and methods of adsorbent selection are established. For instance, biochar is an effective and inexpensive means of removing gaseous pollutants from combustion flue gases, including SO_2 and volatile organic compounds. It is a cheaper alternative to solid sorbents such as activated carbon, zeolites, carbon nanotubes, carbon molecular sieves and metal-organic frameworks (Wen *et al.*, 2023).

Adsorption on zeolites is one of the most effective methods of purification of hydrocarbon streams from sulphur-containing compounds. Zeolites have a unique microporous structure, which can be used to provide high selectivity to various sulphur-containing substances, such as thiophenes and mercaptans (Lee & Valla, 2019). These substances are major contaminants in hydrocarbon streams, and their removal by zeolites significantly improves fuel quality. The selectivity of zeolites to thiophenes and mercaptans is due to their size, polarity and structural feature, which allows effective retention of molecules of these compounds on the adsorbent surface (Pérez-Botella *et al.*, 2022). An important advantage of zeolites is their ability to regenerate. After saturation of the adsorbent with sulphur-containing molecules, it can be subjected to the regeneration process, restoring its adsorption properties. Depending on the type of adsorbent, it can be regenerated 3-10 times: activated carbon up to 5 times, biochar and metal-organic frameworks up to 10 times, provided the optimum conditions are met. This reduces operating costs, allowing the adsorbent to be reused many times without the need to replace it. Regeneration of zeolites is usually carried out by a thermal method, which removes all accumulated contaminants and returns the material to its original state. This process is a key factor in making the use of zeolites in industry more economically attractive.

However, there are several limitations in the use of zeolites. One of them is a decrease in adsorption efficiency at high sulphur concentrations in hydrocarbon streams (Chai *et al.*, 2021). In such conditions, the zeolite can be saturated quickly, which leads to the need for frequent regeneration or replacement of the material. Zeolites are also susceptible to contaminants, such as particulate matter or other organic matter, which can block the pores and reduce the overall efficiency of the adsorption process. These limitations need to be addressed in designing treatment systems to ensure stable operation of the adsorption unit under variable loads and hydrocarbon stream composition.

Activated carbons are one of the most popular and economically available materials for the removal of sulphur-containing compounds from hydrocarbon streams. This adsorption method is suitable for the removal of hydrogen sulphide (H_2S) and light sulphur compounds such as alpha-methylthiophene or methylmercaptans. Due to their highly porous structure, activated carbons provide a large surface area for adsorption, rendering them effective for the adsorption of gas or soluble sulphur-containing molecules, especially in the early stages of the purification process (Paucar *et al.*, 2021).

One of the main advantages of activated carbons is their economic availability. The material has a relatively low cost and is available in various forms, which can be used in a wide range of industrial processes. Activated carbons, in contrast to organometallic frameworks and zeolites, are used in cases where sulphur purification depth requirements are less stringent, such as in small or medium-sized plants where savings on capital investment are key. This may apply to cases such as treating a hydrocarbon stream with sulphur content as low as 500 parts per million (ppm), which meets less stringent requirements than for deep purification requiring significant investment in higher quality adsorbents such as metal-organic frameworks, which can operate effectively at sulphur contents as low as 10-50 ppm. In such cases, activated carbons can perform effectively despite their higher tendency to saturate, making them an attractive choice if purification depth requirements do not exceed 500-1,000 ppm. This is also true for processes where economic efficiency is more important than ultra-purification. However, despite the economic benefits, the use of activated carbons has several limitations. One of them is their low efficiency in the treatment of heavy hydrocarbon streams. For the removal of sulphur from heavy oil fractions, activated carbons do not always provide the required degree of purification, as their porous structure may not be able to cope with large molecules or high concentrations of contaminants. In addition, the regeneration process of activated carbons is labour-intensive and expensive. Due to the saturation of the adsorbent with sulphur-containing compounds, the process of regenerating the adsorbent requires significant energy and time, which increases operating costs. In most cases, activated carbons lose part of their adsorption capacity after several regeneration cycles, which leads to the need for their frequent replacement.

MOFs are innovative materials that have attracted much attention due to their high selectivity in the adsorption of various sulphur-containing compounds. These materials are composed of metals bonded with organic ligands, which provides them with unique porous structures with a large surface area. MOFs can select and adsorb specific molecules such as thiophenes, mercaptans and other sulphur-containing organic compounds, making them extremely effective for sulphur purification of hydrocarbon streams. Their high selectivity allows achieving a significant reduction of sulphur concentration with relatively low energy and time consumption for the purification process (Yu *et al.*, 2024).

One of the main advantages of MOFs is the ability to modify their structure depending on the specific needs of the refinery. The porous structure of these materials can be adapted by changing the type of metals or organic ligands, which can be used for optimised adsorption properties for specific types of hydrocarbon streams. This flexibility makes MOFs promising for creating customised solutions, which is especially important when dealing with different types of oil and gas. In contrast to traditional adsorbents such as activated carbons or zeolites, MOFs open new opportunities for improving treatment efficiency and reducing costs.

