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**Editors office address**:
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony, Kyiv, Ukraine
Tel.: +38(044)-258-42-63
E-mail: info@technicalscience.com.ua
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**Адреса редакції**:
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
Тел.: +38(044)-258-42-63
E-mail: info@technicalscience.com.ua
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**Annaguly Deryaev***

Doctor of Technical Sciences, Principal Researcher
Scientific Research Institute of Natural Gas of the State Concern "Turkmengas"
744036, 58 Archabil Ave., Ashgabat, Turkmenistan
https://orcid.org/0009-0004-8569-6277

# Engineering aspects and improvement of well drilling technologies at the Altyguyi field

**Abstract.** The relevance of the research is justified by the rapid development of the oil industry, which requires constant improvement of methods and equipment to increase extraction efficiency and reduce environmental impact. The aim of this study is to enhance the current engineering aspects of drilling in the Altyguyi field while considering increased productivity and reduced environmental impact. Among the methods used, it is necessary to mention the synthesis method, abstraction method, generalization method, induction method, deduction method, classification method, and others. This study examines the technological aspects of operating wells in the Altyguyi gas-condensate field. Extensive laboratory and industrial research on the properties and composition of oil, gas, and condensate was conducted to properly implement the dual completion technology for gas extraction from one formation and oil extraction from another formation in a single well. By implementing advanced drilling methods, including horizontal and multi-hole drilling, as well as using modern drilling fluids, it was possible to improve well productivity and reduce drilling time. As a result of technology optimization, the overall efficiency of the oil and gas extraction process in the field has been increased, confirming the significance of innovation implementation for improving results in the oil industry. These enhancements not only increased drilling safety and efficiency, but also reduced the negative impact on the environment, emphasizing the importance of integrating modern technologies with environmental considerations in the oil extraction process. This research makes a significant contribution to the development of more efficient and environmentally sustainable drilling methods in oil fields, contributing to increased oil extraction productivity and reduced environmental impact

**Keywords**: oil industry; efficient production; environmental impact; best practices; drilling fluids

## INTRODUCTION

The study of engineering aspects and improvement of well drilling techniques in the Altyguyi field is of strategic importance in the context of ensuring efficient and sustainable energy production. The field represents a significant oil and gas resource, and optimizing drilling processes has a direct impact on its economic value and long-term sustainability. The development of advanced drilling technologies and techniques will increase productivity, reduce operating costs, minimize environmental risks, and maximize production yields, which in turn contributes to the energy security of the region and the country as a whole.

The study includes a set of challenges, such as the complex geological structure of the reservoir, the need to improve production efficiency while adhering to strict safety standards and considering limited resources and costs. The field is characterized by a complex geological structure of the reservoir, which creates challenges in accurately determining its parameters and properties. This requires the development of methods and technologies capable of adapting to the variable conditions of the geological formation and ensuring accuracy when drilling wells. There is a need to improve the efficiency of hydrocarbon production in the

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*Corresponding author

field. This includes the development of innovative drilling methods, optimization of oil and gas lifting and handling processes, and improved systems for monitoring and controlling production processes. Environmental and safety standards place high demands on field operations, which requires the development and implementation of technologies aimed at reducing the environmental impact and risks of production processes (Issa *et al.*, 2024). All these aspects require a continuous innovative approach to the development and implementation of drilling technologies capable of ensuring sustainable and safe operation of the field.

In the work of Sh.E. Avulov & A.S. Agyshev (2023), the authors, emphasize that the development of innovative drilling technologies requires combining advanced drilling techniques with high-tech process control and management systems. This will improve the efficiency and safety of production, minimize costs and reduce environmental impact. The paper does not sufficiently cover the aspects of automation of drilling processes and the use of robotic systems to improve the efficiency and safety of operations. According to a study by J.M. Kabyl (2023), successful implementation of new drilling technologies in the field requires cost-effectiveness analyses and estimation of implementation and operation costs. Equipment costs, labour costs, investment payback periods and potential financial risks need to be considered. The study does not consider the factors of economic efficiency of the long life of new technologies and their impact on the competitiveness of the field.

Researchers E. Soatov & H. Ergashev (2023) note that improving the efficiency of field production should be accompanied by strict compliance with safety and environmental standards. It is necessary to develop and implement monitoring and control systems that will ensure the safety of personnel, prevent accidents, and reduce the environmental impact of production processes. Researchers do not pay attention to the development of preventive control and accident prevention systems in the field. In the work of R.O. Nurlybaev (2021), the author raises an important issue that the development of drilling technologies should be included in the overall strategy for the development of the energy sector in the region. It is necessary to take into account both geopolitical and economic factors, assess the potential contribution to the energy security of the country and develop long-term plans for the development of hydrocarbon production. The study does not consider the impact of global trends in the energy sector, such as the transition to renewable energy sources, on the long-term development prospects of the field.

The purpose of this study is to improve the existing engineering aspects of the drilling process at the Altyguyi field with an eye to increasing efficiency and reducing negative environmental impact.

## MATERIALS AND METHODS

The study region was the Altyguyi location. Drilling rigs of the model "Drilling Unit-5000" (DU-5000) were considered during the study. These rigs were represented by two variants: diesel Uralmash-ZD (factory diesel), and electric diesel ZJ 70 DS (Zoomlion Heavy Industry Science & Technology Co., Ltd. (Zoomlion), China).

The analytical method applied in the study allowed a comprehensive study of various aspects of the drilling process in the Altyguyi field. By collecting data on well specifications, production conditions, equipment utilization and other factors, the main factors affecting drilling performance and efficiency were identified. In addition, by studying environmental parameters and assessing the environmental impact of production, it was possible to identify the most critical aspects and develop proposals to reduce the negative environmental impact.

Using the synthesis method, comprehensive strategies and recommendations were developed to improve the drilling process at the Altyguyi field. By integrating this research with engineering knowledge and experience, new approaches were developed to optimize drilling parameters, equipment selection and process control methods. In addition, the synthesis method allowed environmental aspects to be effectively integrated into the field development strategy, offering innovative technologies and methods to minimize the negative impact on the natural environment.

The method of synthesis helped in highlighting key trends and general patterns based on a variety of data and research results. By studying the information obtained, the main trends and factors determining the efficiency and sustainability of the drilling process at the Altyguyi field were identified. This method allowed forming a holistic view of the state and prospects of hydrocarbon production development, as well as identifying key areas for further research and development.

Applying the induction method, general regularities and trends were identified on the basis of specific observations and data obtained during the study of the Altyguyi field. This method allowed highlighting the main cause-and-effect relationships between various parameters and factors affecting the efficiency of the drilling process. By examining a variety of data on well specifications, production conditions and environmental impacts, general patterns were identified, which became the basis for formulating recommendations to optimize the drilling process and improve its efficiency.

The deduction method helped in forming logically sound conclusions based on generally accepted principles and theories applied to the specifics of the object under study – the drilling process at the Altyguyi field. By examining generally accepted engineering and environmental principles, as well as already available data on drilling at similar fields, this method was applied to formulate hypotheses and assumptions regarding optimal drilling strategies, ways to reduce environmental impact and improve the overall efficiency of the production process at the Altyguyi field.

The classification method was used to structure the various aspects and parameters that characterize the drilling process in the Altyguyi field. This method allowed the identification of the main categories and groups of factors affecting the efficiency and environmental sustainability of mining. By examining the data and results, key trends and problem areas requiring further investigation and improvement were identified. Also, the classification method helped to develop more accurate and targeted strategies to optimize the drilling process and reduce its negative environmental impact.

By applying the abstraction method, the main general principles and patterns underlying effective drilling strategies for the Altyguyi field were identified. This method allowed separating the key success factors from the general description of technological solutions. The results of this method allowed creating a generalized model that can be adapted to different conditions and specifics of the field.

## RESULTS

At the gas and condensate field in the Altyguyi region, the introduction of closed-loop gas lift compressor technology is becoming a key issue. This innovative system plays an important role in ensuring high quality gas treatment for gas lift operations and continuous gas supply to the export pipeline. The strategic implementation of this system promotes operational efficiency and meets environmental and quality standards, making it an integral component of future field development plans. Drilling depths for production wells in the Altyguyi field vary depending on the structural position. Typically, drilling depths average approximately 3,750 m in consolidated areas and reach approximately 4,000 m in the krill parts. It is important to note that all the project wells are vertical (Deryaev, 2023b).

The design of the wells is carefully selected and justified, taking into account the compatibility of their sections under the current mining and geological conditions of the drilling process. These evaluations are based on analyses of reservoir pressure and rock fracture pressure prediction curves, which are usually presented in combined pressure plots. Taking all these factors into account, the well design is tailored to the specific geological and operating conditions of the Altyguyi field to ensure efficient and safe resource extraction. The methods used are in line with industry standards, safety requirements and the collective experience of previous drilling operations in the region.

The following construction structures are used to ensure safe and efficient drilling of wells at a depth of 3,750 m inside the productive horizon of the Well Construction Structure (NK-9), especially in stable mining and geological conditions:

- the guide section consists of Ø720 mm diameter pipes with a length of 10 m, the purpose of which is to prevent erosion of the wellhead and to provide a secure tie-in to the drilling fluid circulation system;
- the extended length section 30 m long and Ø530 mm is used to support the blowout preventer and provide stability while drilling under the conductor;
- the conductor section, consisting of 426 mm diameter pipe and 400 m long, is used to overcome unstable sandy clay quaternary deposits and provide safe well control;
- the first section of the intermediate string with a diameter of Ø324 mm and a length of 1,600 m is used to reduce the risk of hydraulic fracturing by increasing the density of the drilling fluid;
- the second technical string, which is 3,460 m long and Ø324 mm, is used to control the operation of blowout preventer equipment and to cap high-pressure reservoirs;
- the production string consists of Ø140 mm pipes and extends to a depth of 3,750 m, where resources are extracted from the productive horizon.

