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Conceptual principles of building intelligent computer networks for monitoring energy consumption of railways

The paper presents a conceptual approach to creating intelligent computer networks for monitoring and managing energy consumption in railway transport, which serve as the technological foundation for implementing the Smart Grid concept in the industry. Theoretical foundations of the transition from traditional electricity metering systems to integrated Smart Grid class systems are reviewed. Existing information flows in traction power supply systems are analyzed, and their main shortcomings are identified: data discreteness, lack of synchronization with train schedules, and low responsiveness of decision-making. A multi-level network architecture is proposed, including a data collection layer (IoT sensors, Smart meters), a communication layer (heterogeneous communication channels), a processing layer (cloud computing), and an application layer. The principles of integrating data on train movement and substation operation modes within a single information space are described. Requirements for reliability, cybersecurity, and speed of such a network are discussed. It is concluded that the implementation of the proposed concept will allow moving from passive observation to active energy management, which is a prerequisite for further mathematical optimization of railway operation modes.

***Keywords**: intelligent networks, Smart Grid, railway transport, energy monitoring, computer networks, IoT, energy efficiency.*

Introduction. The current stage of global economic development is characterized by fundamental, tectonic changes in approaches to the use and management of energy resources. In the context of the global energy crisis, critical instability of hydrocarbon markets, and the inevitable necessity of implementing international sustainable development strategies, energy efficiency issues are transforming from a purely economic plane into the plane of national security and strategic stability of the state. For railway transport, which is not only the circulatory system of the economy but also one of the largest industrial consumers of electricity, these challenges are particularly acute and urgent [1]. In the structure of railway operating costs, the share of expenses on fuel and energy resources consistently occupies leading positions, often exceeding 15-20%, and even a seemingly minor reduction in specific energy consumption for train traction on the scale of the entire network can yield a colossal multiplicative economic effect measured in billions of currency units.

At the same time, the world stands on the threshold of the Fourth Industrial Revolution (Industry 4.0), the key technological drivers of which are pervasive digitalization, the Internet of Things (IoT), cloud computing, Big Data, and artificial intelligence [2]. These breakthrough technologies are radically changing the very paradigm of managing complex technical systems, which undoubtedly includes the railway power supply system. While throughout the 20th century, increasing the efficiency of traction power supply systems was achieved primarily through extensive modernization of power equipment - installing more powerful transformers, more economical semiconductor converters, reducing active resistance in the contact network and rail circuits - today this path has practically exhausted its innovation potential. Modern power plants and electric machines have already reached an efficiency level close to the maximum physically possible limit, so the further struggle for energy efficiency is moving to another plane.

Consequently, the center of gravity in energy saving issues is shifting to the information plane. The efficiency of energy management today depends not so much on "hardware" as on "software" on how quickly, accurately, completely, and synchronously we receive information about the processes of energy generation, distribution, and consumption [3]. The problem lies in the fact that the existing railway information infrastructure, designed decades ago, remains quite conservative and inertial. Traditional Supervisory Control and Data Acquisition (SCADA) and Automated Meter Reading (AMR) systems often function as isolated "information silos." They cope excellently with the tasks of recording the total volume of consumed energy for fiscal settlements or emergency shutdown of protection lines but prove absolutely powerless before the tasks of deep analytics, searching for hidden anomalies, and operational adaptive management in real time.

The lack of a single, integrated information space leads to a paradoxical situation where power engineers see only the consequences (load peaks, non-normative losses, equipment overheating) but do not have the tools to instantly identify the causes, which often lie in the technology of the transportation process (schedule violations, irrational train weight, incorrect driver's driving style). In conditions where electric rolling stock is a highly dynamic, fast-changing load, traditional discrete metering systems with a polling interval of 30-60 minutes are practically "blind" to real energy exchange processes. Therefore, an urgent scientific task becomes not just installing new meters, but developing conceptual principles for building a holistic intelligent computer network. Such a network should become the "digital nervous system" of the railway, enabling the transition to the Smart Grid paradigm by ensuring total monitoring of energy costs with high sampling rates and creating the necessary technological base for the implementation of future systems for mathematical optimization of power supply modes [4].