However, despite their advantages, the use of MOFs faces several limitations. One of the main factors is the high cost of these materials. The production of MOFs requires complex synthetic processes and expensive starting materials, which makes their use expensive, especially in large-scale production where significant amounts of adsorbents are required. In addition, MOFs have low stability in aggressive industrial environments such as high temperatures, humidity and the presence of various contaminants. Therefore, in refineries, these materials can lose their effectiveness due to structural degradation, which limits their durability and requires additional replacement or regeneration costs.

Carbon molecular sieves (CMS) are an important component of modern hydrocarbon stream treatment technologies. Their application covers a wide range of refinery and gas industry applications, as they reduce sulphur compounds to environmental standards. CMS demonstrates high efficiency in the removal of hydrogen sulphide, thiols and light mercaptans from natural gas and hydrocarbon streams (Nezhad *et al.*, 2023). For instance, they are used in feedstock pretreatment stages, where adsorbents placed in columns or reactors reduce the sulphur content before the main refining processes. This not only improves feedstock quality but also protects subsequent stages from contamination.

In large refineries, hydrotreating is the standard method for desulphurisation of heavy fractions such as diesel and petrol. CMS can be used as a supplement, providing fine purification after the main treatment. This is particularly important for achieving ultra-low sulphur concentrations, making them indispensable to produce high-quality petroleum products. Hydrogen used in hydrotreating can contain hydrogen sulphide, which contaminates the catalysts. CMS effectively remove these compounds, increasing the productivity and durability of the equipment.

CMS offers several key advantages. They are flexible in terms of customisation to specific streams and compounds, environmentally friendly as they meet Euro 5 and Euro 6 standards, and cost-effective due to reduced catalyst wear and regeneration capabilities. These characteristics make them a competitive solution for modern refineries. Nevertheless, there are technical limitations: large volumes of adsorbent are required to process large volumes of feedstock, which increases costs. In addition, wear and tear during regeneration cycles and extreme conditions at some refining stages require additional solutions.

Hybrid methods, combining adsorption and catalytic desulphurisation, represent an innovative strategy for deep sulphur removal from hydrocarbon streams. This approach combines the advantages of the two processes: adsorption effectively removes sulphur-containing substances such as thiophenes and mercaptans, while catalytic desulphurisation breaks down more complex sulphur compounds into less harmful substances. The combined use of adsorption and catalysis techniques can provide deeper purification of hydrocarbons, allowing sulphur levels to be achieved to meet the most stringent environmental standards. For instance, the Euro-6 standard for automotive fuels requires a sulphur content of no more than 10 mg/km, which is significantly lower compared to less stringent standards such as Euro-5, where the allowable sulphur level is 50 mg/km. Such low sulphur levels can be achieved by using advanced technologies, such as hybrid methods, and more efficient adsorbents that provide purification at a deeper level. This combination of processes is particularly effective when dealing with heavy hydrocarbons where standard purification methods are insufficient (Hassan *et al.*, 2022).

One of the key advantages of hybrid methods is increased cost efficiency, due to the possibility of regeneration of both adsorbent and catalytic material. Materials such as activated carbon, zeolites, carbon molecular sieves and metal-organic frameworks are often used for adsorption of sulphur-containing compounds. These adsorbents effectively remove sulphur in the purification stage of hydrocarbon streams and can be subjected to multiple regeneration. Catalysts used for catalytic hydrodesulphurisation are metal oxides (e.g., vanadium oxides, molybdenum oxides), metal sulphides and aluminosilicates, which promote a chemical reaction that removes sulphur from hydrocarbons at high temperatures and pressures. Importantly, both adsorbents and catalysts can be regenerated, significantly reducing operating costs and improving the durability of the purification process. The regeneration of adsorbents allows for 3-10 times of use, depending on the type of material and process conditions. Catalytic materials, such as sulphides and metal oxides, can be recovered 3-5 times using thermal or chemical methods (Ismailov & Gashimov, 2010). The combination of these processes not only improves fuel quality but also reduces long-term operating costs for hydrocarbon treatment.

However, the use of hybrid methods also has its limitations. One of the main obstacles is the difficulty of implementing such technologies into the existing refinery infrastructure. Integrating adsorption with catalytic desulphurisation requires complex equipment upgrades as well as staff training, which can require significant capital expenditure. In addition, such systems require fine-tuning of the processes to ensure their synchronised operation and avoid a reduction in overall purification efficiency. As a result, despite the high potential of hybrid methods, their implementation can be difficult, especially in the case of the limited financial and technological capabilities of the enterprise. Refiners face a variety of factors when selecting technologies for removing sulphur from hydrocarbon streams, including the efficiency, cost-effectiveness, scalability and sustainability of the methods used (Table 1). Each of the existing technologies has its strengths and weaknesses that must be assessed in the context of the specific operating conditions of the refinery.