The well is cemented all the way to the wellhead (Deryaev, 2023c). To solve the geological problems in the krill part of the NK-9 productive horizon, production wells with a depth of 4,000 m are constructed using the following design: 720 mm diameter pipes, lowered by 10 m, prevent erosion of the wellhead, and provide a connection to the drilling fluid circulation system for its efficient movement, preserving the integrity of the wellhead. Ø530 mm pipes at a depth of 30 m protect the wellhead from erosion and cover areas of high gas saturation at shallow depths due to loose sandy-clay deposits. The 426 mm diameter conductor pipes extend for 600 m, crossing water pressure boundaries and isolating the well from hydraulic connections to surface water, preventing gas contamination and providing control during drilling. The first intermediate string with Ø324 mm pipes reaches a height of 2,000 m, protecting against cave-ins and drilling mud absorption by quaternary sediments. The Ø245 mm pipes in the second intermediate string extend to 3,750 m, providing well control and equipment installation in the NK-7 and NK-8 gas condensate horizons. The production string with Ø140 mm pipes extends up to 4,000 m, creating conditions for testing productive formations and carrying out workover operations, considering the data of gas-dynamic studies.

The detailed design of the well structure in the krill section of the Altyguyi field takes into account the unique geological and operational conditions to ensure safe and efficient drilling and successful resource recovery (Fig. 1). Well construction involves several stages, each requiring specific materials and methods (Adjei *et al.*, 2022). The use of cement to form a protective barrier along all the strings extending to the wellhead. This step is key to ensure the structural strength and reliability of the well. The drilling process is rigorously planned and the choice of drilling mud depends on the particular string being worked on. An oil-emulsion humate-lignosulfonate mud is preferred as a conductor. For the intermediate and production string, a polymer-based drilling mud known as ALKAR-3 is used. It should be noted that when drilling production wells, the coring process is not performed on a regular basis. Instead, selective core samples are chosen to analyse their filtration characteristics in more detail. This approach is used to develop effective strategies for discovering aquifers without the risk of contamination or damage.

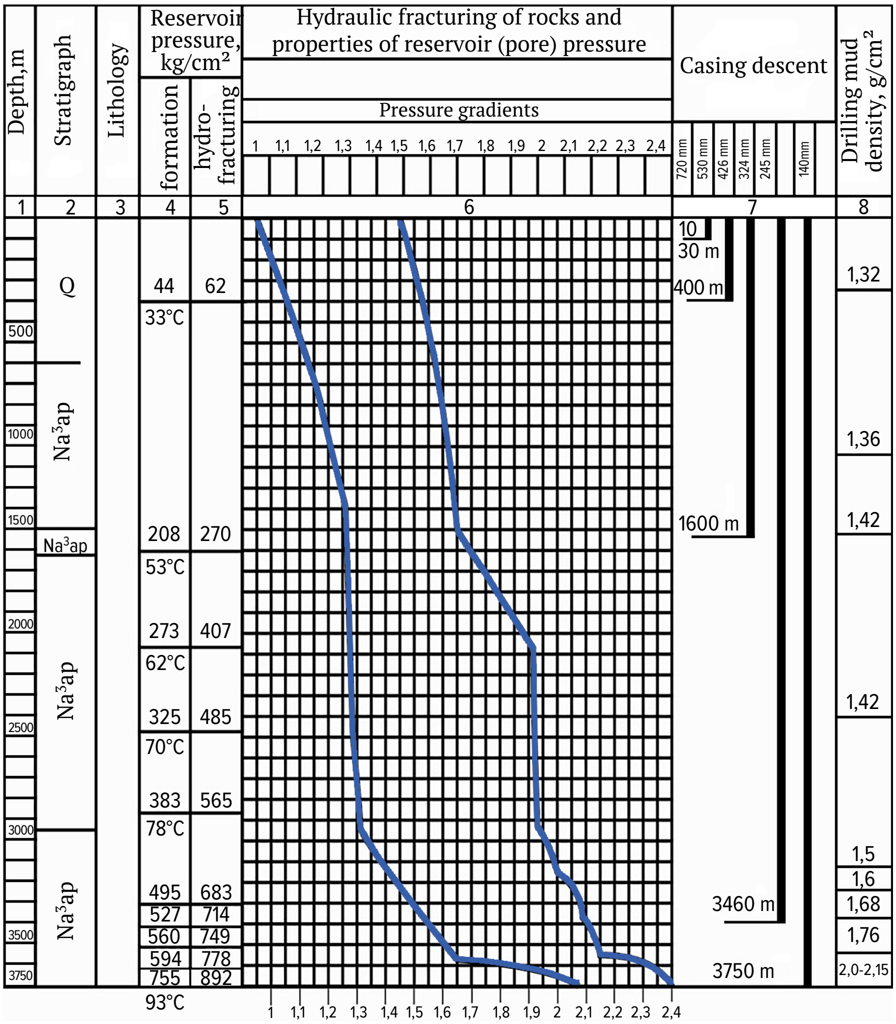


**Figure 1.** Combined pressure graph at the Altyguyi field

**Source:** compiled by the author

A well plan is a carefully designed strategy that includes the prudent selection of drilling fluids and equipment to ensure a continuous and efficient process (Pink *et al.*, 2012). To achieve optimum wellbore performance, water-based clay muds are used, enriched with barite to increase density, and treated with chromolignosulfonate-based chemical additives for high performance. To further enhance fluid properties, cement inhibition is used to ensure well stability and reliability throughout the well construction process. This integrated approach emphasizes the importance of strategic planning and integration of advanced technologies for successful well construction projects. This plan requires drilling rigs from the BU-5000 series. These rigs are available in two versions: diesel Uralmash-ZD and diesel-electric ZJ 70 DS. They are specially designed to meet the specific requirements of the drilling process, especially in difficult desert terrain.

The Uralmash-ZD drilling rig (Fig. 2) in the diesel version is technologically advanced equipment with a number of important features that make it indispensable in the oil industry. One of the key features of this unit is that it is equipped with a diesel engine. This type of engine provides high torque and reliable operation even in conditions with intermittent or limited power supply. In addition, the Uralmash-ZD drilling rig has high power and characteristics that allow it to effectively drill in a wide variety of conditions, including difficult desert terrains. Its ability to operate in such extreme conditions makes it indispensable for many projects where reliable and efficient well drilling is required. The performance and reliability of the Uralmash-ZD drilling rig is another of its important advantages. Thanks to its design and technical characteristics, this rig is able to provide high drilling speed and minimum downtime, which increases the efficiency of projects and reduces time and financial costs. Last but not least, the Uralmash-ZD drilling rig is specially adapted to work in environments where access to the power grid is limited. This makes it an ideal choice for projects in remote or underdeveloped regions where the electrical infrastructure leaves much to be desired. Thus, the Uralmash-ZD diesel drilling rig is a reliable and powerful tool capable of efficiently performing various drilling tasks in the most challenging conditions.

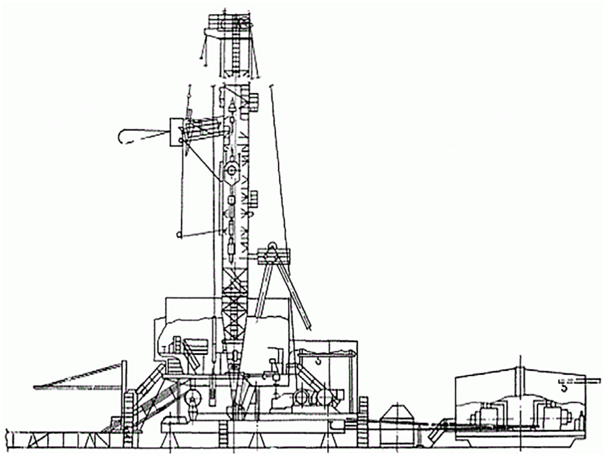

**Figure 2.** Diagram
of the Uralmash-ZD drilling rig (diesel version)
**Source:** H. Suryadi *et al*. (2021)

The ZJ 70 DS diesel-electric drilling rig is innovative equipment that provides optimal solutions for a variety of drilling projects in conditions of varying complexity. Its main difference is the diesel-electric system, which gives the rig significant advantages in efficiency and energy efficiency. With this type of system, the rig provides stable and reliable operation while minimizing fuel consumption, which is an important factor in reducing operating costs and environmental impact. In addition, the ZJ 70 DS offers a versatile solution for drilling in a wide range of conditions. Its high mobility allows the equipment to be easily moved and quickly set up to work in different geological conditions and climatic zones. This makes it an ideal choice for projects requiring rapid deployment and flexibility to adapt to changing conditions.

