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Innovative technologies to improve energy efficiency and security of military facilities

Abstract. The purpose of this study was to analyse the potential of innovative solutions for optimising energy processes and strengthening security systems at military facilities. The study analysed scientific papers, reports, and publications on energy and cyber technologies, using a comparative analysis of approaches to the implementation of renewable energy sources, intelligent control systems and automated technologies at military facilities. The findings confirmed that renewable energy sources (solar panels, wind turbines) reduce dependence on fossil fuels and increase the autonomy of bases. Intelligent energy management systems optimise costs and increase resource efficiency. Microgrids were found to provide a stable power supply even in case of outages. Protecting critical infrastructure using multi-level cybersecurity systems and artificial intelligence significantly reduces the risk of attacks. It was emphasised that microgrids reduce the risk of power outages during crises or cyberattacks, allowing for a quick switch to backup energy sources. Innovative insulation materials and energy-efficient equipment reduce operating costs and improve working conditions for staff. Cyber defence of critical energy systems at military facilities includes multi-level protocols, monitoring of network

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activity and encryption technologies to prevent cyber-attacks. The use of artificial intelligence to analyse threats allows for prompt detection and response to anomalies. It was proved that innovative technologies are key to ensuring energy independence, security, and efficiency of military facilities. The findings of this study can be used to optimise energy consumption and increase the level of autonomy of military bases, which will ensure the stability of the facilities' operation even in difficult conditions or in cases of lack of access to external energy sources

Keywords: renewable energy sources; microgrids; cybersecurity; autonomous energy storage systems; critical infrastructure protection; artificial intelligence

INTRODUCTION

Military bases and infrastructure facilities often operate in challenging environments with limited access to conventional energy sources, requiring the introduction of renewable energy sources such as solar panels and wind turbines, as well as energy storage systems to ensure continuous operation. Energy autonomy is a significant factor in war zones, where the stability of external grids can be disrupted. Innovative technologies can not only reduce dependence on external energy sources but also reduce the cost of energy transportation, which is critical for military operations. Furthermore, the introduction of intelligent energy management systems helps to improve energy efficiency, reduce costs, and increase the battery life of military facilities.

Particular attention should be paid to the cybersecurity of energy systems, as critical military facilities can be targeted by cyberattacks that can disrupt energy infrastructure. The development of secure control systems is a key aspect of security. Thus, the study and implementation of innovative technologies for energy efficiency and security will increase the operational readiness of military facilities, their resilience to external threats and reduce environmental impact, which is critical in the context of current challenges.

T. Vasylieva *et al*. (2021) substantiated the need for innovation to improve the efficiency of Ukraine's energy sector management, especially in the context of the transition to a carbon-neutral economy. The researchers emphasised the significance of a state strategy to attract investment in green technologies and promote energy-saving behaviour. While T. Vasylieva *et al*. focused on the national level, K.-H. Wang *et al*. (2021) and L. Zhang *et al*. (2021) covered the international aspect, examining the relationship between oil, CO_2 emissions, and military spending in importing countries. The findings of K.-H. Wang *et al*. showed cointegration in China, India, and Italy, which is explained by economic growth, high CO_2 emissions, and dependence on oil. In the United States, France, and other countries, this connection is absent due to military strategies and energy policies. The researchers recommended diversifying oil supplies, investing in military research, and developing renewable energy sources to reduce dependence on oil and CO_2.

P. Żuk & P. Żuk (2022) analysed the impact of political conflicts on energy policy, emphasising the significance of diversifying energy sources. The researchers concluded that conflicts encourage countries to make policy changes, such as diversifying energy sources and developing alternative sources, to reduce dependence on imports. A. Azzuni & C. Breyer (2021) proposed a numerical index to assess energy security, which allows quantifying its level in different countries. The findings showed that Germany and the United States have the highest energy security scores, while the Central African Republic and Turkmenistan have the lowest. The researchers concluded that to improve energy security, countries should choose approaches that are suitable to their conditions.

The methodological approach presented by L. Zhang *et al*. (2021) was distinguished by its complexity, as it included seven dimensions of energy security and 28 indicators using Fuzzy AHP and GRA-TOPSIS. The study found that energy security is a multidimensional concept, and it is essential to consider technological, environmental, social, and political aspects to strengthen it. The study by L. Zhang *et al*. was global in nature, while S. Malik *et al*. (2022) focused on local problems and proposed solutions adapted to the specifics of the region. The researchers analysed Pakistan's energy security by analysing it from four aspects (availability, applicability, acceptability, affordability) in the period from 2011 to 2017. The study revealed that despite investments in energy infrastructure, Pakistan is still energy insecure. The researchers recommended the active implementation of green energy solutions such as solar energy, smart meters, and building insulation standards to improve the situation.