Analysis of recent research and problem statement. A detailed and comprehensive analysis of modern scientific and technical literature, as well as a critical review of advanced global practices, indicate a significant and constantly growing interest of both the scientific community and practicing engineers in the problems of building next-generation intelligent energy networks (Smart Grids). The Smart Grid concept, which implies deep, end-to-end integration of modern information and communication technologies directly into the physical processes of electricity generation, distribution, and consumption, has already proven its undeniable effectiveness in the utility energy sector of many developed countries worldwide [5]. Numerous theoretical and applied studies convincingly demonstrate that the introduction of Smart Metering systems and adaptive Demand Response algorithms allows reducing total technical and commercial electricity losses by 10-15%, optimizing daily load schedules by shaving consumption peaks, and significantly improving the general reliability of power supply through the use of predictive power equipment diagnostics methods [6]. However, despite the obvious and documented successes in general energy, the direct and mechanical adaptation of these typical solutions for the specific needs of railway transport proves impossible or extremely ineffective due to the unique technological specifics of the transport industry, which requires the development of fundamentally new, specialized approaches.

The key problem complicating the transfer of Smart Grid experience to railways lies in the fundamental differences between stationary consumers in the utility sector and highly dynamic active consumers in the transport sector. Firstly, the main energy consumers on the railway electric rolling stock are non-stationary objects moving in space at high speeds, constantly and chaotically passing from one feeder zone to another, which creates a non-trivial task of dynamic consumer identification and correct allocation of energy costs in real-time mode [7]. Secondly, the load of traction networks has a clearly expressed stochastic, sharply variable character, where instantaneous power can change from zero values to maximum in a matter of seconds (for example, during the simultaneous starting of several heavy freight trains), which makes standard data averaging methods and the use of typical load profiles absolutely unacceptable for precise control [8].

Existing automated systems, such as AMR (Automated Meter Reading) and SCADA (Supervisory Control and Data Acquisition), on domestic railways function mainly as isolated, technically and informationally disparate "islands" [9]. SCADA systems were traditionally designed and oriented exclusively towards ensuring train traffic safety, operational switching of disconnectors, and rapid protection of the contact network against short-circuit currents, effectively ignoring tasks of energy efficiency and economic optimization. In turn, AMR systems focus primarily on fiscal functions, recording only integral energy consumption indicators over long periods (month, day, or hour), which makes detailed analysis of instantaneous operating modes and detection of short-term anomalies impossible. Such architectural disunity leads to energy data existing separately from data on technological processes.

Particularly acute and critical is the problem of the deep information gap between power supply services and transportation organization services. Information on the actual train schedule, the exact weight of freight trains, the presence of speed restriction warnings, and the complex track profile resides in some departmental databases, while telemetry information on currents, voltages, power flows, and the status of power equipment accumulates in completely different, often software-incompatible systems [10]. The lack of configured automated, time-synchronized data exchange between these functional domains prevents identifying the true causal relationships of energy costs and reasonably answering the question of why exactly an overload occurred at a specific moment on a specific section or why specific energy consumption for traction exceeded the approved norm. Considering the above, there is an urgent scientific and practical need to form a holistic concept and develop the architecture of a specialized intelligent computer network. The research task lies not just in modernizing individual metering nodes or replacing meters, but in creating a single convergent ecosystem for collecting, transmitting, and processing Big Data that would meet modern stringent requirements for reliability, speed, scalability, and cybersecurity in the conditions of the state's critical infrastructure functioning [11].

The purpose and tasks of the study. The main goal of this study is to develop, theoretically substantiate, and systematize the conceptual principles of building an intelligent computer network for monitoring railway energy consumption. This network is positioned as the core information infrastructure required to adapt the Smart Grid concept to the specific conditions of railway transport. Unlike existing analogues, it will ensure deep cross-integration of technological data of the transportation process and power supply parameters, thereby creating the necessary foundation for improving the energy efficiency and reliability of railway transport in the context of digital transformation [12]. Achieving this goal requires the consistent and comprehensive solution of a number of interconnected scientific and practical tasks covering both hardware and software-algorithmic aspects of network construction.

The first task is to conduct a detailed structural-functional analysis of existing information flows in traction and non-traction railway power supply systems. It is necessary to identify their architectural shortcomings, hidden "bottlenecks," data transmission delay factors, and reasons for the informational isolation of subsystems that hinder the implementation of modern energy management methods. This stage involves a critical assessment of the capabilities of existing equipment and the identification of barriers to its integration into a single digital space.