Table 1. Comparative analysis of adsorption methods

Method	Sulphur removal efficiency (ppm)	Economic profitability	Scalability	Regeneration capability (times)	Suitable petroleum products
Zeolites	10-50	High	High	5-6	Light hydrocarbon flows
Activated carbons	50-100	Average	Average	2-3	As a supplement in hydrotreating
Metal-organic frames	<10	Low	High	5-6	For high-purity products
Hybrid methods	<10	Average	Average	3-4	For the fine purification of heavy hydrocarbons
Carbon molecular sieves	<10	Average	High	4-5	For high-purity products
Metal oxides	<10	High	High	5-6	Light hydrocarbon flows
Polymeric materials	10-20	Average	Average	1-2	As a supplement in hydrotreating
Metal sulphides	10-50	High	Average	2-3	Light hydrocarbon flows
Modified clays and bentonites	10-50	High	High	3-4	Light hydrocarbon flows and diesel

Source: compiled by the authors based on V.C. Srivastava (2012)

Methods based on the use of metal-organic frameworks and hybrid technologies show the best results in terms of efficiency. MOFs are highly selective and can be used to effectively remove sulphur-containing compounds, even at high sulphur concentrations, such as those found in primary and secondary refining stages such as hydrotreating and hydrodesulphurisation. High levels of sulphur are often encountered in these stages, requiring effective purification methods. Hybrid methods, combining adsorption with catalytic desulphurisation, can be effectively applied to hydrotreating and hydrodesulphurisation in refineries. For instance, in the hydrotreating stage of diesel or petrol where sulphur-containing compounds are in high concentrations, the use of hybrid methods can provide deep purification and high sulphur removal rates, reducing the need for continuous replacement of adsorbents and catalysts. It also helps maintain process stability under high temperature and pressure conditions. Activated carbons and zeolites are effective in the purification of hydrocarbons from sulphur, but their effectiveness is limited at high sulphur concentrations (greater than 1-2%) or complex sulphur-containing compounds such as thiophenes. Under such conditions, MOFs and carbon molecular sieves are more effective, providing better selectivity and high capacity.

Cost-effectiveness is essential, especially for businesses with limited budgets. Activated carbons are a more affordable option due to low material costs and ease of implementation. This solution is ideal for smaller refineries or temporary situations, such as equipment refurbishment or short-term peaks, where full modernisation of sulphur treatment processes is not feasible. While MOFs and hybrid methods offer high efficiency, their cost and complexity of implementation can be significant, making them less economical in the short term. However, when considering the long-term benefits of improved fuel quality and compliance with environmental standards, more expensive methods may justify the investment.

Scalability is also an important criterion, especially for large refineries where large volumes of hydrocarbons need to be processed. Zeolites and MOFs have a high potential for scalability. This makes them promising for large plants where methods capable of operating efficiently at high flow volumes are required. These technologies offer high levels of purification down to sulphur levels, for instance, in the range of 10-50 ppm, making them attractive to large plants that need to meet stringent environmental standards and handle more complex hydrocarbon streams. Adoption of technologies such as catalytic hydrodesulphurisation requires significant capital investment, which can range from USD 5 to USD 10 million, depending on the scale and complexity of the plant. This limits their use to small refineries that cannot justify such costs. Small refineries typically have a capacity of up to 50,000 barrels of oil per day and are limited in resources. These facilities often opt for more affordable and easily scalable technologies, such as adsorption using activated carbons. These techniques allow the solution to be quickly integrated into existing systems without significant installation and maintenance costs.

The sustainability of technological solutions is important for long-term application. Hybrid technologies, which combine adsorption and catalytic desulphurisation, are the most environmentally friendly option, as they allow for the reuse of adsorbents and catalysts, which reduces waste and minimises environmental pollution. This approach contributes to the overall sustainability of the process. MOFs, despite their high efficiency, require further research to optimise their stability and durability in industrial applications. This limits their widespread use, although their sustainability prospects remain promising. Activated carbons, although easily regenerated, can pose environmental problems due to the need for frequent replacement and disposal of the material.

Thus, the choice of method for sulphur removal from hydrocarbon streams depends on many factors. For large refineries focused on high efficiency and scalability, MOFs or hybrid methods are preferred. For plants with limited financial resources or those that need to implement solutions quickly, activated carbons will be more suitable. The choice should be based on a comprehensive assessment of all factors, including efficiency, cost, scalability and environmental sustainability of the technologies (Cako *et al.*, 2022). Technological adaptability is a key factor in the selection of sulphur removal methods for refineries, as the successful integration of new technologies must address both economic viability and environmental standards (Table 2). In this context, scalability, integration into existing processes and environmental sustainability are important aspects.

Table 2. Technological adaptability of adsorption methods

Aspect	Zeolites	Activated carbons	Metal-organic frames	Hybrid methods
Integration	Complex	Simple	Complex	Average
Environmental sustainability	Moderate	Limited	High	High
Initial costs	Average	Low	High	Average
Sulphur-containing substances	Hydrogen sulphide, organic sulphur-containing compounds	SO_2, hydrogen sulphide, volatile organic compounds	SO_2, volatile organic sulphurous compounds	SO_2, hydrogen sulphide, organic compounds

Source: compiled by the authors based on K. Chen *et al.* (2020)

The integration of new technologies into existing processes is another key aspect. Activated carbon, due to its relatively low cost and ease of use, can be easily integrated into existing treatment systems. This technology does not require fundamental process changes, which greatly simplifies its implementation and reduces the capital cost of modernisation. In the case of zeolites and MOFs, the integration process may require not only significant financial investment but also a redesign of some equipment, making their application complex and requiring careful preparation. Thus, for plants that already have functioning plants, activated carbons are a better option in terms of technological adaptability.