One of the key advantages of the ZJ 70 DS drilling rig is its ability to deliver high efficiency in operation. Thanks to its electric power supply and efficient system control, the rig is able to provide stability and accuracy during the drilling process, resulting in increased productivity and reduced project time. In addition, the ZJ 70 DS drilling rig is adapted to work in remote areas where access to the main power grid may be limited. This makes it ideal for projects in remote or poorly developed areas where reliable and efficient drilling equipment is required. In summary, the ZJ 70 DS diesel-electric drilling rig is an advanced piece of equipment that combines high efficiency, mobility, and energy efficiency, making it an indispensable tool in today's oil industry (Fig. 3). To ensure a smooth drilling process in the harsh desert environment, additional equipment is required, such as blowout preventer systems and specialized devices for preparing, cleaning, and storing weighted drilling fluids. These additions are critical (Kuyken *et al*., 2021). Drilling operations must strictly adhere to the drill string bottom patterns established by the Drilling Technology Laboratory at Nebitgazylmytaslama (Ashgabat, Turkmenistan). These recommended schemes are designed to prevent borehole curvature.

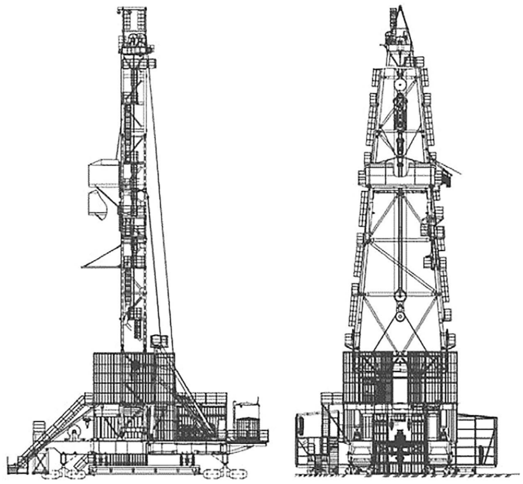

**Figure 3.** Diagram
of the ZJ 70 DS drilling rig (diesel-electric version)
**Source:** A. Deryaev (2023a)

Their use avoids additional well design and drilling prior to casing installation, thereby speeding up the entire drilling operation and reducing potential problems. This method ensures that the borehole is kept securely on track, which increases the efficiency of the process and minimizes potential drilling problems.

To ensure an efficient drilling process, it is recommended to use a high-performance tricone steel bit with a carbide tip, graphite coating and elongated shape, used for universal operations (S-TSGVU) (Fig. 4), manufactured by V. Bakul Institute for Superhard Materials (Ukraine), is another variant of the tricone bit. It is designed for drilling in hard and tough rocks such as granites, gabbro, and basalts and is equipped with synthetic diamond-reinforced cones that provide maximum wear resistance and ability to drill in extreme geological conditions, as well as high mechanical speed.

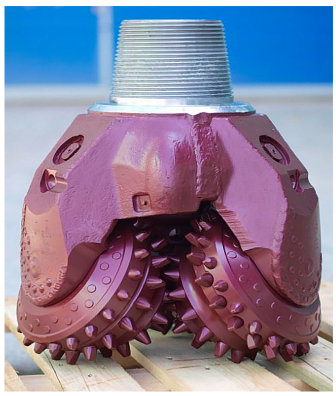

**Figure 4.** Bit S-TSGVU
**Source:** C.W. Kuyken *et al.* (2021)

To achieve precision and efficiency in drilling, it is necessary to strictly control operational parameters in accordance with the technical project or geological-technical assignment. As drilling progresses, a meticulously developed plan for conducting comprehensive geophysical well studies is activated, incorporating various tools and methods. Each of them serves its unique function in enhancing our understanding of subsurface conditions. This comprehensive package includes standard logging, cavernometry, profiling, lateral logging, gamma logging, neutron logging, acoustic logging, thermometry, and inclinometry, representing just a few logging methods. All these operations are conducted with the highest precision and detail on a 1:500 scale for each well. Such thorough analysis provides us with extensive knowledge of subsurface conditions and enables us to make informed decisions at all stages of drilling and subsequent operations.

To achieve the highest technological efficiency, filtration and rheological characteristics of the drilling fluid are meticulously adjusted (Li *et al.*, 2023). This crucial stage ensures that the drilling fluid composition is optimized for the specific operation requirements. The procedure of treating the drilling fluid before penetrating the productive geological formation aims to reduce water production and impart filtrate properties that prevent contamination of surrounding formations. This strategic approach not only contributes to the successful completion of the drilling process but also minimizes negative environmental impacts, ensuring the preservation of underground reservoirs. To fully understand changes in oil and gas reserves in formations and maximize their recovery, a series of complex studies is required. These studies include hydrodynamic analyses, field-geophysical assessments, and laboratory research. The main goal of such studies is to deeply investigate the nature of variations in reservoir hydrocarbon potential and ensure optimal and comprehensive resource extraction during oil and gas field exploitation. By combining these methods, a comprehensive understanding of reservoir dynamics is achieved, enabling informed strategic decisions regarding resource extraction and reservoir management.

Effective management of oil and gas fields, as well as monitoring the condition and performance of wells and equipment, requires the use of a complex set of research and monitoring methods. This set of methods should include the assessment of various parameters of current producing wells, such as formation, bottomhole, and surface pressures. Measurement of these pressures should be conducted regularly and systematically. Bottomhole pressure should be monitored when new wells are brought into production and after major repairs, as well as systematically measured in existing wells at least twice a year. Determining formation pressure is also crucial and should be performed for all wells with productive formations, including those within legal boundaries. These measurements should be taken after drilling or repair operations are completed and regularly, no less than once every six months for active producing wells. Sampling investigations before and after repairs or other geotechnical interventions that may affect the near-wellbore zone should also be conducted. Additionally, comprehensive studies of active producing wells should be conducted at least once every two years. Pressure build-up studies are also beneficial and should be conducted for all new and repaired wells, with planned pressure build-up tests conducted no less than once every two years for active producing wells. These methods are necessary to ensure safe, efficient, and productive operation of oil and gas wells. Regular monitoring and assessment of pressure parameters play a crucial role in maintaining reservoir integrity, optimizing production, and preventing potential issues. By implementing these comprehensive research and monitoring protocols, the industry can make informed decisions, maximize resource recovery, and enhance the long-term sustainability of oil and gas production.

Furthermore, active monitoring and control of changes in current and overall production of oil, water, and gas throughout the field are crucial. This monitoring should cover all formations, zones, and each individual well to ensure effective and stable exploitation of oil and gas reserves. For wells operating in multiple formations, it is recommended to use various research methods, often combining them with geophysical techniques. These methods include inflow analysis, monitoring of contact and saturation zones, temperature determination, evaluation of production tubing, assessment of gas lift valves, sample collection and oil analysis, as well as obtaining samples for physicochemical tests. All these measures ensure optimal conditions for oil and gas fields, enabling efficient and environmentally friendly extraction of these valuable resources. In-depth analysis of geological and operational data has identified shortcomings in the hydrodynamic characteristics of several wells actively used in production. These shortcomings relate to their interaction with productive formations. To optimize the performance of these wells, it is necessary to accurately determine completion and perforation locations, especially in areas with high gas content, which is particularly important for gas condensate production projects in this region.

To increase the efficiency of low-productivity wells, two key methods are recommended (Li *et al.*, 2023). The first method involves treating the near-wellbore zone of the formation with clay acid to dissolve clay particles and other obstacles hindering hydrocarbon flow. This may contribute to improved reservoir connectivity and overall productivity. The second method, hydraulic fracturing, is also an important approach. This method involves creating fractures in the reservoir by injecting fluid under high pressure into the wellbore. These fractures allow hydrocarbons to be extracted from previously inaccessible zones, significantly increasing well productivity. Implementing simultaneous well operations has yielded promising results, especially at the Altyguyi field, where this approach is recommended to be extended to low-productivity wells both in the tubing and annulus spaces. The use of a comprehensive approach, including pinpoint completions and perforations, clay acid treatment, hydraulic fracturing, and continued simultaneous well operations, allows for a significant increase in their productivity and overall efficiency at the Altyguyi field.

During well operation, systematic monitoring and analysis are carried out to ensure the reliability of the production column, equipment integrity, and compliance with established technological parameters (Burton *et al.*, 2021). The main goal of this process is to collect data for optimizing technological processes and increasing production efficiency. Within the monitoring framework, a comprehensive inspection of wells and associated equipment is conducted. This includes checking the integrity of cement, the condition of casing and pump-compressor pipes, analysis of the near-wellbore zone of the formation, as well as checking for well contamination and equipment operability at various depth levels. The main task of monitoring is to ensure compliance with equipment performance parameters and the technical mode of the well. This guarantees optimal equipment operation and maximum production efficiency. Continuous assessment of the reliability and operability of equipment components is also an essential part of the monitoring process. This allows for timely identification of malfunctions and conducting repair work, minimizing downtime, and ensuring reliable operation. The collected data is used for planning repair work and optimizing technological processes in wells. This contributes to increased productivity and ensures stable well operation in the long term.

Regular monitoring and analysis of well performance play a key role in ensuring the safety, efficiency, and overall productivity of the production process. This ensures reliable operation of equipment and wells under established standards, which in turn helps make informed decisions regarding technical maintenance and process optimization. Departments responsible for oil and gas production collaborate with research organizations and geophysical companies to determine the types, volumes, and frequencies of necessary surveys and measurements to monitor equipment performance under various well operation methods (Fan *et al*., 2021). Decisions are made in conformity with project proposals and ultimately approved by association management. Scientific research aimed at controlling the operation of producing wells must strictly adhere to safety standards in the oil and gas industry and comply with existing regulations for the protection of mineral resources and the environment, ensuring responsible and sustainable well operation (Klemz *et al*., 2021).