The second task is to develop a multi-level hierarchical architecture of the intelligent network, with a clear definition of the functional purpose, interfaces, and interaction protocols for each level: from the level of physical sensors, transducers, and actuators (Perception Layer) to the level of communications and data transport (Network Layer) and, finally, the level of cloud computing, analytics, and decision-making (Application Layer). The architecture must be flexible, modular, and open for further scaling. The third task is the scientific substantiation of the choice of optimal data transmission technologies for building a reliable heterogeneous communication environment. It is necessary to take into account the specific, often extreme limitations of railway transport, such as the significant linear extent of infrastructure objects, complex terrain, high mobility of subscribers (trains), and the presence of powerful electromagnetic interference from the traction network, which can significantly affect the quality of wireless communication.

The fourth task is to formulate methodological principles for integrating heterogeneous databases in a single information space. This requires determining algorithms for preprocessing "raw" data, methods for synchronizing time series from different sources (for example, superimposing a power profile on a traffic schedule), and approaches to correlation analysis, which will allow identifying non-obvious dependencies between operating modes and energy consumption.

The fifth task is to determine comprehensive requirements for the information security (cybersecurity) of the proposed network. Since the power supply system is part of the state's critical infrastructure, it is necessary to develop strategies for protecting communication channels from unauthorized access, ensuring the integrity and authenticity of telemetry data, as well as the network's resilience to cyberattacks and software failures.

Materials and methods of research. The methodological basis of this study is a comprehensive systems approach to analyzing energy exchange processes in heterogeneous transport systems. Traditional methods of researching railway power supply often consider the traction network as a separate electrotechnical system, the parameters of which depend on the load modeled as a random process. In this paper, a fundamentally different approach is applied: the power supply system is considered as an integral part of a Cyber-Physical System (CPS), in which the physical processes of transmission and conversion of electrical energy are inextricably linked with information processes of control, computing, and communication [4]. To develop the conceptual principles for building an intelligent network, a synthesis of fundamental provisions of information systems theory, automatic control theory, principles of building distributed computing networks, and reference models of the Internet of Things (IoT) was used [2]. In particular, the structural-functional modeling method was applied to formalize the architecture of the proposed network, which allowed decomposing a complex system into separate functional levels (perception, network, application) and clearly defining interaction interfaces between them. The comparative analysis method was used to compare the effectiveness of traditional hierarchical centralized control systems (SCADA) and modern decentralized approaches (Edge Computing), which allowed substantiating the feasibility of transferring part of the computing power to the network periphery. Additionally, the information flow simulation modeling method was utilized to estimate the required bandwidth of communication channels under peak load conditions, when telemetry data from dozens of locomotives and substations are transmitted simultaneously.

Characteristics of the empirical basis and analysis of regulatory support. As materials for the research, a significant array of technical documentation and legal acts regulating the operation of existing dispatching and metering systems in railway transport was analyzed. Statistical data regarding the load schedules of DC and AC traction substations were subjected to critical rethinking. The analysis of daily and monthly load profiles revealed high stochasticity of consumption processes, where peak power values can exceed averages by 3-4 times. This served as the basis for the conclusion about the insufficiency of existing measurement sampling intervals (30 minutes) for operational control purposes. International standards of the IEC 61850 series ("Communication networks and systems for power utility automation"), which define modern data exchange protocols in digital energy, were also analyzed [13]. Based on this analysis, requirements for equipment compatibility within the proposed intelligent network were formulated. Special attention was paid to studying the characteristics of modern telecommunications equipment capable of operating in harsh conditions of electromagnetic interference, vibrations, and temperature changes characteristic of railway infrastructure [14].

Method of building the Perception Layer architecture. The developed methodology for building the lower level of the network is based on the concept of "sensor saturation." Unlike existing systems, where metering points are only the inputs of traction substations, the proposed method involves the total digitalization of all active system elements. For stationary objects (traction substations, sectioning posts, parallel connection points), the use of Intelligent Electronic Devices (IEDs) is substantiated. The methodology involves installing IEDs on each feeder of the contact network. A key requirement is a high signal sampling rate, which allows recording not only effective values of current and voltage but also power quality parameters: the voltage waveform distortion factor, the level of higher harmonics, and phase asymmetry [15]. This allows diagnosing the condition of rectifier units and detecting precursors of emergency modes. For mobile objects (electric rolling stock), a dynamic energy metering method has been developed. It is based on the continuous recording of three energy vectors: energy consumed for traction; energy returned to the contact network in regenerative braking mode; energy spent on the locomotive's auxiliary needs (compressors, fans, heating). A critically important element of the methodology is the synchronization of measurements with spatiotemporal coordinates. Each data packet is marked with an exact timestamp and geolocation data (GPS/GNSS coordinates), which allows linking consumption to a specific point of the track profile [16].