M. Krelina (2021) investigated military applications of quantum technologies and their potential effects on defence and security. The conclusions stated that quantum technologies could considerably improve the efficiency and accuracy of military operations, leading to new military strategies and ethics. The report provides an overview of quantum technologies, estimates their timeline for implementation, and describes their application in various areas of warfare, including land, air, space, electronic, cyber, and undersea warfare.

The purpose of this study was to analyse modern technological innovations that can help optimise energy use and improve security measures at military facilities. The objectives of the study were to consider technologies for improving the energy efficiency of military facilities, review innovative security solutions, and examples of the implementation of such technologies in global military structures, and make recommendations for future use.

MATERIALS AND METHODS

The theoretical part of the study was based on a series of scientific papers, reports, and publications describing the use of the latest technologies in the military sphere (Table 1). To consider energy aspects, the study used publications on energy technologies, as well as works on energy efficiency strategies at military facilities. Documents related to automation and intelligent control systems at military facilities were used to analyse the effectiveness of such technologies in the context of military infrastructure. Proceeding from these sources, key technologies that can contribute to energy efficiency and security were identified.

Table 1. Classification of sources and their use in the study

Source type	Focus	Source example	Use in the study
Scientific articles	Analysis of innovative technologies, energy efficiency, cybersecurity	T. Vasylieva *et al.* (2021) – implementation of "green" technologies; L. Zhang *et al.* (2021) – energy security assessment	Sources were used for theoretical analysis of innovative technologies, determination of multidimensional approaches to assessing energy security and the role of microgrids in crisis conditions
Reports of international organisations	Implementation of renewable energy sources, integration of microgrids, technology development	International Renewable Energy Agency (2024) – renewable energy; Defense Advanced Research Projects Agency (2023) – artificial intelligence; NATO (2024) reports – cybersecurity of military facilities	Sources were used to analyse practical examples of energy solutions, cyber defence of critical infrastructures, and the implementation of microgrids at military facilities
Regulations	Regulation of energy technologies, energy efficiency standards, cybersecurity	Laws of the USA (Clover *et al.*, 2024) and Canada (Government of Canada, 2020), European directives (European Defence Agency, 2024) on energy efficiency	These sources helped to formulate recommendations for the integration of technologies in line with international safety norms and standards
Practical cases	Implementation of energy and security solutions at military facilities	Fort Bliss base (USA) – microgrids; military facilities in Germany – insulation materials; base in Canada – wind turbines	Illustrations of the implementation of the latest technologies in real-world conditions helped to confirm the effectiveness of the proposed approaches

Note: NATO – North Atlantic Treaty Organization
Source: compiled by the authors

To determine the effectiveness of the use of innovative technologies in military facilities, a series of reports and publications on the use of alternative energy sources and intelligent systems in the military sphere were analysed. This included the reports of international organisations such as International Renewable Energy Agency (2024), Defense Advanced Research Projects Agency (2023), NATO (2024), as well as national institutions in the United States (Clover *et al.*, 2024), Canada (Government of Canada, 2020), and Europe (European Defence Agency, 2024). The study also reviewed relevant regulations and programmes that promote the development of energy technologies at military bases.

One of the principal research methods was a comparison of different approaches to ensuring energy efficiency and security of military facilities in different countries. The comparative analysis included the study of examples of the use of solar panels, wind turbines, hydrogen fuel cells, as well as cybersecurity technologies and automated systems at bases in the United States, Canada, the United Kingdom (Government of the..., 2024), and Germany. This helped not only to understand which technologies are the most effective, but also to identify the key factors influencing their implementation.

RESULTS

Energy efficiency has become a key element in the design and operation of modern military facilities. Apart from reducing operating costs, it ensures independence from unstable fuel supplies and reduces the need for regular deliveries, which is especially significant for facilities in remote and dangerous areas. According to International Renewable Energy Agency (2024) reports, the use of renewable energy sources in military facilities can provide a sustainable, independent energy supply, and reduce the risks for personnel involved in the supply of energy resources.

