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THE USE OF ARTIFICIAL INTELLIGENCE IN ENERGY MANAGEMENT OF INDUSTRIAL ENTERPRISES

ВИКОРИСТАННЯ ШТУЧНОГО ІНТЕЛЕКТУ В ЕНЕРГОМЕНЕДЖМЕНТІ ПРОМИСЛОВИХ ПІДПРИЄМСТВ

The article presents the results of a study focused on the implementation of artificial intelligence (AI) technologies in the energy management systems of industrial enterprises. The topic's relevance stems from increasing demands for efficient energy use in the context of economic decarbonization, the development of decentralized energy systems, and the growing role of renewable energy sources. As some of the largest energy consumers, industrial enterprises require innovative approaches to managing energy consumption. The use of AI in this context is viewed as a strategically important direction for improving energy efficiency, reducing operational costs, and ensuring production flexibility. The study aims to provide a comprehensive analysis of AI application opportunities in energy management, identify implementation barriers, and develop a framework model for the integration of intelligent technologies into enterprise energy management systems. The article systematizes key areas of AI use– namely, predictive maintenance of equipment, energy consumption optimization, participation in demand response programs, integration of renewables, and anomaly detection. It offers an overview of current technologies, such as machine learning, deep neural networks, reinforcement learning, and big data analytics. The proposed implementation framework addresses the need for digital infrastructure, data governance systems, qualified personnel, integration with existing IT/OT solutions, and the development of policies for ethical AI use. The scientific novelty lies in the formalization of AI integration stages into the energy management of industrial enterprises and in highlighting the potential of AI to strengthen the role of enterprises as active participants in a decentralized energy system. The study's practical significance lies in the potential use of the proposed framework as a guideline for enterprises in the digital transformation of their energy consumption management systems.

Keywords: *artificial intelligence, internet of things, energy management, industrial enterprises, decentralization.*

У статті представлено результати дослідження, присвяченого впровадженню технологій штучного інтелекту (ШІ) в системи енергоменеджменту промислових підприємств. Актуальність теми зумовлена зростаючими вимогами до ефективного використання енергетичних ресурсів в умовах декарбонізації економіки, розвитку децентралізованих енергетичних систем та зростання ролі відновлюваних джерел енергії. Промислові підприємства, як одні з найбільших споживачів енергії, потребують інноваційних підходів до управління енергоспоживанням, і використання ШІ в цьому контексті розглядається як стратегічно важливий напрям підвищення енергоефективності, зниження витрат та забезпечення гнучкості виробничих процесів, адаптації до змін в енергетичному середовищі та збереження конкурентоспроможності. Метою дослідження є комплексний аналіз можливостей застосування ШІ в енергоменеджменті, виявлення бар'єрів та розробка рамкової моделі інтеграції інтелектуальних технологій у систему управління енергоспоживанням підприємства. У роботі систематизовано напрями практичного використання ШІ – зокрема прогнозне технічне обслуговування обладнання, оптимізація енергоспоживання, участь у програмах керування попитом, інтеграція ВДЕ та виявлення аномалій. Здійснено огляд сучасних технологій, таких як машинне навчання, глибинні нейронні мережі, підкріплене навчання та аналітика великих даних. Запропонована структура впровадження ШІ враховує потребу в цифровій інфраструктурі, системах управління даними, кваліфікованих кадрах, інтеграції з наявними IT/OT-рішеннями та формуванні політик з етичного, безпечного та прозорого використання інтелектуальних систем. Наукова новизна полягає у формалізації етапів впровадження ШІ в енергоменеджмент промислових підприємств та у висвітленні потенціалу ШІ для посилення ролі підприємств як активних учасників децентралізованої енергосистеми. Практичне значення полягає в можливості використання запропонованої моделі як орієнтиру для підприємств у процесі цифрової трансформації системи управління енерговитратами, що сприяє досягненню стратегічних цілей сталого розвитку.

Ключові слова: *штучний інтелект, інтернет речей, енергоменеджмент, виробничі підприємства, децентралізація.*

Problem statement. Industrial enterprises globally face unprecedented challenges in the energy domain, including the need to reduce energy costs, improve energy efficiency, comply with environmental regulations, and integrate into modern energy networks. These challenges are compelling enterprises to seek innovative solutions through digital transformation of energy management systems, where artificial intelligence is becoming a key element of change [5, p. 26]. The integration of AI technologies into energy management systems of industrial enterprises represents a fundamental shift from traditional management models to intelligent systems capable of prediction, optimization, and autonomous decision-making.