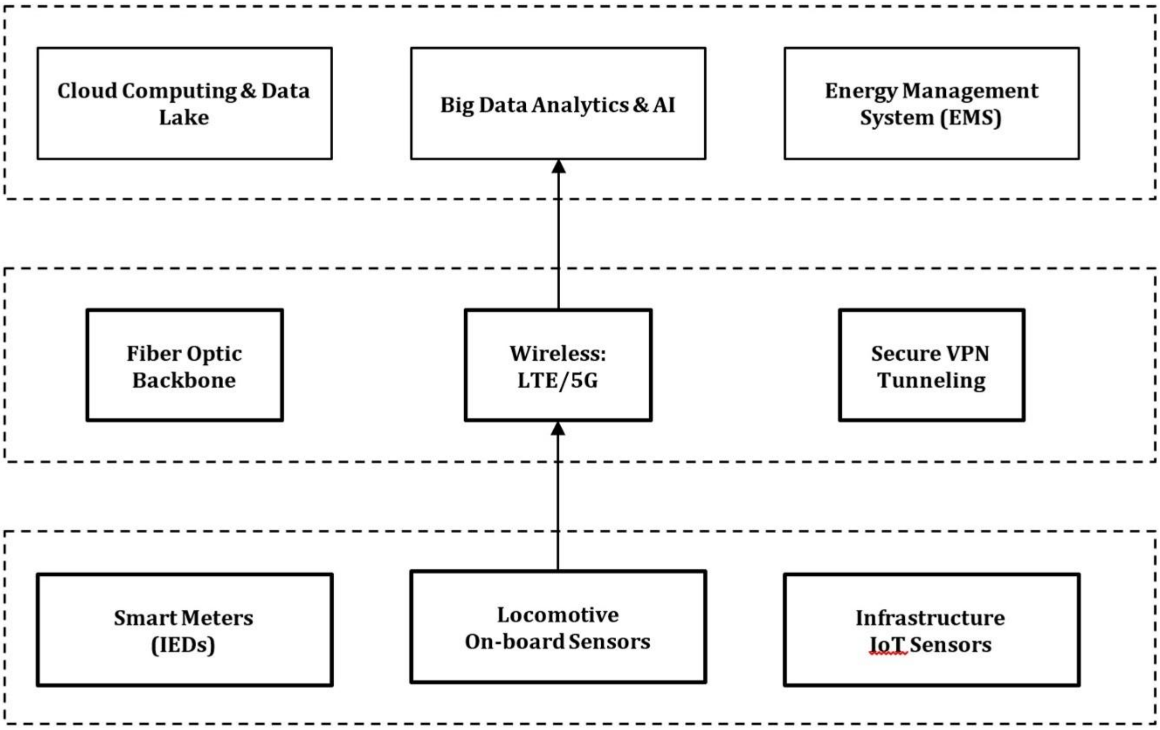

Fig. 1. **Three-level architecture of the intelligent railway energy monitoring network**

Substantiation of the choice of Network Layer technologies. Building a reliable data transmission system under conditions of significant linear extent of railway infrastructure (thousands of kilometers) requires the use of a hybrid communication model. The study analyzed available communication technologies based on criteria of bandwidth, latency, reliability, and implementation cost. For backbone communication channels between stationary objects, the lack of alternatives to using fiber-optic communication lines (FOCL) with Dense Wavelength Division Multiplexing (DWDM) technology is substantiated. This ensures gigabit data transmission speeds required for aggregating streams from thousands of sensors and complete immunity to electromagnetic fields of the traction network [13]. To organize the "last mile" communication with moving objects, the efficiency of GSM-R, LTE-R, and 5G standards was analyzed. It was established that the existing GSM-R standard is unable to provide the necessary data transmission speed for real-time monitoring tasks. Therefore, a transition to broadband LTE-R (Long Term Evolution for Railways) technologies or prospective 5G networks is proposed, which support a stable connection at train speeds up to 300-350 km/h, neutralizing the Doppler effect [17].