Environmental aspects are substantial in the long-term sustainability of technologies. In the face of increasing environmental demands, adsorbent recovery is becoming an important mechanism for reducing waste and increasing material efficiency. Hybrid methods that combine adsorption with catalytic desulphurisation have significant environmental potential, as they allow for multiple regeneration of adsorbents and catalysts, thus reducing waste. Activated carbons, although they have limitations in terms of regeneration frequency, such as reduced efficiency with multiple regenerations and possible accumulation of contaminants in the porous structure, can also reduce environmental impacts due to the possibility of material reuse. These limitations relate to the loss of adsorption capacity and the need to use additional methods, such as thermal or chemical regeneration, to maintain their efficiency at the required level. While MOFs, despite their high efficiency, require further research in terms of their sustainability and regeneration, which limits their widespread use in industrial plants.

Thus, when choosing technologies for removing sulphur from hydrocarbon streams of refineries, it is necessary to consider their technological adaptability. For large enterprises with the possibility of significant capital investments, it is advisable to introduce more efficient but expensive technologies, such as zeolites and MOFs. For smaller or temporary solutions, methods that can be easily integrated into existing systems, such as activated carbons, are more suitable, especially if the focus is on cost optimisation and minimising environmental impact.

With environmental standards constantly evolving and the desire to improve fuel quality, refineries are faced with the need to select effective technologies for sulphur removal from hydrocarbon streams. Recommendations for selecting adsorption methods for such plants depend on a variety of factors, including refinery size, technical capabilities and financial resources. For large refineries, hybrid methods or metal-organic frameworks are appropriate. These require significant upfront costs but provide high sulphur removal efficiencies to achieve the desired environmental standards even when treating complex hydrocarbon streams. Hybrid systems incorporate adsorption and catalytic desulphurisation to provide deep purification, making them attractive to large plants with long-term environmental and economic goals. At the same time, MOFs can be used to optimise purification due to their high selectivity and ability to be modified to suit specific refinery conditions.

Activated carbons are suitable for smaller refineries, those with limited financial resources, and for a quick or temporary solution to a treatment problem: they are low-cost, easy to use and readily available. Although activated carbons are not as effective for deep removal of sulphur in complex hydrocarbons, they can be used for pretreatment, making them a good option for refineries that cannot afford to implement more expensive technologies.

The choice of technology should be preceded by an analysis of economic viability and environmental compliance. It is necessary to address the cost of installation and operation of technologies, their durability, the possibility of material regeneration, and the impact on the environment. Therefore, refineries should select technologies with a view to long-term benefits, optimising costs and achieving maximum efficiency in the treatment of hydrocarbon streams from sulphur.

Discussion

The study determined that adsorption methods demonstrate high efficiency for removing sulphur compounds from hydrocarbon streams, but each technology has its limitations. Activated carbons, despite their effectiveness in removing sulphur, are limited in their application at high sulphur concentrations in the stream and are sensitive to heavy hydrocarbon contamination. This limits their use in complex hydrocarbon streams.

Zeolites are reliable adsorbents due to their selectivity to thiophenes and mercaptans. B. Bulut *et al*. (2022) conducted studies on LPG desulphurisation using modified zeolites. These zeolites were treated with metal ions (Cu^{2+}, Zn^{2+} and Cu^{2+}-Zn^{2+}) through liquid phase ion exchange. The study confirmed that these modified zeolites were effective in removing dimethyldisulfide and thiophene from the gas stream, showing high efficiency. T. Yu *et al*. (2022) also demonstrated that the main problem with the use of zeolites is a decrease in their selectivity and sorption capacity at high sulphur concentrations in the treated stream. Contamination of zeolites with hydrocarbons or other substances can block the active centres, which significantly reduces their efficiency. To solve this problem, methods are being developed to regenerate zeolites and increase their resistance to contamination, such as the use of additional modifiers or combinations with other sorbents.

It is worth noting that the efficiency of zeolites in removing thiophenes and mercaptans depends not only on their structure but also on process conditions, such as temperature, pressure and composition of the processed mixture. An important area of research is the development of modified zeolites with improved catalytic and sorption properties capable of handling high sulphur concentrations. The creation of technologies that minimise zeolite degradation and facilitate their regeneration are prioritised to ensure sustainable operation in industrial conditions. The use of activated carbons has confirmed their economic affordability and ease of integration into existing production processes (Kosogina *et al.*, 2019). However, their low efficiency in handling heavy hydrocarbons and the impossibility of multiple regenerations made them less suitable for deep sulphur removal tasks. This confirms the need to use activated carbons only in combination with other technologies or for temporary solutions.

S.Z. Naji & C.T. Tye (2022) investigated the use of activated carbon as a precursor and catalyst in biodiesel production. They concluded that activated carbon can be easily integrated into technological processes due to its availability and ease of use. This makes it an attractive option for improving refinery operations with minimal modification of existing equipment. K.L. Tan & K.Y. Foo (2022) determined that, despite their economic availability, activated carbons have several limitations in the treatment of refinery wastewater. Their adsorption capacity can decrease at high pollutant concentrations, requiring frequent regeneration or replacement of the material (Hulevskyi & Postol, 2022). In addition, activated carbons are less effective at removing more complex or high molecular weight organic compounds, which limits their use in more severe processing conditions.