Digital transformation in energy management encompasses various technological innovations, including Internet of Things (IoT) devices, big data analytics, distributed ledger technologies, and artificial intelligence. Among these technologies, AI stands out for its potential to fundamentally reshape energy management practices by enabling predictive maintenance of energy equipment, energy consumption forecasting, energy distribution optimization, and facilitating enterprise integration into decentralized energy networks [12, p. 45].

Analysis of recent research and publications. The application of artificial intelligence in energy management has attracted significant scholarly attention in recent years. Soni et al. [3] examined AI's impact on enterprises across various economic sectors, highlighting its transformative potential in industry. Their research emphasized that AI adoption follows distinct patterns depending on industry characteristics and organizational readiness for change.

Mondal et al. [5] provided a theoretical review of generative artificial intelligence, analyzing its potential across various domains. Their findings suggest that generative AI represents a qualitative leap in capabilities compared to traditional AI systems, with particularly promising applications in sectors requiring pattern recognition and predictive analytics, including energy management.

Focusing specifically on the energy sector, Yatsenko et al. [9] analyzed the impact of digitalization on economic development, noting that enterprises adopting digital technologies demonstrated improved operational efficiency and market competitiveness. Their research highlighted the particular importance of digital infrastructure development as a prerequisite for successful AI implementation in energy management.

Shlapak et al. [10] investigated digital transformation in the context of global competition, focusing on technological innovations and investment priorities. Their conclusions have direct relevance to the implementation of AI in energy management of industrial enterprises, emphasizing the importance of a strategic approach to investments in digital technologies.

Turlakova and Lohvinenko [6] developed theoretical frameworks for using AI tools in managing the behavior of economic agents at the micro level. Their conceptual provisions for digital space management using AI tools [7] provide valuable insights for enterprise managers seeking to implement AI solutions for energy consumption optimization.

The integration of AI in energy management of industrial enterprises can be conceptualized through the lens of digital transformation theory, which views technological adoption as a comprehensive process involving changes in technology, organization, and business models [1, p. 480]. Within this framework, AI represents a specific technological capability that, when properly integrated, enables new forms of value creation.

Digital ecosystem theory provides another useful perspective, conceptualizing industrial enterprises as participants in complex networks of interdependent actors connected through digital platforms [2, p. 275]. In this context, AI serves as a coordination mechanism that enables more efficient resource allocation, information exchange, and collaborative decision-making across energy ecosystem participants.

Furthermore, the resource-based view explains how AI capabilities can serve as sources of competitive advantage for industrial enterprises. This perspective suggests that AI technologies, when developed as unique, valuable, and difficult-to-imitate resources, can provide sustainable competitive advantages [8, p. 270].

Formulating the purposes of the article. This research aims to comprehensively analyze the role of AI in energy management of industrial enterprises with a focus on their further integration into Ukraine's decentralized energy system. The study examines practical applications of AI in energy management, identifies implementation barriers, and proposes strategies for successful integration. Results are based on recent theoretical developments and practical experience in implementing AI technologies to optimize the energy consumption of industrial enterprises.

Methodology. This research employs a qualitative analytical approach, synthesizing findings from existing literature, industry reports, and case studies. The methodology involves a systematic review and analysis of scholarly publications focusing on AI applications in energy management of industrial enterprises. The analysis identifies common patterns, success factors, and challenges across multiple implementation contexts.

To supplement the literature review, the research incorporates an analysis of industry reports and white papers from leading technology providers and energy sector consultancies. This provides practical insights into current implementation approaches and emerging best practices in the field.

Presentation of the main research material. Industrial enterprises are implementing AI technologies across various domains of energy management. Table 1 summarizes the primary application areas and associated benefits.

Predictive maintenance of energy equipment represents one of the most mature AI applications in industrial enterprises. By analyzing data from sensors installed on energy equipment, transformers, transmission lines, and distribution assets, AI algorithms can detect early signs of potential failures before they occur [4, p. 32]. This capability enables maintenance teams to transition from scheduled preventive maintenance to condition-based maintenance, resulting in significant cost savings and improved reliability.