Modern military bases are increasingly implementing solar panels as the main or additional source of energy (Katalenich & Jacobson, 2022). Renewable sources not only reduce dependence on conventional fuels, but also ensure the sustainability of energy supply in conditions of remoteness or limited access to resources. Countries such as the United States are actively using solar panels at military bases, with a study by K. Belousova (2022) showing that solar energy projects substantially reduce costs and increase the autonomy of military facilities.

Wind turbines are used to provide additional energy supply, especially at military bases located in areas with stable wind flows. Wind turbines, as part of a combined energy system, reduce the overall consumption of conventional energy resources (Kanwal *et al.*, 2022). The principle of operation of a microgrid with the integration of wind turbines is presented below (Fig. 1).

The use of insulating materials and energy-efficient coatings can reduce heat or cold loss, providing comfortable conditions for personnel and equipment. Effective insulation reduces the need for air conditioning or heating, which is essential for energy savings, especially in large military facilities (Wen *et al.*, 2021). Intelligent lighting systems with automatic control can save energy by using motion and light level sensors. This reduces the load on the power grid and increases the efficiency of resource use.

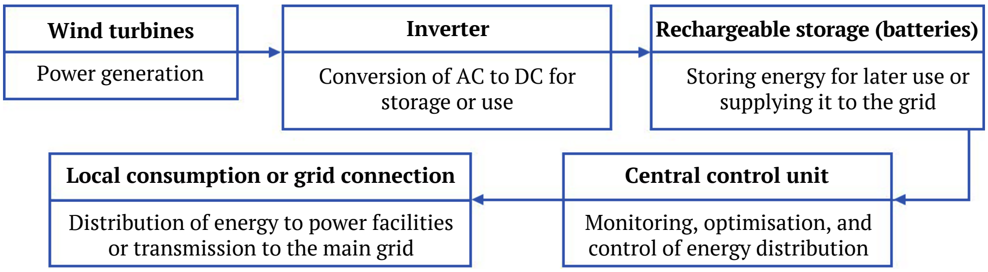

Figure 1. Operation of a microgrid with the integration of wind turbines
Source: compiled by the authors based on O. Saritas & S. Burmaoglu (2016)

Intelligent systems based on the Internet of Things (IoT) allow monitoring and optimising the use of electricity at military facilities (Prozuments *et al.*, 2019). They collect data on energy consumption, automatically detect costs, and allow systems to be adjusted to reduce consumption. Microgrids provide energy storage and distribution within the facility, optimising consumption, and providing flexible management of energy flows. They can operate autonomously in case of a loss of the primary energy source, which is especially useful for military facilities located in areas with unstable energy supplies. Such systems allow creating autonomous energy networks that can operate independently of the central power grid (Shah *et al.*, 2022). In case of an emergency, microgrids can automatically switch to backup energy sources, ensuring that the facility's energy needs are met without interruption. Although the prohibitive cost of investment and the need for qualified personnel to maintain these systems are major challenges, their use at remote military bases provides the necessary energy independence and increases resilience to external threats.

The use of artificial intelligence technologies to process and analyse video surveillance data allows for the rapid detection of potential threats. Thanks to machine learning algorithms, systems can analyse the behaviour of people and vehicles in real time, recognise abnormal actions, and immediately alert security. For example, Defense Advanced Research Projects Agency (2023) research suggests that the use of artificial intelligence video analytics at military facilities substantially increases the efficiency and speed of response to threats.

Intelligent sensors and artificial intelligence systems allow detecting suspicious activity on the territory of military facilities and sending real-time notifications to security services. For instance, cameras with built-in artificial intelligence algorithms can recognise anomalous activities, such as unauthorised movement or intrusion. The US is already actively using such systems at military bases, which reduces the need for constant physical patrols (Clover *et al.*, 2024). This considerably increases the speed of response to threats and reduces the need for additional forces to protect facilities.

Modern sensor systems can detect any movement on the territory of an object, even at night or in harsh weather conditions. Infrared barriers are installed around important facilities and are triggered by any crossing of the perimeter (Huang *et al.*, 2021). Such systems are widely used in NATO (2024) military structures to strengthen the protection of bases and warehouses. With the growing threat of cyberattacks, the protection of information networks and databases has become a priority for military facilities. Military structures are implementing multi-level security protocols, encryption, and artificial intelligence-based network activity monitoring technologies. This allows them to quickly detect unauthorised access attempts (Mittal & Davidson, 2020).