For collecting data from autonomous infrastructure sensors (wire temperature, insulator condition) powered by batteries, a method of using energy-efficient long-range networks LPWAN (Low Power Wide Area Network), in particular LoRaWAN technology, is proposed. This allows deploying a dense network of sensors with minimal maintenance costs since the battery life can reach 5-10 years.

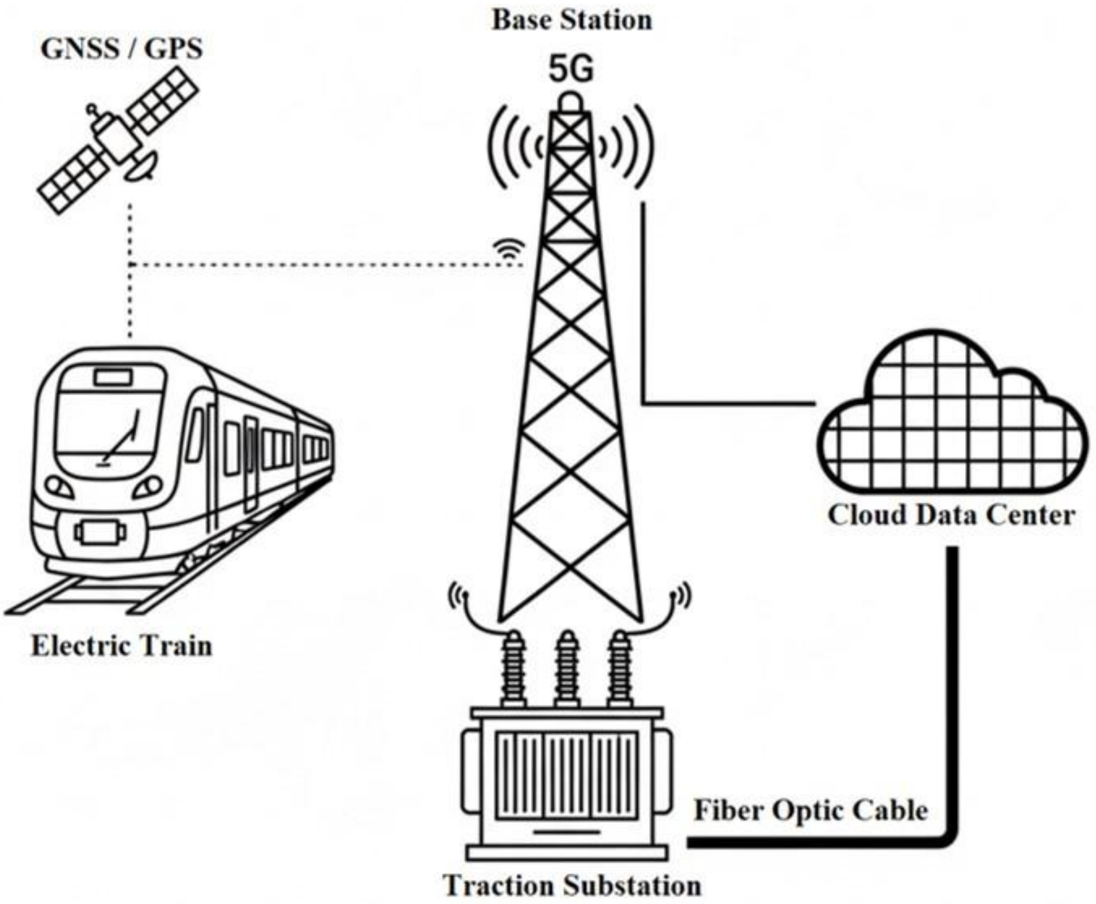

Fig. 2. **Structural diagram of the hybrid communication system for mobile and stationary objects**

Data processing and intellectualization methodology. The methodology for processing the obtained information arrays is based on the use of cloud technologies and Big Data architecture. Instead of traditional relational databases, the use of specialized Time-Series Databases, optimized for fast writing and reading of chronologically ordered metrics, is proposed.