The engineering service within oil and gas production companies is responsible for the systematic study and use of materials for equipment monitoring to ensure compliance with designated well operation modes. All primary research materials, except for echograms and dynamograms (stored for a minimum of three years), must be stored throughout the entire well operation period, ensuring the preservation of a complete data archive for long-term assessment and analysis. Applying these measures will enable the Altyguyi field to maintain gas production at planned levels, ensuring operational efficiency and facilitating data-driven decision-making, ultimately contributing to further success and productivity of the operation. To activate and maximize the potential of idle and underutilized oil wells, it is strongly recommended to carry out a series of activities for their restoration, development, and commissioning. These measures include tasks such as restoring communication between the wellbore and upper and lower reservoirs, performing water isolation procedures based on comprehensive analysis of geophysical research, thorough inspection of production columns, and removal of emergency packers. Throughout these operations, it is crucial to consider the results of geophysical surveys conducted during repairs. Additionally, the use of innovative technologies such as Slickline and flexible tubing plays a crucial role in optimizing the efficiency and effectiveness of restoration work.

The duration of repair work depends on various factors, including geological aspects such as the size of the exploitation zone and proximity to other wells, as well as on-site testing results. Furthermore, the condition of the well and the availability of necessary equipment play a key role in determining the time required for the work. Therefore, it is impossible to accurately predict the schedule of repair work for specific wells in advance. The decision on the feasibility and timing of these projects will be made during field operation, taking into account the individual characteristics of each well. Recent research in the Altyguyi area has included extensive geochemical and hydrodynamic studies aimed at determining the composition of oil, gas, and condensate. These efforts have yielded valuable results, allowing for accurate determination of condensate and natural gas reserves, as well as related calculated characteristics.

Well exploitation in the Altyguyi field is complicated by several factors, including deep reservoirs, variable daily liquid flow rates, high initial pressure, pressure drop, working with under-saturation pressure, high gas coefficient, complex well geometry, reservoir composition changes, and paraffin issues. It is important to consider the unique characteristics of each well and adapt exploitation strategies to their features, as well as prepare for future changes, including adjusting gas lift depths. It is important to note that the adoption of technical and technological decisions can significantly vary depending on the unique conditions of each gas condensate field. The complex interaction of these factors can cause difficulties in fully complying with all requirements, especially in the case of previously drilled wells under certain circumstances. Well depth and casing diameter are major factors that exert significant influence. In the context of existing operational wells, as observed in the Altyguyi field, the use of well equipment fully compliant with gas reservoir development requirements may be limited by the combination of significant well depths and relatively small production column diameters.

Implementing mechanized oil extraction at the Altyguyi field requires a thorough and comprehensive approach, taking into account the interaction of various factors, including geological, operational, and technical aspects. Achieving harmony among these components is critical for production optimization, ensuring high operational efficiency and equipment durability, especially in conditions unique to this area. The primary goal of comprehensive equipment analysis for gas condensate extraction at the Altyguyi field was to determine the most effective approach to developing the resources of this field. This was achieved by studying various methods of gas condensate separation across three horizons where both oil and gas are present, using the same well. The analysis also involved evaluating sets of well equipment, including technical solutions from renowned global manufacturers. This assessment was based on data obtained from the construction and operation of gas and oil wells at the Altyguyi field.

Assessing the technological characteristics of these equipment systems involves a comprehensive analysis of various key parameters critical for determining their performance and compatibility. Factors considered in such assessment include:

- working pressure, determining equipment operation efficiency;
- maximum gas production capacity, a key indicator for production optimization;
- nominal diameter of lifting pipes, influencing liquid transport within the system;
- minimum borehole diameter, affecting liquid flow and overall efficiency;
- passage diameter for interchangeable choke valves, regulating liquid flow;
- nominal diameter of production tubing, determining overall system productivity;
- external packer diameter, important for wellbore sealing and isolation;
- maximum packer setting depth, influencing its applicability in various well configurations;
- technical conditions of the working environment, ensuring compatibility with the surroundings;
- maximum temperature stability of the working environment, determining equipment's operational limits;
- packer dimensions and weight, influencing installation and transportation logistics, excluding lifting pipes.

Together, these parameters form the basis for comprehensive evaluation, determining the selection and implementation of equipment systems in various operating scenarios. Collectively, they form the basis for assessing the technological capabilities and suitability of the considered equipment complexes.

A comprehensive assessment of these technological characteristics has identified the most suitable equipment set for the effective development of the Altyguyi gas condensate field. This analysis has contributed to defining the optimal approach to extraction and resource management of this unique geological reserve. For the development of the Altyguyi gas condensate field, various complex equipment configurations have been carefully studied, with special attention to the constant current method, which involves extracting gas and oil from three different horizons. In this context, two main configurations have been considered: simultaneous suspension of pump and compressor tubing for dual completion systems. This configuration is designed to facilitate simultaneous gas production by the fountain method and oil production by the gas lift method from three separate horizons. It includes a complex setup that optimizes resource recovery efficiency. Additionally, this configuration has been studied for its potential to provide dual completion, allowing simultaneous gas and oil production. The use of dual hydraulic packers is an important element of this setup, improving control over well operation.

When implementing such a constant current scheme, a key technological aspect is the ratio of predicted depressions within the exploited reservoirs, which is critical for ensuring efficient and effective resource extraction. Analysis of available data shows significant differences in depressions between upper and lower reservoirs during simultaneous gas production from the NK-8 and NK-7 reservoirs through a single oil-gas-condensate production tubing (NKT). It is particularly important to note that the upper layer is characterized by relatively low depression, which is a determining factor for achieving the desired gas production rate. This specific aspect should be considered in the design and operation of equipment complexes. Various factors can potentially contribute to an increase in pressure within the wellbore filtration zone. One such factor involves the formation of seals inside the pump-compressor tubing in the near-surface area or directly in the wellbore, leading to increased wellhead pressure. This may create conditions conducive to inter-reservoir flows, where different fluids from different horizons may mix. However, it should be noted that the risk of such inter-reservoir flows is somewhat reduced during simultaneous exploitation of the NK-7 and NK-8 horizons at later stages of field development. However, it is important to understand that this does not diminish the fundamental requirements for the equipment used.

Oil and gas fields in Turkmenistan represent a unique geological complexity, with multiple layers containing hydrocarbons overlapping each other. This multi-layered geological landscape promises significant potential for resource extraction. However, a balance must be found between strategic development and significant capital expenditures, especially on drilling new wells (Byashimov *et al.*, 2023). One of the most reasonable approaches to developing such multi-layered reservoirs involves creating separate well networks for each layer. This strategy allows for the efficient utilization of resources, considering the unique characteristics and behaviour of each reservoir. However, this approach is associated with significant costs for drilling new wells. In fact, more than half of the total capital expenditures on oil and gas field development go towards drilling. This high financial threshold often questions the economic and technical feasibility of such an approach.

In response to budget constraints, an alternative strategy has emerged. When working with multi-layered reservoirs, it has become common practice to combine multiple productive layers into a single operational unit. This approach optimizes the development process in several ways. Firstly, it reduces the time required for field development, as management of multiple layers is done concurrently.

Secondly, it reduces significant capital expenditures associated with well drilling, improving the overall economic and technical feasibility of the project. Simultaneous development of multiple geological formations by a single operating entity presents an attractive approach, but it depends on several critical factors. It is essential that the physical and chemical properties of oil, gas, and condensate in all integrated layers are consistent. This means that the influx of oil and gas from each reservoir must be sufficient to maintain the corresponding bottomhole pressure in the well. Additionally, the reservoir pressure in the combined layers must be accurately balanced to prevent undesirable oil and gas flows between the layers. It is equally important for the water content in these layers to be consistent.

However, it should be noted that in some cases, it is not possible to ensure compliance with these conditions. When the physical and chemical properties of the reservoirs, their flow rates, pressures, and water content significantly differ, the development of multi-layered deposits requires an alternative approach. In such scenarios, the dual completion method using a single well is employed. The choice of a specific dual completion scheme depends on the unique geological and technical conditions of the field development, as well as the operational characteristics of the involved wells.

## DISCUSSION

The implementation of innovative engineering solutions and the improvement of drilling technologies at the Altyguyi field open up new horizons for the efficient extraction of oil and gas from complex geological formations. This process requires a deep understanding of the geological and engineering characteristics of the field, as well as the development of innovative methods and equipment to address emerging challenges. One of the main aspects that requires attention is the depth of the field. In the Altyguyi field, productive reservoirs are located at significant depths, presenting serious technical challenges for drilling and well operation. Specialized drilling rigs and tools capable of ensuring safety and operational efficiency are required to penetrate such depths effectively.

An important direction in drilling technology development is the improvement of control and monitoring processes. Modern drilling methods at the Altyguyi field include the use of advanced monitoring and control systems, such as data logging systems and geophysical technologies, to obtain accurate information about well conditions and the geological environment. This helps minimize risks and enhances drilling efficiency. Another important aspect is the development of engineering designs specifically adapted to field conditions. For example, guide sections and reinforced casing columns can be used to protect wells from erosion and ensure their stability in complex geological conditions. In addition to this, innovative approaches to managing drilling waste and drilling fluid treatment can reduce the negative impact on the environment and increase the sustainability of extraction processes (Ozdoyev *et al.*, 2019). Overall, engineering aspects and the improvement of drilling technologies at the Altyguyi field play a key role in ensuring efficient and safe oil and gas extraction. The development of new methods and technologies adapted to the unique conditions of this field allows for the optimization of production processes and increased overall extraction productivity.