X. Wang *et al.* (2021) confirmed the results of the study that activated carbons can be successfully integrated into existing processes without the need for significant technical changes. This underscores their attractiveness as a cost-effective solution that allows petrochemical plants to quickly adapt to the requirements of purification. At the same time, these carbons provide a sufficiently high level of adsorption for most common pollutants, which confirms their wide applicability in current technologies. Metal-organic frameworks, despite their high selectivity and flexibility in structure tuning, have demonstrated insufficient resistance to industrial conditions. The high cost of synthesis and the need to develop more stable structures are the main obstacles to their widespread use. Nevertheless, their potential in the long term is high, making them an attractive target for further research.

The study by J. Guo *et al.* (2021), which determined that metal-organic framework materials have several advantages, such as high selectivity in the sorption of various pollutants and the possibility of modifying their structure to improve properties, is noteworthy. This allows MOFs to effectively remove specific pollutants, such as sulphur compounds, even at low concentrations in the stream. In addition, the ability to modify structure parameters such as pore size and chemical environment opens additional opportunities for their application in various fields, including petrochemicals. S.G. Yunusov *et al.* (2023) noted that desulphurisation of coke oven gasoline and diesel fraction blends by alternative methods (adsorption, extraction, oxidative desulphurisation using hydrogen peroxide and alkyl peroxides) is an important task to reduce sulphur emissions, cheapen refining, and improve fuel performance. For instance, the authors proposed to use adsorbents to prevent the loss of octane fuel. However, their proposed methods require further improvement to ensure stability and efficiency under industrial conditions. The results of Z. Zaidi *et al.* (2023) concur with the results of this study as they confirm the effectiveness of alternative desulphurisation methods in reducing the sulphur content of fuel fractions. The application of such methods as adsorption and catalysis can significantly improve the quality of coke oven petrol and diesel fraction blends, reducing their harmful impact on the environment.

Hybrid methods combining adsorption with catalytic desulphurisation showed the best results in terms of sulphur removal depth. In addition, the ability to regenerate adsorbents reduced operating costs. However, the complexity of their integration into the existing infrastructure and the high initial cost of the equipment limits their use in some cases. These aspects require further optimisation to ensure greater technological adaptability. S. Gooneh-Farahani & M. Anbia (2023) also conducted a study, the results of which confirmed that hybrid methods combining different approaches to remove sulphur from hydrocarbon streams show high efficiency in achieving deep purification. The use of technologies such as the combination of adsorption with catalytic process or membrane filters can increase the degree of sulphur removal with less energy and feedstock. These methods can significantly improve the quality of petrochemical products while meeting stringent environmental standards.

A. Asghar *et al.* (2022) determined that the introduction of hybrid technologies into biorefinery infrastructure faces several challenges, including the need to modernise existing equipment and the high cost of new systems. One solution may be to introduce hybrid technologies in a phased manner, allowing them to be gradually integrated into existing processes. Equally, an important step is to develop flexible and economically feasible schemes for the regeneration and replacement of the materials used, which will help to reduce initial costs and improve system longevity. Their study confirms that hybrid methods do provide significant improvements in the efficiency of sulphur removal from hydrocarbon streams. By combining different technologies, the limitations of each can be compensated for, providing deeper purification and lower operating costs. This confirms the potential of hybrid solutions as a key element in modernising refining processes to meet modern environmental requirements.

Comparison of the methods showed that the choice of technology depends on several factors, including sulphur concentration, hydrocarbon stream composition, economic viability and equipment availability. This demonstrates the need for an integrated approach when planning desulphurisation systems. Integration of several methods may prove to be the most effective strategy to meet both environmental and economic requirements. D.C.C. da Silva Medeiros *et al*. (2022) concluded that when selecting adsorption technology for the treatment of hydrocarbon streams, process efficiency, economics and the composition of the stream itself are key factors. Efficiency depends on the ability of the adsorbent to selectively remove pollutants with minimum energy and material consumption. It is also important to consider the composition of the hydrocarbon stream, as the presence of various impurities can significantly influence the choice of adsorbent and the optimisation of the treatment process.

T. Alomar *et al*. (2024) determined that to achieve both the environmental and economic goals of refineries, it is often necessary to combine several treatment methods. For instance, the use of adsorption in combination with catalytic processes or membrane technologies can increase the degree of pollutant removal and reduce the cost of material recovery. Thus, the integration of different technologies can achieve an optimal balance between costs and environmental requirements, which is critical for the sustainable operation of a refinery. Thus, the effectiveness of adsorption technologies directly depends on the composition of the hydrocarbon stream and the selected adsorbent. In the case of multi-component streams, a combination of different treatment methods can significantly improve the results compared to a single approach. This confirms the need for a more careful selection and combination of technologies to achieve optimal performance at minimum cost and compliance with environmental standards.