A separate, critically important stage of the research involves the development of algorithmic support for synchronizing heterogeneous data streams, which is a fundamental challenge in distributed monitoring systems. Since telemetry data originates from diverse sources - stationary smart meters at substations, mobile sensors on rapidly moving locomotives, and external meteorological services these data streams possess different sampling rates and latency characteristics. To address this, a comprehensive Data Pre-processing method is proposed. This method includes multi-stage filtration to remove noise and artifacts caused by electromagnetic interference, reconstruction of missing values using linear interpolation algorithms, and normalization of timestamps to a unified standard.

To ensure the high precision of event synchronization across the distributed network, the use of the Precision Time Protocol (PTP, IEEE 1588v2) is substantiated. Unlike the standard Network Time Protocol (NTP), which provides millisecond-level accuracy, PTP ensures sub-microsecond accuracy by using hardware timestamping at the physical layer of the network interface. This level of precision is mandatory for correctly correlating instantaneous current values measured at the electric train pantograph with the corresponding values recorded at the substation feeder, thereby neutralizing the impact of stochastic delays (jitter) in data transmission channels.

At the application logic level, an advanced Anomaly Detection model based on comparative analysis has been developed. The system automatically constructs a specific "energy passport" for each trip in real-time, comparing the actual energy consumption with a theoretically calculated reference model. This reference model is dynamically generated by solving the differential equation of train motion, taking into account variable parameters such as the track profile (gradients, curves), the actual weight of the train, aerodynamic resistance, and the specific efficiency curve of the locomotive type. If the deviation of the actual consumption from the reference value exceeds a predefined threshold (e.g., 5-7%), the system triggers an automated incident report for further investigation. This approach allows for the detection of not only technical malfunctions, such as increased motion resistance due to chassis defects or brake system drag, but also organizational shortcomings, specifically violations of energy-efficient driving mode maps by locomotive crews. A key element of the methodology is the developed algorithm for cross-correlation of energy and logistics data. The essence of the method lies in the automatic superimposition of the electricity consumption schedule on the executed train traffic schedule. The system analyzes the deviation of actual consumption from the reference profile calculated based on traction calculations for a specific locomotive series, train weight, and track section. This allows separating technologically justified energy costs from unproductive losses caused by equipment malfunction or irrational actions of the driver [10]. The methodology also includes the application of Machine Learning methods for implementing predictive analytics [18]. Based on historical consumption data, the planned traffic schedule, and weather forecasts, a neural network builds a load forecast for traction substations with a planning horizon from 1 hour to 1 day. This enables dispatching personnel to optimize the power supply scheme in advance, for example, by switching backup transformers on or off to reduce no-load losses [19].

To solve the problem of latency and reduce the load on backbone communication channels, the architecture provides for the implementation of the Fog Computing paradigm. Unlike the classic cloud model, where all data is transmitted to a central server for processing, Fog Computing involves the deployment of an intermediate layer of computing nodes directly at the level of traction substations or large railway junctions. These "fog" nodes perform primary filtration, aggregation, and compression of telemetry data. For example, raw oscillograms of currents and voltages with a frequency of several kilohertz are processed locally to calculate vector values (Phasors), and only the calculated parameters are transmitted to the cloud with a frequency of 1-10 Hz. This approach reduces traffic volume by 90-95% without losing informational value for the operational dispatcher. Furthermore, particular attention is paid to the optimization of application-layer data transfer protocols. For the segment of interaction with resource-constrained IoT sensors (e.g., battery-powered temperature sensors on catenary supports), the use of the CoAP (Constrained Application Protocol) or MQTT-SN (Message Queuing Telemetry Transport for Sensor Networks) is substantiated. These protocols operate over UDP and have a significantly smaller header overhead compared to standard HTTP/TCP, which is critical for low-bandwidth networks such as LoRaWAN. For critical control commands requiring guaranteed delivery (Quality of Service - QoS), the system utilizes the priority tagging mechanism (VLAN 802.1p), ensuring that technological traffic is processed by network switches with higher priority than diagnostic or video surveillance data.

Methods of ensuring information security and reliability. Since the railway power supply system belongs to critical infrastructure facilities, the research methodology includes the development of a set of cybersecurity measures. The necessity of physical and logical separation of the technological monitoring network and public networks is substantiated. The use of tunneling methods (VPN), traffic encryption using TLS 1.3 protocols, and the implementation of Public Key Infrastructure (PKI) for authenticating each device in the network is proposed.