Critical energy systems of military facilities are also subject to protection from cyberattacks, as their damage can lead to severe disruptions (Hemmati & Rahmani, 2022). In case of an emergency, such as a failure of the main power source or a physical attack on the facility, military facilities must be able to quickly switch to backup or autonomous power sources. For this purpose, generators, high-capacity batteries, and energy storage systems are used. Military organisations in different countries are actively implementing modern technologies to ensure energy efficiency and security. This allows not only to reduce operating costs but also to increase the autonomy and security of facilities from external threats. Below are a few examples from different countries that have already succeeded in this area (Table 2).

Table 2. Technologies and use examples

Country	Technology	Use example	Outcomes and advantages
USA	Solar panels and microgrids	The Fort Bliss military base uses a microgrid with solar panels and batteries for energy storage	Improved autonomy of the base and reduced electricity costs by 20-25%
Canada	Wind turbines and energy management system	The base in northern Canada has wind turbines and a system for monitoring and optimising energy consumption	Reduction of dependence on traditional fuels and cost savings on transportation of resources
United Kingdom	Cybersecurity and backup power systems	Use of multi-level cybersecurity protocols and autonomous energy storage systems at key facilities	Increased resilience to cyber-attacks and ensure continuity of operations even during attacks

Continued Table 2.

Country	Technology	Use example	Outcomes and advantages
Germany	Energy-saving lighting and intelligent sensors	LED lighting with motion sensors and automatic light control is installed at military facilities	Reduced lighting costs by 30-40% and reduced electricity consumption
Japan	Autonomous microgrids and hydrogen fuel cell generators	Implementation of microgrids powered by hydrogen fuel cells to ensure energy independence on the islands	Provision of facilities in remote areas with an independent and environmentally friendly source of energy

Note: LED – light-emitting diode
Source: compiled by the authors based on Government of Canada (2020), L. Clover *et al*. (2024), European Defence Agency (2024), Government of the United Kingdom (2024), Y. Tsuji (2024)

Military bases that use alternative energy sources, microgrids, and modern control systems can considerably reduce operating costs and ensure the resilience of facilities even in case of emergencies. These innovations have proven to be effective and have become a vital aspect in improving the security and energy independence of military facilities (Tutak & Brodny, 2022). Furthermore, due to the reduced environmental impact from the use of clean energy sources, such solutions are supported by environmental programmes.

The use of renewable energy sources at military facilities is becoming increasingly popular, as it not only reduces dependence on fossil fuels but also increases the autonomy of the facilities (Yaghoubi *et al.*, 2022). Military bases located in remote regions face logistical challenges in terms of regular fuel supply, which can be dangerous or costly. Solar panels installed on buildings and special stations provide a stable supply of electricity even in the absence of a connection to the central grid (Shahini *et al.*, 2024). Such units are available in the US and the UK, where they cover a major portion of the energy needs of bases, reducing fuel costs and minimising the risks associated with fuel transportation.

Energy management systems based on the IoT enable detailed monitoring of all electricity consumers at facilities, ensuring optimised use of resources (Affum *et al.*, 2021). Intelligent sensors installed on electrical appliances and buildings provide information on consumption levels, allowing unused devices to be automatically switched off or power to be reduced during off-peak periods. For example, according to research.

New insulation materials and coatings for buildings at military facilities help reduce heat and cold loss, which can greatly reduce heating and air conditioning costs. For example, NATO bases in Northern Europe are actively using modern thermal insulation materials that provide protection against harsh climatic conditions and help keep buildings warm in winter (Nuchturee *et al.*, 2020). This not only creates a comfortable environment for personnel, but also reduces the energy load on the base, providing great resource savings and reducing environmental impact.

Protecting energy systems from cyber threats is a critical part of the security strategy of military facilities, as cyber-attacks can lead to a complete power outage and disruption of critical infrastructures (Sandri *et al.*, 2020). Military facilities are implementing multi-level security systems, including encryption, continuous monitoring of activity, and automatic detection of suspicious activity using artificial intelligence. For example, NATO is actively researching the cybersecurity of energy systems, including microgrids, to ensure continuous operation even in case of cyber-attacks (Ige *et al.*, 2024).