Energy consumption forecasting has evolved significantly with the integration of AI technologies. Traditional statistical methods have been enhanced with machine learning algorithms capable of processing diverse data sources, including weather patterns, economic indicators, and historical consumption data. The improved accuracy of AI-based forecasting enables industrial enterprises to better plan energy consumption, optimize energy supply contracts, and avoid penalties for exceeding contractual limits [10, p. 340].

Table 1

AI Applications in Energy Management of Industrial Enterprises

Application Area	AI Technologies Used	Key Benefits	Implementation Challenges
Predictive Maintenance of Energy Equipment	Machine Learning, IoT Sensors	Reduced downtime, Extended equipment life, Lower maintenance costs	Data quality issues, Integration with legacy systems
Energy Consumption Forecasting	Deep Learning, Time Series Analysis	Improved resource allocation, Optimization of energy supply contracts	Weather dependency, Consumption pattern variability
Energy Distribution Optimization	Reinforcement Learning, Neural Networks	Reduced energy losses, improved load balancing	Computational complexity, Real-time requirements
Integration of Renewable Energy Sources	Predictive Analytics, Machine Learning	Carbon emission reduction, Cost savings, Energy independence	Generation instability, Integration complexity
Participation in Demand Response Programs	Conversational AI, Recommendation Systems	Additional revenue, Peak load reduction	Privacy concerns, Alignment with production processes
Energy Anomaly and Leakage Detection	Anomaly Detection, Pattern Recognition	Resource protection, Regulatory compliance	False positives, Data access limitations

Energy distribution optimization through AI involves real-time analysis of the enterprise's energy infrastructure state and automated adjustment of parameters to maximize efficiency. Reinforcement learning algorithms have demonstrated particular promise in this domain, learning optimal control strategies through simulated interactions with energy system models [13, p. 95]. These applications help reduce energy losses and improve the integration of renewable energy sources.

Integration of renewable energy sources is becoming increasingly important for industrial enterprises seeking to reduce their carbon footprint and cut energy costs. AI systems help predict generation from solar panels and wind turbines, optimize their use, and balance them with traditional energy sources. This is particularly relevant in the context of Ukraine's energy system decentralization, where industrial enterprises can become active participants in the energy market [10].

Participation in demand response programs allows enterprises to receive additional income or discounts by reducing consumption during periods of peak load on the energy system. AI systems analyze production processes and identify opportunities for load reduction without significantly impacting productivity. This creates prerequisites for enterprise integration into a decentralized energy system, where they can act not only as consumers but also as active participants in energy system balancing [14].

Energy anomaly and leakage detection using AI enables the identification of inefficient energy use and the prevention of unexpected losses. Algorithms analyze energy consumption patterns and detect deviations from normal models, signaling potential problems. This helps enterprises maintain energy efficiency and comply with regulatory requirements [11, p. 145].

Framework for AI Implementation in Energy Management of Industrial Enterprises. Successfully implementing AI in energy management of industrial enterprises requires a structured approach that addresses technical, organizational, and strategic considerations. The following framework, synthesized from research findings, guides enterprises embarking on AI implementation initiatives in energy management.

1. Development of Digital Infrastructure. Enterprises must develop a comprehensive digital infrastructure that enables data collection, storage, processing, and exchange. This infrastructure includes sensor networks, communication systems, data lakes, and computing resources capable of supporting AI workloads [10]. Without adequate digital infrastructure, AI applications will be limited in scope and effectiveness.

2. Implementation of Appropriate Data Governance Mechanisms. Establishing data governance mechanisms is crucial for ensuring data quality, security, and accessibility. This includes establishing data standards, defining ownership and access rights, implementing security measures, and ensuring compliance with relevant regulations [8, p. 272]. Enterprises must pay particular attention to privacy concerns related to energy consumption data.

3. Development of AI Capabilities. Building AI capabilities requires both technology acquisition and talent development. Enterprises can choose between developing in-house AI solutions, partnering with technology providers, or adopting commercial off-the-shelf systems [1, p. 481]. Regardless of the approach chosen, developing internal expertise is crucial for the successful implementation and ongoing management of AI systems.

4. Integration with Existing Systems. Integrating AI systems with existing operational technology (OT) and information technology (IT) systems presents significant challenges. Enterprises must develop integration strategies that enable seamless data flow between systems while maintaining operational integrity and security [12, p. 47]. This often requires modernizing legacy systems or implementing middleware solutions.