Considering the exponential growth of cyber threats targeting critical infrastructure facilities, the paper details a robust architecture for the information security subsystem based on the "Defense in Depth" paradigm. This approach implies a multi-layered security strategy that covers physical, network, and application levels. At the level of peripheral devices (Edge), hardware-based authentication of sensors is implemented using Trusted Platform Modules (TPM) and cryptographic chips. This measure effectively prevents "Device Spoofing" attacks, where an attacker attempts to emulate a legitimate sensor to inject false data into the system.

At the network level, strict traffic segmentation is applied through the implementation of Virtual Local Area Networks (VLANs). Technological data traffic is logically isolated from the corporate office network and the public Internet, creating a demilitarized zone (DMZ) for external connections. Furthermore, the deployment of industrial-grade Intrusion Detection and Prevention Systems (IDS/IPS) is substantiated. These systems are specifically configured to perform Deep Packet Inspection (DPI) of industrial protocols such as IEC 60870-5-104, DNP3, or Modbus TCP. This capability allows the system to detect and block anomalous control commands or malformed packets that may indicate a sophisticated cyberattack attempt, such as a Man-in-the-Middle (MitM) attack or a Denial of Service (DoS) aimed at disrupting energy monitoring operations. Additionally, regular automated vulnerability scanning and penetration testing are recommended as part of the security lifecycle management. To ensure the integrity of commercial metering data, the possibility of using distributed ledger technology (Blockchain) is considered, which makes unauthorized modification of archival data impossible [8]. To increase network reliability, structural and informational redundancy methods were applied. In particular, duplication of communication channels and the creation of backup data processing centers with automatic information replication are provided.

Evaluation of expected efficiency. The theoretical assessment of the effectiveness of the proposed intelligent network architecture indicates a significant potential for energy saving and operational optimization. Calculation modeling demonstrates that the transition from passive metering to active energy consumption management based on real-time data will allow reducing specific electricity consumption for train traction by approximately 3-5%. This reduction is primarily achieved through the optimization of train driving modes (adhering to energy-optimal velocity profiles) and the minimization of braking losses.

Furthermore, an additional 2-3% reduction in energy losses within the power supply network is expected due to the optimization of power flow distribution and the intelligent management of reactive power compensation devices. On the scale of the entire railway network, these percentage reductions translate into the saving of tens of millions of kilowatt-hours of electricity annually, resulting in a substantial decrease in operational expenses (OPEX).

Beyond the direct economic effect, the implementation of the system will yield a significant positive environmental impact. By reducing overall energy consumption, the indirect emissions of CO2 and other greenhouse gases associated with electricity generation will be lowered. This contributes to the decarbonization of the transport sector and aligns the railway infrastructure development with the environmental strategies of European integration and the "Green Deal" initiatives. The system also facilitates the transition from a rigid system of planned preventive repairs to a flexible Condition-Based Maintenance (CBM) strategy, extending the service life of traction transformers and contact network components by monitoring their actual thermal and electrical loads.

Integration with renewable energy sources and storage systems. The proposed intelligent network concept lays the foundation for the transformation of the railway power supply system into an active grid with distributed generation. The architecture provides for the seamless integration of renewable energy sources (RES), such as solar power plants installed on the roofs of station buildings or noise barriers, as well as wind turbines located in the railway right-of-way. The intelligent monitoring system allows for real-time balancing of generation from RES and consumption by traction loads, directing surplus energy to charge stationary Energy Storage Systems (ESS) based on lithium-ion or supercapacitor batteries. The integration of ESS is particularly effective for stabilizing voltage in the catenary network on remote sections and for utilizing excess recuperation energy that cannot be absorbed by other trains or returned to the external grid due to inverter limitations. The developed algorithms for the "Energy Management System" (EMS) module allow controlling the charge/discharge cycles of storage devices based on the current tariff policy (charging at night at a low rate and discharging during peak hours), which ensures additional economic benefits and reduces peak demand charges from the external grid operator. Thus, the railway transforms from a passive consumer into a "prosumer" (producer-consumer), actively participating in the regional energy market and providing demand response services.