Autonomous energy storage systems, such as generators, large batteries, or hydrogen fuel cells, allow military facilities to stay energy independent for a prolonged time. Hydrogen fuel cells, for instance, can provide autonomous power for facilities for several days, which is crucial for military bases located in remote regions or in unstable situations. For example, military bases in Japan use hydrogen fuel cells to ensure continuous operation even during crises, which provides a strong advantage in terms of energy sustainability (Tsuji, 2024). As indicated in Table 3, various autonomous energy storage technologies have already been applied in practice, demonstrating their effectiveness in ensuring energy autonomy in crisis conditions.

Table 3. Technologies and use examples

Technology	Country	Use example	Outcomes and advantages
Renewable energy sources	USA	Use of solar panels on military bases for basic/additional energy supply	Reduced dependence on fossil fuels, increased autonomy of bases, reduced operating costs
Intelligent energy management systems	United Kingdom	Installation of IoT sensors to monitor and optimise energy consumption	Optimisation of energy consumption by 15-20%, prevention of overloads, and increased resource efficiency
Microgrids	USA	Use of an autonomous microgrid with solar panels and batteries based on Fort Bliss	Increase facility resilience, ensure uninterrupted power supply in case of accidents or cyber threats, and save money
Modern insulation materials	Germany	Use of thermal insulation materials in military buildings to reduce heat loss	Reduced heating and air conditioning costs, increased energy efficiency, improved staff comfort
Cybersecurity of energy systems	NATO	Implementation of network activity monitoring systems based on artificial intelligence	Protection against cyber-attacks, ensuring the security of energy systems, reducing the risk of energy supply loss

Continued Table 3.

Technology	Country	Use example	Outcomes and advantages
Autonomous energy storage systems	Japan	Use of hydrogen fuel cells as a backup power source at remote military bases	Provision of energy independence, possibility of autonomous operation for several days, reduction of costs for imported fuel
Artificial intelligence and sensors for security	USA	Using artificial intelligence analysis of video surveillance to recognise abnormal behaviour at facilities	Rapid response to threats, increased efficiency of the security service, reduced need for physical patrols
Energy-saving lighting	Germany	Installation of LED lighting with automatic light intensity control	Reduced electricity consumption by 30-40%, improved lighting efficiency, reduced operating costs

Source: compiled by the authors based on Government of Canada (2020), L. Clover *et al*. (2024), European Defence Agency (2024), Government of the United Kingdom (2024), Y. Tsuji (2024)

Since modern technology is developing rapidly, many military organisations recognise the potential of such solutions. However, a series of technical, economic, and organisational aspects must be considered for their successful implementation. Solar panels and wind turbines are environmentally friendly and cost-effective sources of energy in the long term (Szafraniec *et al*., 2021). They can provide energy to military bases, reducing dependence on fossil fuels, which is especially significant for remote military facilities. However, these systems require extensive upfront investment, and their efficiency can be affected by erratic weather conditions. To increase the efficiency of such systems, supplementary energy storage is required. The combined use of solar and wind energy together with microgrids and energy storage can solve these problems, as is already the case in the US, Canada, and Germany.

The use of heat-insulating materials can greatly reduce heat loss, which decreases the cost of heating and air conditioning (Serdyuk *et al*., 2024). Energy-efficient lighting, such as LED lamps, helps to save energy. However, retrofitting existing military facilities can be challenging due to their specific structure and the prohibitive cost of some modern materials. In the long-term, investments in such materials are cost-effective, as they contribute to sustainable energy savings. Protecting critical energy infrastructures from cyber threats is becoming increasingly critical. Integration of cyber defence technologies reduces the risk of attacks but requires constant security updates and integration with other security systems, which requires extensive financial and technical resources (Metelskyi & Kravchuk, 2023). Implementing multi-level security systems, encryption, real-time activity monitoring, and the use of artificial intelligence to detect anomalies can greatly improve security.

Intelligent monitoring systems and artificial intelligence can quickly detect potential threats by analysing data from video cameras and sensors, which increases the efficiency of facility security. However, they require qualified personnel to process large amounts of data and store confidential information. Sensor systems and infrared barriers also play an essential role in detecting movement at facilities in difficult conditions or at night. While such systems can be expensive to deploy over large areas, the combined use of sensors and surveillance cameras with artificial intelligence analytics can reduce the probability of false alarms. The introduction of innovative technologies at military facilities increases their autonomy, reduces dependence on conventional fuels, and reduces risks to personnel. It also increases the level of energy independence and security, enabling an effective response to challenges and ensuring that military facilities are prepared to operate in emergency conditions.