5. Establishment of Appropriate AI Governance Mechanisms. Establishing appropriate governance mechanisms for AI systems is essential for ensuring ethical use, managing risks, and maximizing benefits. This includes developing policies for algorithm transparency, decision accountability, and continuous performance monitoring [9, p. 265]. Enterprises must also address workforce concerns related to AI adoption, including potential job displacement and skill requirements.

Challenges in Implementing AI in Energy Management of Industrial Enterprises. Despite the significant potential benefits, industrial enterprises face numerous challenges when implementing AI solutions in energy management systems.

Technical challenges include data quality issues, integration complexity, and computational requirements. Many energy assets generate large volumes of data but lack standardization, making data preparation a significant burden [3, p. 12]. Legacy systems often operate in isolation, complicating data integration efforts necessary for comprehensive AI applications.

Organizational challenges include resistance to change, skill gaps, and alignment difficulties between technical and business teams. Industrial enterprises typically have established operational practices that may conflict with new AI-driven approaches [6, p. 15]. The specialized expertise required for AI implementation is often scarce, particularly in combination with domain-specific energy knowledge.

Regulatory challenges present another barrier, as the energy sector is a highly regulated environment with strict requirements for reliability, safety, and data protection. AI systems must comply with these regulatory requirements while also addressing emerging concerns specific to algorithmic decision-making [11, p. 145]. The rapid evolution of AI technologies often outpaces regulatory frameworks, creating uncertainty for implementation initiatives.

Prospects for AI Use in Energy Management of Industrial Enterprises in Ukraine. The future of AI in energy management of industrial enterprises will be shaped by several emerging trends.

First, the convergence of AI with other technologies, including blockchain, edge computing, and digital twins, will enable new applications and business models [5, p. 32]. For example, blockchain combined with AI could enable automated peer-to-peer energy trading with intelligent pricing optimization, which is a key element of decentralized energy systems.

Second, the evolution of AI capabilities toward more explainable and trustworthy systems will address current limitations related to transparency and accountability [2, p. 280]. This will be particularly important for applications involving critical infrastructure decisions or consumer-facing services.

Third, the democratization of AI through low-code/no-code platforms and pre-trained models will make implementation more accessible to industrial enterprises with limited technical resources [14]. This trend will accelerate adoption across the sector and enable smaller enterprises to benefit from AI capabilities.

In the context of Ukraine, implementing AI in the energy management of industrial enterprises has strategic significance for several goals:

1. Energy Security and Independence. AI enables enterprises to optimize the use of local energy resources, including renewables, reducing dependence on centralized supplies and imported energy resources.

2. Decarbonization and Sustainable Development. Intelligent energy management systems contribute to carbon emission reduction through increased efficiency and integration of clean energy technologies, aligning with European “green transition” goals.

3. Integration into a Decentralized Energy System. AI creates the technological foundation for enterprise participation in a decentralized energy system, where they can act as prosumers (producer-consumers), network balancing participants, and flexibility service providers.

4. Increased Competitiveness. By reducing energy costs and gaining additional revenue from participation in energy markets, AI-powered energy management systems enhance the competitiveness of Ukrainian industrial enterprises in global markets.

Conclusions. Artificial intelligence represents a transformative force in energy management of industrial enterprises, enabling new capabilities in energy consumption optimization, renewable energy integration, predictive maintenance, and participation in decentralized energy systems. The research findings indicate that successful AI implementation requires a comprehensive approach addressing technical infrastructure, data governance, capability development, system integration, and appropriate governance mechanisms.

Industrial enterprises that successfully navigate the implementation challenges can achieve significant benefits, including operational efficiency, cost reduction, improved reliability, and readiness for participation in Ukraine’s decentralized energy system. However, realizing these benefits requires sustained commitment to digital transformation and willingness to adapt organizational structures and processes.

As AI technologies continue to evolve, industrial enterprises must maintain awareness of emerging capabilities and develop flexible implementation approaches that can accommodate new developments. Establishing partnerships with technology providers, research institutions, and industry peers can help enterprises stay at the forefront of AI innovation while sharing implementation costs and risks.

The integration of AI in energy management of industrial enterprises represents not merely a technological upgrade but a fundamental transformation in how enterprises consume, produce, and interact with energy. By adopting structured implementation approaches and addressing the identified challenges, Ukrainian industrial enterprises can harness the transformative potential of AI to achieve operational excellence, energy resilience, and become key participants in Ukraine’s future decentralized energy system.

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