According to the findings of recent research by H. Wang *et al.* (2022), drilling technologies for deep and ultra-deep oil and gas wells are constantly progressing, reflecting rapid changes in the oil and gas industry. With the development of deepwater drilling and drilling on the continental shelf, as well as the discovery of new deposits at significant depths, the need for advanced technologies becomes increasingly relevant. In this context, it is important to discuss both existing progress and prospects in this area. One of the major achievements in the field of deep and ultra-deep drilling technologies is the development of highly efficient drilling systems and tools. Modern drilling rigs have enhanced power and precision, allowing them to overcome technical challenges when operating at great depths (Ihnatov *et al.*, 2022). The application of advanced drilling technologies, such as horizontal and directional drilling, enables increased production volume and reduced drilling and well operation costs. These findings align with the theses outlined in the previous section. In the future, the development of drilling technologies for deep and ultra-deep wells will continue towards increasing automation and the use of artificial intelligence. Automated drilling and monitoring systems will help improve operational safety and efficiency, while machine learning algorithms and data analysis will optimize processes and predict potential issues before they occur.

Referring to the definition by G. Jiang *et al.* (2022), the innovative water-based drilling and completion fluid technology represents a significant step in the development of drilling and well operation methods. This technology is based on the use of special water-based compositions designed to improve wellbore quality and protect unconventional reservoirs. It provides an efficient solution for drilling in various geological conditions, including heterogeneous and sparse reservoirs, and ensures reliable well protection from various issues, such as potential reservoir damage and degradation of their productivity. It should be noted that the advantages of this technology include increased resistance to high temperatures and pressures, as well as improved adhesion properties, which contribute to more effective operation in conditions of increased complexity. Thanks to the use of a water-based solution, this technology is environmentally friendly and does not have a negative impact on the environment (Fedorov *et al.*, 2023). Additionally, it reduces drilling and well operation costs by increasing their productivity and reducing drilling time.

A. Bani Mustafa *et al.* (2021) identified that improving drilling performance is a key challenge in the oil and gas industry, and optimizing controllable parameters plays an important role in this. This approach aims to enhance the efficiency and accuracy of the drilling process, ultimately reducing project duration and costs. Optimization of controllable parameters includes various aspects such as drill rotation speed, drilling fluid pressure, drill bit selection, and the use of modern control and monitoring systems. These findings confirm the aforementioned study, as the implementation of modern technologies and automation systems allows for more precise control of these parameters, adapting them to the specific conditions of each well. This provides optimal drilling conditions in both standard and complex geological conditions, contributing to increased drilling speed and efficiency. Ultimately, optimizing controllable parameters not only reduces project duration but also improves its effectiveness, enhancing overall productivity and economic benefits (Stavychnyi *et al.*, 2023).

F. Farahbod (2021) demonstrated through their work that experimental research on the thermophysical properties of drilling fluid using nanoparticles represents a promising approach to enhancing drilling efficiency. The integration of nanotechnologies into drilling fluid compositions significantly improves their characteristics, leading to a more efficient well drilling process. Nanoparticles added to the fluid can influence its thermophysical properties such as thermal conductivity and heat capacity, opening up new possibilities for optimizing heat transfer during drilling (Dzhalalov *et al.*, 2021). This opinion agrees with the main advantages of using nanoparticles in drilling fluids, which include increased heat transfer in the drilling zone, improved control over temperature regimes, and reduced risk of negative consequences associated with equipment overheating and wellbore deformation. This is particularly relevant for drilling deep and complex wells where thermal regimes play a crucial role. Therefore, experimental research on the thermophysical properties of drilling fluid with nanoparticles represents an important direction for development aimed at enhancing drilling efficiency and reducing costs.

As noted by S.W. Lai *et al.* (2021), the widespread implementation of a closed-loop drilling optimization system is a key stage in the development of modern technologies in the oil and gas production field. This system incorporates comprehensive data monitoring and analysis methods, allowing real-time adjustment of drilling parameters according to changing well conditions. The main goal is to increase drilling productivity, reduce costs and risks, and improve operational safety. Implementing a closed-loop drilling optimization system at fields demonstrates significant results. It enables prompt responses to change in geological conditions, maintains drilling process stability, and optimizes the use of drilling equipment. Analysing the obtained results and conclusions, it is evident that through automation and algorithmic drilling process management, efficiency, and accuracy improvements are achieved, as well as task completion time reduction. Such innovative solutions play an important role in enhancing the competitiveness of companies in the oil and gas industry market (Ivanenko, 2023).

M.R. Isbell *et al.* (2021) determined that the integration of digital technologies into well planning and construction opens up new prospects for efficient operations at fields. Using modern software solutions and algorithms allows for more detailed and precise modelling of drilling processes. This includes analysis of geological data, drilling trajectory optimization, and forecasts of well productivity. Additionally, digital technologies also provide the opportunity for multi-faceted planning, allowing engineers and drilling specialists to consider numerous factors when making decisions. This includes accounting for geological features of the field, equipment technical characteristics, safety conditions, and environmental factors. As a result, it becomes possible to develop more reliable and optimized action plans, contributing to increased efficiency and reduced costs in well drilling projects.

## CONCLUSIONS

In the Altyguyi field, engineering aspects play a key role in optimizing and improving well drilling techniques. Due to the geological peculiarities of this area, which include significant well depths and variability in reservoir characteristics, it is necessary to continuously develop methods and equipment for efficient oil and gas production.

One of the key areas of technology improvement is the introduction of modern modelling and forecasting techniques that allow for more accurate determination of well parameters and selection of optimal drilling strategies. This includes the use of specialized computer programmes to analyse geological data, predict pressures and calculate well performance, which significantly increases the efficiency and accuracy of the process of designing and developing oil and gas fields. Also, an important area is the research and development of innovative drilling fluid technologies, which are aimed at improving wellbore quality and protecting reservoirs from possible damage. The introduction of such technologies makes it possible to reduce the time and costs of the drilling process and significantly improve the efficiency of hydrocarbon resource extraction at the fields. Importantly, there is a drive to increase drilling productivity by optimizing controlled parameters and implementing innovative control systems. This includes the use of automated systems for monitoring and controlling the drilling process, which facilitates more accurate control and prevention of potential problems, ensuring more efficient and safer field operations.

In summary, improvements in drilling technology in the Altyguyi field are aimed at increasing efficiency, ensuring safety, and achieving economic benefits in the oil and gas production process, which is a key aspect for the sustainable development of the oil and gas industry in the region. Further research should focus on developing and testing new drilling technologies that can improve production efficiency and reduce environmental impacts in the Altyguyi field.

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## CONFLICT OF INTEREST

None.

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**Аннагули Деряєв**

Доктор технічних наук, головний науковий співробітник
Науково-дослідний інститут природного газу державного концерну “Туркменгаз”
744036, просп. Арчабіл, 58, м. Ашхабад, Туркменістан
https://orcid.org/0009-0004-8569-6277

# Інженерні аспекти та вдосконалення технологій буріння свердловин на Алтигуйському родовищі

**Анотація.** Актуальність дослідження обґрунтована стрімким розвитком нафтової промисловості, що вимагає постійного вдосконалення методів і обладнання для підвищення ефективності видобутку та зниження екологічного впливу. Метою даного дослідження є поліпшення поточних інженерних аспектів буріння на Алтигуйському родовищі з урахуванням підвищення продуктивності та зниження екологічного впливу. Серед використаних методів слід зазначити метод синтезу, метод абстрагування, метод узагальнення, метод індукції, метод дедукції, метод класифікації та інші. У цьому дослідженні розглянуто технологічні аспекти експлуатації свердловин Алтигуйського газоконденсатного родовища. Для правильної реалізації технології подвійного закінчування для видобутку газу з одного пласта і видобутку нафти з іншого пласта в одній свердловині були проведені великі лабораторні та промислові дослідження властивостей і складу нафти, газу і конденсату. Шляхом впровадження передових методів буріння, включно з використанням горизонтального і багатостовбурного буріння, а також застосуванням сучасних бурових розчинів, вдалося досягти поліпшення продуктивності свердловин і скорочення часу на буріння. У результаті оптимізації технологій вдалося підвищити загальну ефективність процесу видобутку нафти і газу на родовищі, що підтверджує значущість впровадження інновацій для поліпшення результатів у нафтовій промисловості. Ці удосконалення не тільки підвищили безпеку та ефективність буріння, але також знизили негативний вплив на навколишнє середовище, що підкреслює важливість інтеграції сучасних технологій з урахуванням екологічних аспектів у процесі нафтовидобутку. Це дослідження робить значний внесок у розробку більш ефективних і екологічно стійких методів буріння на нафтових родовищах, сприяючи підвищенню продуктивності нафтовидобутку і зниженню негативного впливу на навколишнє середовище

**Ключові слова**: нафтова промисловість; ефективний видобуток; екологічний вплив; передові методи; бурові розчини

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**Roman Sivak**
Doctor of Technical Sciences, Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-7459-2585

**Volodymyr Kulykivskyi***
PhD in Technical Sciences, Associate Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-4652-0285

**Vasyl Savchenko**
PhD in Technical Sciences, Associate Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-0921-1424

**Olena Sukmaniuk**
PhD in Historical Sciences, Associate Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0003-2485-488X

**Viktor Borovskyi**
Senior Lecturer
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-1759-8155

# Application of resource-saving extrusion technologies and an integrated approach to assessing the plasticity of metal parts in agricultural engineering