For the successful implementation of such technologies, it is recommended to invest in research and development, continuously improve energy saving technologies and security systems, develop human resources through staff training, cooperate with the private sector to develop and implement high-tech projects, and regularly monitor the effectiveness of the implemented technologies to adjust the strategy and improve efficiency. Thus, the integration of the latest technologies at military facilities is a necessary step to ensure energy sustainability, operational readiness, and national security in the face of emerging challenges and threats.

DISCUSSION

This study focused on the analysis of innovative technologies that improve the energy efficiency and security of military facilities, which are increasingly vulnerable to cyber and physical attacks. The key findings of the study revealed that the introduction of renewable energy sources, such as solar panels and wind turbines, considerably increases the energy autonomy of military facilities. In addition, the use of innovative insulation materials and energy-efficient lighting systems helps to reduce operating costs and provides comfortable conditions for personnel.

Intelligent energy management systems based on IoT help optimise resource use and reduce energy consumption (Boiko *et al*., 2023). A crucial aspect of the study is to improve the cybersecurity of military facilities. The use of artificial intelligence to monitor and analyse video data, as well as modern sensor systems for motion detection and perimeter control, ensures prompt detection of potential threats. Multi-level cyber defence protocols and autonomous energy storage systems increase the resilience of facilities to attacks and ensure their operational readiness even in crisis situations.

A. Soni (2019) investigated potential major changes in the way the US military uses energy technologies and their effects on national security. The energy chain was used to analyse energy technologies – production, storage, transmission, and use of energy. The lethality-survivability-mobility triangle was used to assess deployed technologies to identify potential locations and methods for strategic change. The study provided suggestions for significant research areas and organisational aspects of energy technology procurement for the US military. The current study confirmed the significance of these aspects, specifically the approach to autonomous energy systems, but focused more on their impact on fixed military facilities, while A. Soni (2019) focused on the strategic use of technology in mobile military operations.

O. Saritas & S. Burmaoglu (2016) analysed the growing energy needs in military operations due to changes in warfare. The study focused on the evolution of energy requirements from World War II to Operation Desert Storm in 1991, and on to modern technologies that include night vision, laser targeting, advanced sensing, and communications capabilities, as well as drones and robotics. Using trend analysis, technology mining, and scientometrics, the study developed future scenarios and a strategic roadmap for priority technology areas in military energy research and development. The current study confirmed the trend of increasing energy requirements due to the growing dependence on technologies such as IoT, drones, and laser systems. At the same time, the present study added an analysis of the impact of microgrids and energy management systems that increase the energy autonomy of modern military bases.

In the study by M.N. Norrrahim *et al*. (2021), nanocellulose also demonstrated great functionality and potential for many applications, including body armour, materials with fire-resistant properties, and filtration elements, which can reduce dependence on conventional materials and increase the efficiency of military facilities. Both studies were aimed at developing solutions to improve security. The use of nanocellulose in military materials can improve protection due to its mechanical and heat-resistant properties. The conducted study addressed cybersecurity and the protection of energy systems at military facilities, which is also significant for the protection of critical infrastructure. In the current study, the author agreed that innovative materials play a key role in enhancing protection but focused on the integration of the latest cybersecurity technologies to protect energy systems, which is critical in the modern military context.

The study by A.Z. Isiksal (2021) on the impact of military spending and renewable energy consumption on CO_2 emissions has much in common with the study on the energy efficiency of military facilities, particularly in the context of reducing the carbon footprint and increasing the energy independence of military structures. The study on military spending and CO_2 emissions indicates that increased military spending contributes to increased CO_2 emissions, confirming the "treadmill of destruction" hypothesis. This hypothesis states that an increase in defence spending is accompanied by an increase in pollution. The study focuses on improving energy efficiency and reducing environmental impact through the introduction of modern technologies (solar panels, wind turbines, microgrids). The introduction of renewable energy sources is significant for reducing the carbon footprint, promoting environmental sustainability, and ensuring energy autonomy of military facilities. The use of solar panels and wind turbines minimises dependence on fossil fuels and optimises energy costs (Qawaqzeh *et al.*, 2020).

Overall, the study demonstrated that the integration of innovative technologies is necessary to improve the energy efficiency and security of military facilities. It is recommended to continue the development and implementation of these technologies, invest in research, personnel training, and cooperate with the private sector to implement high-tech projects.