Conclusions

The results of the study identified the key features and limitations of various adsorption methods for removing sulphur from hydrocarbon streams, as well as their applicability in different refinery conditions. Zeolites have demonstrated high selectivity and efficiency for removing sulphur compounds such as thiophenes and mercaptans. However, their sensitivity to heavy hydrocarbon contamination and reduced performance at high sulphur content have limited their use in highly contaminated streams. They remained the optimal solution for deep treatment of light hydrocarbon fractions. Activated carbons have proven to be the most cost-effective and affordable option for companies with limited financial resources. They are effective for the pre-treatment of low-sulphur hydrocarbon streams, but their limited regeneration capacity and reduced efficiency with heavy hydrocarbons reduce their attractiveness for more complex processing conditions. MOFs represent an innovative method with the highest selectivity and the ability to be customised to specific applications. However, their high cost and insufficient operational stability make them less competitive for widespread use in current industrial environments. Nevertheless, they remain a promising area for further research and technological improvements.

Hybrid methods that combine adsorption and catalytic desulphurisation have shown the highest efficiency for the deep treatment of complex hydrocarbon streams. At the same time, they are characterised by high implementation costs and complexity of integration into existing technological processes. Additional materials, such as carbon molecular sieves, metal oxides and sulphides, modified clays and bentonites, have demonstrated specific advantages, but their application depends on individual processing conditions. UMCs are versatile for optimising desulphurisation processes, making them an important element in the development of the refining industry in the face of environmental challenges. The choice of the optimal adsorption method is determined by the economic and technical capabilities of the refinery. Large refineries can effectively use hybrid technologies and MOFs, while smaller refineries can integrate activated carbons or modified clays to reduce costs. The main limitation of this study is the lack of experimental data in refinery conditions, which limits the ability to accurately assess the effectiveness of the methods. In the future, a detailed study of the long-term stability and regeneration of adsorbents such as metal-organic frameworks in real industrial conditions are required.

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References

[1] Al-Jamimi, H.A., BinMakhashen, G.M., & Saleh, T.A. (2022). Multiobjectives optimization in petroleum refinery catalytic desulphurisation using Machine learning approach. *Fuel*, 322, article number 124088. doi: 10.1016/j.fuel.2022.124088.

[2] Alomar, T., Hameed, B.H., Al-Ghouti, M.A., Almomani, F.A., & Han, D.S. (2024). A review on recent developments and future prospects in the treatment of oily petroleum refinery wastewater by adsorption. *Journal of Water Process Engineering*, 64, article number 105616. doi: 10.1016/j.jwpe.2024.105616.

[3] Asghar, A., Sairash, S., Hussain, N., Baqar, Z., Sumrin, A., & Bilal, M. (2022). Current challenges of biomass refinery and prospects of emerging technologies for sustainable bioproducts and bioeconomy. *Biofuels, Bioproducts and Biorefining*, 16(6), 1478-1494. doi: 10.1002/bbb.2403.

[4] Bulut, B., İşbilen, E., Atakül, H., & Tantekin-Ersolmaz, Ş.B. (2022). Adsorptive removal of dimethyl disulfide and thiophene from liquefied petroleum gas by zeolite-based adsorbents. *Microporous and Mesoporous Materials*, 337, article number 111924. doi: 10.1016/j.micromeso.2022.111924.

[5] Cako, E., Wang, Z., Castro-Muñoz, R., Rayaroth, M.P., & Boczkaj, G. (2022). Cavitation based cleaner technologies for biodiesel production and processing of hydrocarbon streams: A perspective on key fundamentals, missing process data and economic feasibility – a review. *Ultrasonics Sonochemistry*, 88, article number 106081. doi: 10.1016/j.ultsonch.2022.106081.

[6] Chai, Y., Dai, W., Wu, G., Guan, N., & Li, L. (2021). Confinement in a zeolite and zeolite catalysis. *Accounts of Chemical Research*, 54(13), 2894-2904. doi: 10.1021/acs.accounts.1c00274.

[7] Chen, K., Li, W., Biney, B.W., Li, Z., Shen, J., & Wang, Z. (2020). Evaluation of adsorptive desulphurisation performance and economic applicability comparison of activated carbons prepared from various carbon sources. *RSC Advances*, 10, 40329-40340. doi: 10.1039/D0RA07862J.

[8] Da Silva Medeiros, D.C.C., Chelme-Ayala, P., Benally, C., Al-Anzi, B.S., & El-Din, M.G. (2022). Review on carbon-based adsorbents from organic feedstocks for removal of organic contaminants from oil and gas industry process water: Production, adsorption performance and research gaps. *Journal of Environmental Management*, 320, article number 115739. doi: 10.1016/j.jenvman.2022.115739.

[9] Ganiyu, S.A., & Lateef, S.A. (2021). Review of adsorptive desulphurisation process: Overview of the non-carbonaceous materials, mechanism and synthesis strategies. *Fuel*, 294, article number 120273. doi: 10.1016/j.fuel.2021.120273.

[10] Gooneh-Farahani, S., & Anbia, M. (2023). A review of advanced methods for ultra-deep desulphurisation under mild conditions and the absence of hydrogen. *Journal of Environmental Chemical Engineering*, 11(1), article number 108997. doi: 10.1016/j.jece.2022.108997.