**Abstract.** Among the promising resource-saving technologies to produce parts with improved performance characteristics, the processes of volumetric plastic deformation of products occupy a prominent place. The research relevance is determined by the need to improve the mechanical properties of deformed metal, increase tool life, and produce high precision stamped products with an appropriate level of technological heredity. The study aims to create the required level of strain hardening and damage resistance of deformed metal and products of complex configuration, which will replace expensive steel grades with cheaper ones with similar service characteristics. To calculate the components of the stress tensor under non-monotonic loading, the anisotropic-strengthening body model is used. The study of theoretical and experimental findings suggests that cold combined extrusion methods should be used to manufacture parts with a flange, which can significantly

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*Corresponding author

increase the boundary dimensions and improve the technological heredity of the product. The study presents a methodology for determining the kinematic characteristics of plastic metal flow using analytical functions obtained from experimental studies of the motion of a continuous medium. The tensor approach was used to create a model of damage accumulation under non-monotonic deformation. The presented complex of calculations can be used to determine the stress state and the amount of the spent plastic deformation resource during non-monotonic volumetric deformation with a sufficiently high accuracy, without preliminary heating of the metal. Based on the information on the stress-strain state and the tensor model of damage accumulation, the ultimate forming of parts with a flange was estimated. The practical value of the research lies in the use of the proposed approaches to solve several technological problems of metal processing by pressure when the material undergoes non-monotonic plastic deformation under conditions of bulk stress

**Keywords**: cold combined extrusion; non-monotonic deformation; complex loading; metal ductility; three-dimensional stamping

## INTRODUCTION

The main focus of machine building development is the study and implementation of the latest technologies based on scientific research. Instead of traditional methods of forming parts by material removal, such as chip peeling, three-dimensional plastic deformation processes are becoming more common. Improvements in engineering technology through the introduction of these processing methods will significantly improve the accuracy and quality of parts. In modern conditions, this is a key factor in ensuring the efficient use of resources (Sivak *et al.*, 2023).

Among the potential processes in the forging and stamping industry, technological operations of volumetric irreversible deformation are necessary. The production of three-dimensional workpieces by stamping, pressing or forging is distinguished by its unique capabilities, variety of types and high efficiency compared to other shaping methods. The development of volumetric deformation technologies indicates a steady increase in the production of precision parts with guaranteed quality, an expansion of the size range and the use of various materials. The results of research on new technologies described by G. Faraji & H. Torabzadeh (2019) show the effectiveness, competitiveness and prospects of plastic-forming processes.

I.S. Aliiev *et al.* (2023) noted that conventional plastic deformation schemes based on the use of two tools – an active moving tool and a fixed fixture – do not meet current requirements and complex technological tasks. Controlling the properties, plastic flow and technological factors requires much more complex force and kinematic effects. The deformation methods developed based on this approach will create innovative processes for producing high-quality products from affordable materials at low cost.

The use of combined plastic processing methods is increasing in the mechanical engineering industry. These shaping methods are characterised by complex loads created by additional kinematic movements of the tool. The resulting force on the workpiece creates a high level of hydrostatic pressure and multi-variable alternating deformation. This gives the product material unique physical and mechanical characteristics that result from the formation of the required level of macrostructure, strain hardening and damage to the plastically processed metal. In many cases, modern processing methods make it possible to replace expensive steel grades with more economical ones without compromising the performance of the products. According to the results of experimental studies by Y. Beygelzimer *et al.* (2023), the use of combined extrusion leads to a 16-40% reduction in deformation force compared to traditional methods.

The quality of products manufactured by pressure treatment is significantly affected by the stress-strain state of the workpiece during volumetric plastic deformation. According to V. Mykhalevych *et al.* (2023), many factors affect the metal flow and stress-strain state of the workpiece during the forming process. The main ones are the deformation method, tool configuration, product shape, kinematic mode, workpiece material, etc. The properties of a product are formed under the influence of external kinematic and force factors on the workpiece and depend on the dominant mechanical deformation pattern. V. Kukhar *et al.* (2022) determined that kinematic impact can significantly improve the structure of the deformed metal, eliminate stagnant zones, and reduce deformation irregularities.

However, the theoretical methods for solving the problems of metal forming with reliable results remain imperfect and are not adapted to their practical use. This becomes especially evident when the task requires accounting for the volumetric nature of the metal stress state and non-monotonic loading. In studies of modern methods for assessing stresses and ultimate deformations conducted by M. Brünig *et al.* (2023), significant discrepancies between theoretical and experimental results obtained during deformation under non-monotonic loading were noted. This is determined by the imperfect and insufficiently justified physical equations used in these calculations. The structure of the equations should include independent information on the kinematics of the plastic flow of the metal, plasticity assessment, and the relevant mechanical and functional properties of the material.

Thus, the design of combined cold-forming processes based on the development of new methods for calculating the stress-strain state, as well as assessing the deformability of workpieces under non-monotonic loading and the volumetric stress-strain pattern is important for the creation and improvement of metal-forming processes.

Thus, the study aims to create a clear sequence of calculations taking into account the characteristic features of non-monotonic plastic deformation in the processes of cold combined extrusion to obtain the most accurate assessment of the deformability of workpieces.

## MATERIALS AND METHODS

In the theory of plasticity, it is extremely difficult to obtain a solution to a system of differential equations that satisfies the boundary conditions for non-monotonic loading. Therefore, the following mathematical model was used to address the effect of non-monotonicity in stress calculations. To obtain the kinematically velocity field for the problems of axisymmetric stationary flow during extrusion (Dou *et al.*, 2023), a method that can be used in the study of steady-state plastic deformation modes of solid bodies was addressed.

The components of the strain rate tensor $\dot{e}_{ij}$ were determined from equations approximating the curvature of the dividing grid lines in mixed Eulerian-Lagrangian variables (Fernandez *et al.*, 2020):

$$r = f(\psi, z), \tag{1}$$

where $\psi$ – the curvature function of the dividing grid lines.

The components of the stress tensor $\sigma_{ij}$ for axisymmetric deformation must comply with the differential equilibrium equations (Yu *et al.*, 2022):

$$\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\phi}{r} = 0; \tag{2}$$

$$\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r} = 0. \tag{3}$$

The boundary conditions were taken in an integral form at the boundaries of the elastic and plastic regions $G_1$ and $G_2$ (respectively, at the entrance to the matrix and the exit to the cavity):

$$P_n = 2\pi \int_{Gn} r(\sigma_z v_z + \tau_{rz} v_r) dG, \tag{4}$$

where $P_n$ – the force at the boundary $G_n$, $n = 1, 2$; $v_z$, $v_r$ are components of the vector of the external normal to $G_n$, or in the form of homogeneous boundary conditions on a free surface (Reese *et al.*, 2021):

$$\sigma_z v_z + \tau_{rz} v_r = 0; \ \tau_{rz} v_z + \sigma_r v_z = 0. \tag{5}$$

The magnitude of the loads $P_n$ is known from an experiment or the problem statement. The components of the stress deviator were determined by the following equation:

$$S_{ij} = \frac{2}{3}\sigma_u(e_u)\frac{\dot{e}_{ij}}{\dot{\varepsilon}_u} - \frac{1}{3}\int_0^{e_u} \left(1 - \beta(e_u^*)\right)\sigma_u(e_u^*)\phi(e_u^* - e_u^0)\frac{d^2 e_{ij}}{de_u^2}(e_u^*)de_u^*. \tag{6}$$

Material characteristics $\sigma_p(e_u)$, $\beta(e_u)$ and $\phi(e_u - e_u^0)$ were determined experimentally.

The parameter $\beta$ which characterises the Bauschinger effect, was determined by the formula:

$$\beta = \frac{\sigma_{0,2}}{\sigma_u(e_u^0)}, \tag{7}$$

where $\sigma_{0,2}$ – the conditional yield strength at compression testing of the sample, primarily stretched to deformation $e_u^0$ according to the flow curve $\sigma_u(e_u^0)$.

The dependence of $\beta$ from the $e_u$ was approximated by the formula (Tu *et al.*, 2020):

$$\beta = \beta_m + (1 - \beta_m) exp(c \cdot e_u). \tag{8}$$

The function $\phi$, which addresses the hereditary effect of the deformation process on the current state of the material during plastic deformation, was also determined based on the results of tensile and subsequent compression tests of cylindrical specimens. At the same time, the value of the function was calculated using the formula:

$$\phi(e_u - e_u^0) = \frac{\sigma_p(e_u) - |\sigma_c(e_u)|}{\sigma_p(e_u^0)\left(1 - \beta(e_u^0)\right)}, \tag{9}$$

where $e_u^0$ – the accumulated strain, at which the unloading or breakage of the deformation trajectory occurs; $\sigma_p(e_u)$ – stress under monotonic tension; $\sigma_c(e_u)$ – stresses during compression of the specimen up to the strain $e_u$, pre-tension up to $e_u^0$ the stress $\sigma_p(e_u^0)$; $\beta(e_u^0)$ – the value of the Bauschinger parameter at $e_u = e_u^0$.

The experimental values $\phi$ determined by formula (9), were approximated by the dependence:

$$\phi(e_u - e_u^0) = \phi_0 + (1 - \phi_0) exp(c_1 (e_u - e_u^0)^{c_2}), \tag{10}$$

where $\phi_0$ is the asymptotic value $\phi$ obtained experimentally (for steel 10, $\phi_0 = 0.19$).

The coefficients $c_1$ and $c_2$ were calculated using the least squares method and the following values were obtained for steel 10: $c_1 = -22.3$; $c_2 = 0.806$.