Conclusions.In the presented scientific work, the urgent scientific and practical task consisting in the development, theoretical substantiation, and systematization of the conceptual principles of building intelligent computer networks for monitoring, analyzing, and optimizing energy consumption in railway transport is solved. The conducted research allowed formulating a number of important conclusions that have both theoretical and applied significance for the further development of the industry's digital infrastructure. Firstly, a detailed and critical analysis of the current state of information support for the railway energy economy revealed significant systemic shortcomings that hinder energy efficiency improvements. It was established that traditional automated systems (SCADA, AMR) function as isolated information domains, operating with data of low time discretization and a complete lack of mutual synchronization with transportation management systems. Such architectural disunity makes it impossible to implement adaptive algorithms for energy consumption control in real-time and creates information barriers to identifying and localizing unproductive energy losses.

Secondly, a three-level intelligent monitoring network architecture has been developed and structurally formalized, based on the principles of building distributed cyber-physical systems and including the Perception Layer, Network Layer, and Data Processing Layer. The proposed architecture ensures complete digital transparency of energy exchange processes at all stages of energy transformation - from the traction substation input to the electric train pantograph. A distinctive feature and element of scientific novelty of the developed concept is the integration of rolling stock as an active, mobile element of the Internet of Things (IoT) network. This allows continuous monitoring of energy recuperation efficiency and assessing the energy efficiency of train driving modes with precise reference to geographical coordinates and the track profile.

Thirdly, the choice of optimal data transmission technologies for building a reliable heterogeneous communication environment is scientifically substantiated. It is determined that under the specific and harsh conditions of railway transport (significant linear extent, powerful electromagnetic interference, high subscriber mobility), a hybrid model is required. It must combine high-speed fiber-optic backbones for stationary infrastructure objects and secure broadband wireless networks of LTE-R or prospective 5G standards for mobile objects. This approach allows minimizing packet transmission latency, ensuring guaranteed delivery of critically important telemetry data, and creating the necessary bandwidth reserve for future services.

Fourthly, a new methodological approach to integrating heterogeneous databases - energy and logistics - in a single cloud information space is proposed. Synchronization of electrical load schedules with executed train traffic schedules creates the necessary basis for implementing predictive analytics and machine learning algorithms, as well as for creating a "Digital Twin" of the power supply system. This allows moving from reactive incident response to proactive management, forecasting peak loads, and optimizing power supply schemes in advance. The practical value of the work lies in creating a technological foundation for the transition from a system of planned preventive repairs to Condition-Based Maintenance.

Summarizing the results, it can be stated that the implementation of the developed intelligent computer network architecture is a necessary technological prerequisite for the transformation of railway transport to the Smart Grid model.

This will create a reliable basis for further scientific research in the direction of developing mathematical models for optimizing power supply modes, which in the future will ensure a significant reduction in operating costs, an increase in transportation reliability, and contribute to the decarbonization of the transport sector.

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Концептуальні засади побудови інтелектуальних комп’ютерних мереж для моніторингу енерговитрат залізниць

Анотація. *У статті розроблено та обґрунтовано концептуальні засади побудови інтелектуальних комп’ютерних мереж для моніторингу енерговитрат на залізничному транспорті в умовах цифрової трансформації галузі. Проведено критичний аналіз існуючих систем обліку електроенергії, виявлено їхню функціональну обмеженість, яка полягає у дискретності вимірювань, відсутності єдиного інформаційного простору та неможливості зіставлення енергетичних параметрів із технологічними показниками перевізного процесу в режимі реального часу. Запропоновано нову архітектуру системи моніторингу, що базується на принципах Smart Grid та технологіях Інтернету речей (IoT). Детально описано трирівневу модель мережі: рівень сприйняття (Smart-сенсори та бортові системи локомотивів), комунікаційний рівень (гетерогенні канали зв’язку) та рівень інтелектуальної обробки даних (хмарні та туманні обчислення). Окрему увагу приділено питанням кібербезпеки та захисту критичної інфраструктури при передачі даних, а також методології синхронізації часових рядів енергоспоживання з графіком руху поїздів. Визначено, що впровадження запропонованої концепції дозволить перейти від пасивної констатації витрат до активного енергоменеджменту, що є необхідною передумовою для подальшої математичної оптимізації режимів електропостачання.*

Ключові слова*: інтелектуальні мережі, Smart Grid, залізничний транспорт, енергомоніторинг, Інтернет речей (IoT), енергоефективність, цифрова трансформація, кібербезпека.*

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