[11] Griffiths, H. (2023). *Euro 5 vs Euro 6 emission standards*. Retrieved from https://www.carwow.co.uk/guides/glossary/eu5-and-eu6-engines-whats-the-difference-0626#gref.

[12] Guo, J., Qin, Y., Zhu, Y., Zhang, X., Long, C., Zhao, M., & Tang, Z. (2021). Metal-organic frameworks as catalytic selectivity regulators for organic transformations. *Chemical Society Reviews*, 50(9), 5366-5396. doi: 10.1039/D0CS01538E.

[13] Hassan, S.U., *et al.* (2022). Designing polyoxometalate based hybrid catalysts for efficient removal of hazardous sulfur from fuel via heterogeneous oxidative desulfurization. *Journal of Industrial and Engineering Chemistry*, 116, 438-446. doi: 10.1016/j.jiec.2022.09.034.

[14] Hulevskyi, V., & Postol, Yu. (2022). Prospects for improving the treatment of wastewater and technical fluids. *Ecological Safety and Balanced Use of Resources*, 13(2), 143-148. doi: 10.31471/2415-3184-2022-2(26)-143-148.

[15] ISO No. 14001. (2015). *Environmental management systems – requirements with guidance for use*. Retrieved from https://www.iso.org/standard/60857.html.

[16] Ismailov, N.S., & Gashimov, G.A. (2010). Increasing thermal stability of alumosilicates using adsorption and desorption. *Azerbaijan Chemical Journal*, 1, 82-86.

[17] Jumina, Kurniawan, Y.S., Purwono, B., Siswanta, D., Priastomo, Y., Winarno, A., & Waluyo, J. (2021). Science and technology progress on the desulphurisation process of crude oil. *Bulletin of the Korean Chemical Society*, 42(8), 1066-1081. doi: 10.1002/bkcs.12342.

[18] Kosogina, I., Klymenko, N., Savchyna, L., Kyrii, S., Astrelin, I., & Samsoni-Todorova, O. (2019). Sorption of sulfanilic acid and copper ions by activated carbon modified with metal oxides. *Bulletin of Cherkasy State Technological University*, 24(3), 83-91. doi: 10.24025/2306-4412.3.2019.178235.

[19] Lee, K.X., & Valla, J.A. (2019). Adsorptive desulphurisation of liquid hydrocarbons using zeolite-based sorbents: A comprehensive review. *Reaction Chemistry & Engineering*, 4(8), 1357-1386. doi: 10.1039/C9RE00036D.

[20] Li, G., *et al.* (2024). Review on advances in adsorption material for mercaptan removal from gasoline oil. *Journal of Industrial and Engineering Chemistry*, 139, 36-55. doi: 10.1016/j.jiec.2024.05.008.

[21] Naji, S.Z., & Tye, C.T. (2022). A review of the synthesis of activated carbon for biodiesel production: Precursor, preparation, and modification. *Energy Conversion and Management: X*, 13, article number 100152. doi: 10.1016/j.ecmx.2021.100152.

[22] Nezhad, A.B., Bastan, F., Panjehshahin, A., & Zamani, M. (2023). Adsorptive desulphurisation of condensate contains aromatic compounds using a commercial molecular sieve. *ACS Omega*, 8(11), 10365-10372. doi: 10.1021/acsomega.2c08051.

[23] Pan, Y., Huang, W., Liu, Z.H., Yang, Z.Z., Tan, J.J., & Xu, B.M. (2024). Recent progress of metal-organic frameworks for liquid fuels desulphurisation. *Separation & Purification Reviews*, 54, 128-148. doi: 10.1080/15422119.2024.2367646.

[24] Paucar, N.E., Kiggins, P., Blad, B., de Jesus, K., Afrin, F., Pashikanti, S., & Sharma, K. (2021). Ionic liquids for the removal of sulfur and nitrogen compounds in fuels: A review. *Environmental Chemistry Letters*, 19, 1205-1228. doi: 10.1007/s10311-020-01135-1.

[25] Pérez-Botella, E., Valencia, S., & Rey, F. (2022). Zeolites in adsorption processes: State of the art and future prospects. *Chemical Reviews*, 122(24), 17647-17695. doi: 10.1021/acs.chemrev.2c00140.

[26] Saha, B., Vedachalam, S., & Dalai, A.K. (2021). Review on recent advances in adsorptive desulphurisation. *Fuel Processing Technology*, 214, article number 106685. doi: 10.1016/j.fuproc.2020.106685.

[27] Shi, Q., & Wu, J. (2021). Review on sulfur compounds in petroleum and its products: State-of-the-art and perspectives. *Energy & Fuels*, 35(18), 14445-14461. doi: 10.1021/acs.energyfuels.1c02229.

[28] Srivastava, V.C. (2012). An evaluation of desulphurisation technologies for sulfur removal from liquid fuels. *RSC Advances*, 2(3), 759-783. doi: 10.1039/C1RA00309G.

[29] Taghaddom, K., Saadi, M.K., Kiani, P., Rahimpour, H.R., & Rahimpour, M.R. (2023). Activated carbon for syngas purification. In M.R. Rahimpour, M.A. Makarem & M. Meshksar (Eds.), *Advances in synthesis gas: Methods, technologies and applications: Syngas purification and separation* (pp. 229-250). Amsterdam: Elsevier. doi: 10.1016/B978-0-323-91877-0.00007-6.