Figures 1 and 2 show the experimental dependences for the Bauschinger parameter $\beta(e_u)$ and the function $\phi$ $(e_u - e_u^0)$. The model of damage accumulation under non-monotonic loading is based on the hypothesis that damage is described by a second-rank tensor (Lin *et al.*, 2023). The components of this tensor are determined by the mechanics of plastic deformation in a particular technological process, as well as by material functions that describe the physical and mechanical properties of the metal.

Based on the data of S. Reese *et al.* (2021), a damage tensor $\psi_{ij}$ was introduced, the components of which were defined as follows:

$$\psi_{ij} = \int_0^{e_u^*} F(e_u, \eta, \mu_\sigma)\, \beta_{ij}\, de_u, \tag{11}$$

where $F(e_u, \eta, \mu_\sigma)$ – a positive function that describes the reaction of the material to the stress pattern.

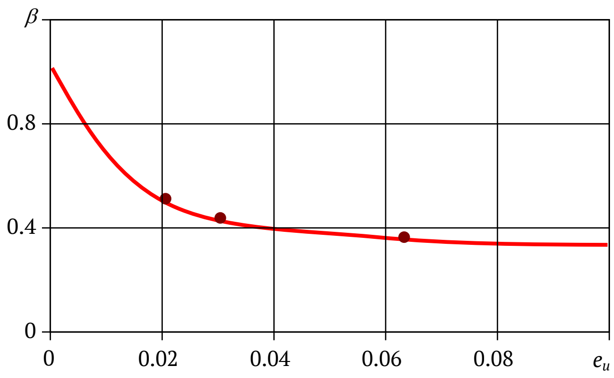


**Figure 1.** Dependence of the parameter $\beta$ on $e_u$
**Note:** steel 10, approximation $\beta = 0.34 + 0.66exp(-62e_u)$
**Source:** compiled by the authors

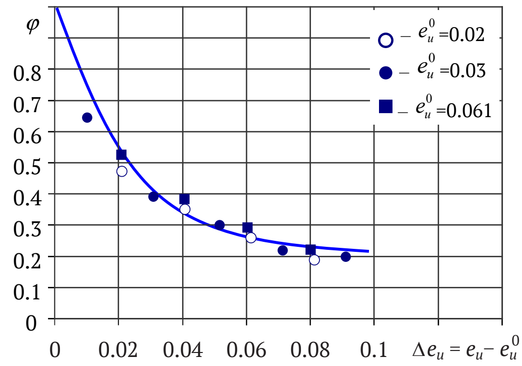


**Figure 2.** The dependence of a function $\phi$ on $\Delta e_u$
**Note:** steel 10, approximation $\phi = 0.19 + 0.81exp(-22.3 \cdot (e_u - e_u^0)^{0.806})$
**Source:** compiled by the authors

The components of the tensor $\beta_{ij}$ are equal:

$$\beta_{ij} = \sqrt{\frac{2}{3}\frac{d\varepsilon_{ij}}{de_u}}. \tag{12}$$

From the correlations of the flow theory:

$$d\varepsilon_{ij} = \frac{3}{2}\frac{de_u}{\sigma_u} S_{ij}. \tag{13}$$

According to S. Tu *et al.* (2020):

$$\beta_{ij} = \sqrt{\frac{3}{2}\frac{S_{ij}}{\sigma_u}} = \sqrt{\frac{3}{2}\frac{S_{ij}}{\sqrt{\frac{3}{2}}\tau}} = S^0_{ij}. \tag{14}$$

In solid state physics, there is an analogue of the tensor $\psi_{ij}$, the dislocation density tensor, which can also be considered as damage. Both tensors are deviators.

When the function of the three invariants of the tensor $\psi_{ij}$ takes on a certain value, this is the beginning of fracture. Exclude from this function the influence of the first invariant, since it is zero, and the third invariant, the fracture condition can be noted as follows:

$$\psi_{ij} \cdot \psi_{ij} = const. \tag{15}$$

To determine the kinematic characteristics of deformation, the Eulerian and Lagrangian strain tensors were used as the basis (Milenin *et al.*, 2020):

$$E_{ij} = \frac{1}{2}\left(\delta_{ij} - \frac{\partial a_k}{\partial x_i} \cdot \frac{\partial a_k}{\partial x_j}\right); \tag{16}$$

$$L_{ij} = \frac{1}{2}\left(\frac{\partial x_m}{\partial a_i} \cdot \frac{\partial x_m}{\partial a_j} - \delta_{ij}\right), \tag{17}$$

where $a$ is the coordinates of the particle before deformation; $x$ is the coordinates of the particle during deformation, as well as the ratio for determining the deformation rate:

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right), \tag{18}$$

where $v$ are the components of the velocity of the particles of the deformed body.

The components of the Eulerian strain tensor can be determined if the displacements are specified according to the current coordinates, and the Lagrangian tensor if the position changes are specified depending on the initial coordinates.

## RESULTS AND DISCUSSION

It is believed that in the cylindrical coordinate system $(r, z)$ the surface of a matrix can be described by the analytical function $R = R(z)$, which has the corresponding asymptotes: at a $z \to -\infty$, $R = R_0 = 1$; at $z \to \infty$, $R = R_1$, where $R_0$ i $R_1$ – start and end radii (Fig. 3).

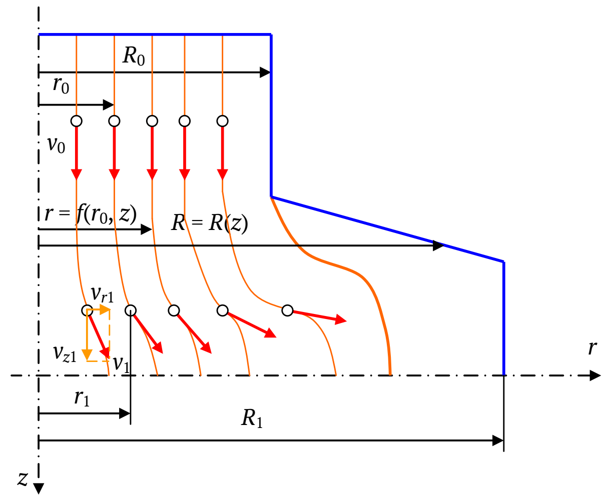


**Figure 3.** Calculation scheme of curvature of dividing grid lines under axisymmetric deformation, in the general case
**Note:** $r$ – radius of the contour of a material particle; $R$ – radius of the matrix contour; $v_1$ – the velocity of a particular particle in the deformation process; $v_{r1}$, $v_{z1}$ – projections of the velocity of a certain particle in the process of deformation on the axes of the cylindrical coordinate system
**Source:** compiled by the authors

When constructing the approximations of the dividing grid lines, the following constraints on the functions were set:

- in the steady-state stage of motion, all material particles of the deforming metal that have a certain initial coordinate $r_0=\sqrt{\psi}$ will have the same final coordinate $r_1=R_1 \cdot r_0$. On the symmetry axis, $r=0$, and the contour, $r=R(z)$. This is possible if equation (1) satisfies the conditions:

$$\lim_{z\to-\infty} f(\psi,z)=\sqrt{\psi};\ \lim_{z\to\infty} f(\psi,z)=R_1\sqrt{\psi};$$
$$f(\psi,z)=\begin{cases}0 & \text{at}\quad \psi=0;\\ R(z) & \text{at}\quad \psi=1;\end{cases} \tag{19}$$

- on the axis of symmetry, the particle velocities are limited everywhere and, in general, are not equal to zero and the cross-sectional average velocity. That is, at $\psi=0$, the following relations are valid for the components of the velocity vector:

$$v_r(\psi,z)=0;\ v_z(\psi,z)<0;\ v_z(\psi,z)\neq 0;\ v_z(\psi,z)\neq 1/R^2(z). \tag{20}$$

At $z\to\pm\infty$ for all $\psi$, the components of the velocity vector take the values:

$$\lim_{z\to-\infty} v_z(\psi,z)=1;\ \lim_{z\to\infty} v_z(\psi,z)=1/R_1^2, \tag{21}$$

are the components of the strain rate tensor:

$$\dot{e}_{rz}(\psi,z)|_{\psi=0}=0;\ \lim_{z\to\pm\infty}\dot{e}_{ij}(\psi,z)=0. \tag{22}$$

Conditions (1), (19)-(22) imply the following restrictions on the approximation of the curved lines of the dividing grid:
at $\psi=0$:

$$\left|2f\frac{\partial f}{\partial\psi}\right|<\infty;\ 2f\frac{\partial f}{\partial\psi}\neq 0;$$
$$2f\frac{\partial f}{\partial\psi}\equiv R^2(z);\ \frac{\partial f}{\partial z}=0;\ 0<\left|\frac{\partial f}{\partial z}/f\right|<\infty; \tag{23}$$

at $z\to\pm\infty$:

$$\lim_{z\to-\infty}\left(2f\frac{\partial f}{\partial\psi}\right)=1;\ \lim_{z\to\infty}\left(2f\frac{\partial f}{\partial\psi}\right)=R_1^2;\ \lim_{z\to\infty}\frac{\partial f}{\partial z}=0. \tag{24}$$

The simplest expression for grid lines that satisfies the requirements (19), (20), (23), (24):

$$f^2(\psi,z)=\psi R^2+\psi(1-\psi)\cdot(F_0+\psi(F_1-F_0)). \tag{25}$$

Functions $F_0$ and $F_1$ depend on the projections onto the axis of the particle velocities along the axis $v_0(z)$ and outline $v_1(z)$:

$$F_0=\frac{1}{v_0(z)}-R^2(z);\ F_1=R^2(z)-\frac{1}{v_1(z)}. \tag{26}$$

Velocity components $v_z(\psi, z)$ the velocity vectors of particles located on the grid line can be determined by the real parameters of the coordinate grid applied to the meridional section. If the grid spacing along the axis $z$ is constant and equal to $\Delta z_0$, then in their motion the particles move from position 1 to position 2, from position 2 to position 3, and so on, in a period:

$$\Delta t=\frac{\Delta z_0}{v_0}=\Delta z_0. \tag{27}$$

Accordingly, the average speed of particle movement along the *z-coordinate* from position $i$ to position $i+1$ equals:

$$v_{z_i}=\frac{\Delta z_i}{\Delta z_0}. \tag{28}$$

Velocity determination $v_0=v_0(0, z)$ and $v_1=v_1(1, z)$ and expression (28) then in their motion the particles move from position 1 to position 2, from position 2 to position 3, and so on, in a period.