CONCLUSIONS

Innovative technologies to improve the energy efficiency and security of military facilities provide major benefits, including energy independence and resilience, efficient resource management, and enhanced cyber security. The introduction of renewable energy sources, such as solar panels, wind turbines and hydrogen fuel cells, makes military facilities less dependent on external energy sources. This reduces the need for a constant supply of fuel and increases autonomy, especially for remote facilities. Energy management systems and microgrids optimise the use of resources and enable rapid response to threats or energy disruptions. Microgrids ensure a stable power supply, even in case of an outage in the central grid. As military facilities are becoming major targets of cyber-attacks, multi-level defence systems and intelligent monitoring systems are essential to ensure the security of critical infrastructures.

Considering the growing significance of energy efficiency and security of military facilities, it is recommended to expand the use of renewable energy sources, develop autonomous energy systems, improve cyber defence, and expand the use of energy-saving technologies. The introduction of alternative energy sources should be continued, especially in remote bases and facilities where it may be challenging to ensure a constant supply of fuel. The use of autonomous microgrids maintains access to electricity even during emergencies, reducing the risk of power outages and providing flexible management of energy flows. Continuous improvement of cybersecurity is critical to protecting information and energy systems. It is vital to develop systems with early detection of threats and backup infrastructures. Military facilities should be equipped with intelligent energy monitoring systems and energy-efficient equipment (e.g., LED lighting with motion sensors and automatic temperature control systems).

Further research could be aimed at expanding the analysis of the effectiveness of introducing microgrids and renewable energy sources at military facilities in diverse climatic conditions. Particular attention should be paid to the effects of innovative technologies on reducing operating costs and increasing energy autonomy in extreme environments. Another promising area is the development of cybersecurity systems to protect the energy infrastructures of military bases. In this context, it is essential to evaluate the use of artificial intelligence for early threat detection and automated crisis management.

The development of new insulating materials and energy-efficient systems could be another area of research, particularly in the context of reducing the environmental impact of military operations. Integration of these technologies with modern IoT solutions can considerably optimise energy processes. Further research could also focus on creating scalable and cost-effective microgrid models for small and medium-sized military bases, as well as assessing opportunities for cooperation with commercial entities to develop joint innovative projects.

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CONFLICT OF INTEREST

None.

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Інноваційні технології для підвищення енергоефективності та безпеки військових об'єктів

Анотація. Метою даного дослідження був аналіз потенціалу інноваційних рішень для оптимізації енергетичних процесів та посилення систем безпеки на військових об'єктах. В ході дослідження було проаналізовано наукові праці, звіти та публікації з питань енергетики та кібертехнологій, за допомогою порівняльного аналізу підходів до впровадження відновлюваних джерел енергії, інтелектуальних систем управління та автоматизованих технологій на військових об'єктах. Результати дослідження підтвердили, що відновлювані джерела енергії (сонячні панелі, вітрогенератори) зменшують залежність від викопних видів палива та підвищують автономність баз. Інтелектуальні системи управління енергією оптимізують витрати і підвищують ефективність використання ресурсів. Мікромережі забезпечують стабільне електропостачання навіть у разі відключень. Захист критичної інфраструктури з використанням багаторівневих систем кібербезпеки та штучного інтелекту значно знижує ризик атак. Було підкреслено, що мікромережі знижують ризик відключення електроенергії під час кризових ситуацій або кібератак, дозволяючи швидко переходити на резервні джерела енергії. Інноваційні ізоляційні матеріали та енергоефективне обладнання зменшують операційні витрати та покращують умови праці персоналу. Кіберзахист критичних енергетичних систем на військових об'єктах включає багаторівневі протоколи, моніторинг мережевої активності та технології шифрування для запобігання кібератакам. Використання штучного інтелекту для аналізу загроз дозволяє оперативно виявляти аномалії та реагувати на них. Доведено, що інноваційні технології є ключовими для забезпечення енергетичної незалежності, безпеки та ефективності військових об'єктів. Результати дослідження можуть бути використані для оптимізації енергоспоживання та підвищення рівня автономності військових баз, що забезпечить стабільність роботи об'єктів навіть у складних умовах або у випадках відсутності доступу до зовнішніх джерел енергії

Ключові слова: відновлювальні джерела енергії; мікромережі; кібербезпека; автономні системи накопичення енергії; захист критичної інфраструктури; штучний інтелект