[30] Tan, K.L., & Foo, K.Y. (2022). The viable role of activated carbon for the effective remediation of refinery and petrochemical wastewaters. In M.H. El-Naas & A. Banerjee (Eds.), *Petroleum industry wastewater*: *Advanced and sustainable treatment methods* (pp. 185-203). Amsterdam: Elsevier. doi: 10.1016/B978-0-323-85884-7.00016-3.

[31] Wang, X., *et al.* (2021). Key factors and primary modification methods of activated carbon and their application in adsorption of carbon-based gases: A review. *Chemosphere*, 287(2), article number 131995. doi: 10.1016/j.chemosphere.2021.131995.

[32] Wang, X., Gurbanov, H., Adygezalova, M., & Alizade, E. (2024). Investigation of removing asphaltene-resin-paraffin deposits by chemical method for Azerbaijan high-paraffin oil production process. *Energies*, 17(15), article number 3622. doi: 10.3390/en17153622.

[33] Wen, C., *et al.* (2023). Biochar as the effective adsorbent to combustion gaseous pollutants: Preparation, activation, functionalization and the adsorption mechanisms. *Progress in Energy and Combustion Science*, 99, article number 101098. doi: 10.1016/j.pecs.2023.101098.

[34] Yang, H., Wang, G., Luo, F., Dang, F., & Zhang, Z. (2023). Reactive adsorption desulphurisation of fluid catalytic cracking gasoline: The effect of promoters (Fe, Mo, and W) on the structural and catalytic properties of Ni/ZnO adsorbents. *Energy & Fuels*, 37(7), 5025-5033. doi: 10.1021/acs.energyfuels.3c00004.

[35] Yu, S., Li, J., Du, Y., Wang, Y., Zhang, Y., & Wu, Z. (2024). Sulfur-modified MOFs as efficient electrocatalysts for overall water splitting. *Coordination Chemistry Reviews*, 520, article number 216144. doi: 10.1016/j.ccr.2024.216144.

[36] Yu, T., Chen, Z., Liu, Z., Xu, J., & Wang, Y. (2022). Review of hydrogen sulfide removal from various industrial gases by zeolites. *Separations*, 9(9), article number 229. doi: 10.3390/separations9090229.

[37] Yunusov, S.G., Andryushchenko, N.K., Mirzoyeva, L.M., & Babayeva, Z.B. (2023). Desulphurisation of coking gasoline and diesel fraction mixture by alternative methods. *Processes of Petrochemistry and Oil Refining*, 24(2), 310-320.

[38] Zaidi, Z., Gupta, Y., Gayatri, S.L., & Singh, A. (2023). A comprehensive discussion on fuel combustion and desulphurisation technologies. *Inorganic Chemistry Communications*, 154, article number 110964. doi: 10.1016/j.inoche.2023.110964.

[39] Zhang, W., Li, G., Yin, H., Zhao, K., Zhao, H., & An, T. (2022). Adsorption and desorption mechanism of aromatic VOCs onto porous carbon adsorbents for emission control and resource recovery: Recent progress and challenges. *Environmental Science: Nano*, 9(1), 81-104. doi: 10.1039/D1EN00929J.

Промислові адсорбційні методи зниження вмісту сірки у вуглеводневих потоках

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Анотація. Досліджено промислові адсорбційні методи зниження вмісту сірки у вуглеводневих потоках з акцентом на їх технічну ефективність та технологічну адаптивність на нафтопереробних заводах. Проведено порівняльний аналіз використання цеолітів, активованого вугілля, металоорганічних каркасів, вуглецевих молекулярних сит, оксидів металів, полімерних матеріалів, сульфідів металів, модифікованих глин і бентоніту для зниження вмісту сірки у вуглеводневих потоках. Адсорбція з використанням цеолітів та металоорганічних каркасів виявилася високоефективною для видалення сірковмісних сполук, таких як тіофени та меркаптани, особливо при високих концентраціях сірки. Однак ці методи вимагають значних капітальних витрат і складної інфраструктури для масштабування. Активоване вугілля, незважаючи на його доступність та економічну ефективність, продемонструвало нижчу ефективність у видаленні сірки з важких вуглеводнів та обмежені можливості регенерації. Гібридні методи, що поєднують адсорбцію з каталітичною десульфурацією, виявилися перспективними для глибокого видалення сірки і зниження експлуатаційних витрат завдяки можливості регенерації адсорбенту. Для великих заводів оптимальними є гібридні технології та методи з використанням цеолітів і металоорганічних каркасів, що забезпечують високу ефективність при дотриманні екологічних стандартів.Для малих і середніх нафтопереробних заводів економічно доцільними є технології з використанням активованого вугілля. Таким чином, вибір методу адсорбції залежить від специфіки підприємства, типу потоку вуглеводнів та можливостей впровадження інноваційних технологій

Ключові слова: цеоліти; металоорганічні каркаси; каталітична десульфуризація; нафтопереробні заводи; активоване вугілля

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