In addition, the velocities $v_z(\psi, z)$ can be determined from experimentally obtained curved grid lines. In each fixed section $z=const$ (Fig. 3):

$$v_z=\frac{1}{2r}\cdot\frac{\partial\psi}{\partial r}=\frac{\Delta\psi}{\Delta(r^2)}=\frac{r_{0(n+1)}^2-r_{0(n)}^2}{r_{n+1}^2-r_n^2}. \tag{29}$$

The experimental information on $v_0(z)$ and $v_1(z)$ was approximated by analytical functions. These functions must satisfy conditions (19), (20), (23), (24). Furthermore, on the symmetry axis:

$$\dot{e}_{rz}=0;\ \dot{e}_r=\dot{e}_\phi=-\frac{1}{2}\dot{e}_z;\ \dot{e}_z=\frac{\partial v_0(z)}{\partial z}. \tag{30}$$

Condition (30) implies that at $z=z^*$ which corresponds to the maximum value of $v_0(z)$, all components of the strain rate tensor are equal to zero. This circumstance leads to additional restrictions on the choice of approximation functions for grid lines. Integrating the equilibrium equations along the symmetry axis leads to the result:

$$\sigma_z(0,z)=\sigma_z(0,z_0)+\frac{1}{\sqrt{3}}\int\frac{\partial^2 v_0/\partial z^2+4v_0(\partial v_z/\partial\psi)|_{\psi=0}}{|\partial v_0/\partial z|}. \tag{31}$$

This means that the equations of the grid lines must also satisfy the following conditions, when $z=z^*$, $\psi=0$:

$$\frac{\partial^2 v_0}{\partial z^2}+4v_0\frac{\partial}{\partial\psi}\left(\frac{1}{2f\frac{\partial f}{\partial\psi}}\right)=0. \tag{32}$$

Since the integral in expression (31) is taken without complications, at $z=z^*$ and $\psi=0$ velocity variables $v_0(z)$ and $v_1(z)$ must satisfy the following equality:

$$\frac{\partial^2 v_0}{\partial z^2}+8v_0^2\left(2+\frac{v_0}{v_1}-3v_0R^2\right)=0. \tag{33}$$

Therefore, the approximations for the functions $v_0(z)$ and $v_1(z)$ can be represented by dependencies:

$$v_0(z)=\frac{1}{R^2(z+c_0)}+\alpha_0 exp(-\beta_0(z+\gamma_0)^2); \tag{34}$$
$$v_1(z)=\frac{1}{R^2(z+c_1)}+\alpha_1 exp(-\beta_0(z+\gamma_1)^2). \tag{35}$$

After substituting dependence (29) into expressions (25) and (26), the final formulas for the equations of the grid lines are obtained, which can be used to calculate all the kinematic characteristics of the plastic flow of metal under steady-state axisymmetric deformation.

The components of the stress deviator are calculated by formula (6), and the stresses under axisymmetric deformation are determined by integrating the differential equilibrium equations (2), and (3) using expression (4). To obtain the tensor model of damage accumulation, the flow theory relations (13) are used, which follow:

$$\frac{d\varepsilon_{ij}}{de_u} = \sqrt{\frac{3}{2}}\beta_{ij} = \frac{3}{2}\cdot\frac{S_{ij}}{\sigma_u}. \tag{36}$$

Therefore, expression (11), considering formula (9), can be represented as follows:

$$\psi_{ij} = \int_0^{e_u^*} F(e_u, \eta, \mu_\sigma) S_{ij}^0 de_u \tag{37}$$

or

$$\psi_{ij} = \int_0^{e_u^*} F(e_u, \eta, \mu_\sigma) S_{ii}^0 f(\alpha_{ij}) de_u, \tag{38}$$

where $\psi_{ij}$ – the main components of the strain tensor; $S_{ii}^0$ – the main components of the guiding mathematical object that determines the direction of the main axes of the tensor of internal force intensity; $f(\alpha_{ij})$ – a function that determines the effect of load variability; $\alpha_{ij}$ – guiding cosines, which are determined by the angles between the directions of the principal stresses and the coordinate axes associated with the fixed fibres.

To determine the type of a function $F(e_u, \eta, \mu_\sigma)$, a simple load is considered, under which $\beta_{ij}$, $S_{ii}^0$ $\eta$, $\mu_\sigma$ remain constant, therefore:

$$\psi_{ij} = \beta_{ij}\int_0^{e_u^*} F(e_u, \eta, \mu_\sigma) de_u = \beta_{ij}\phi(e_u, \eta, \mu_\sigma), \tag{39}$$

where $\phi(e_u, \eta, \mu_\sigma) = \int_0^{e_u^*} F(e_u, \eta, \mu_\sigma) de_u$.

By normalising the sub integral functions in expressions (11), (38) and (39), condition (15) can be brought to the condition accepted in phenomenological theory:

$$\psi_{ij}\cdot\psi_{ij} = 1. \tag{40}$$

From condition (40), considering $\beta_{ij}\cdot\beta_{ij} = 1$, it follows that at $e_u = e_p$ function $\phi(e_u, \eta, \mu_\sigma) = 1$. In addition:

$$\phi(0, \eta, \mu_\sigma) = 0. \tag{41}$$

Satisfying these conditions, it is assumed that:

$$\phi = \sum_{k=1}^{m} b_k \left(\frac{e_u}{e_p(\eta, \mu_\sigma)}\right)^{n_k}; \ \sum b_k = 1; n_k > 0, \tag{42}$$

where $e_p(\eta, \mu_\sigma)$ is the surface of ultimate plasticity.

Similarly approximated is the function $f(\alpha_{ij})$, as $S_{ij}^0 \cdot S_{ij}^0 = 1$ (Dai *et al.*, 2022; Chandran & Verleysen, 2024).

As an example, the proposed approach and calculation sequence are used to estimate the plasticity of a metal part with a flange obtained by combined two-stage extrusion. The first stage involves radial extrusion to form a thickening in the centre of the workpiece. Then, in the second stage, the contouring of the thickening is carried out to form a flange. A schematic diagram of the radial extrusion process, followed by the deposition of a cylindrical specimen of steel 10, is shown in Figure 4. The components of the stress deviator for this process are calculated using the formula (6). Hydrostatic stress $\sigma$ is determined by integrating the differential equilibrium equations, which, under axisymmetric deformation, are of the form (2), (3). At the same time, the integral equilibrium equation is used:

$$P = 2\pi\int_0^R \sigma_z \cdot r \cdot dr, \tag{43}$$

where $P$ is the force determined during the deformation of the body under study; $R$ is the radius of the deformed body.

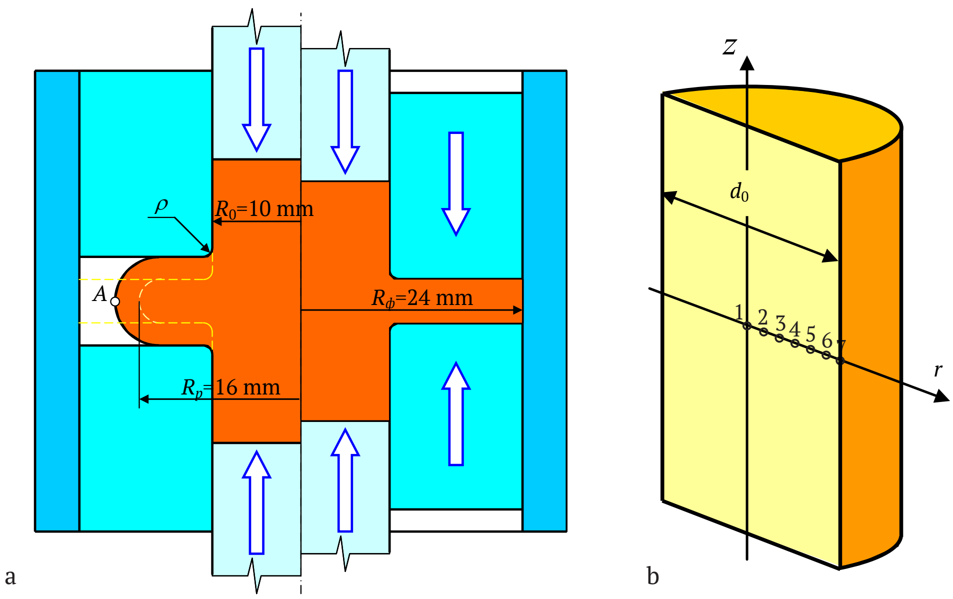


**Figure 4.** Schematic of a two-stage radial extrusion process followed by contouring of a billet from steel 10 (a) and location of points on the meridional section before deformation (b)

**Source:** compiled by the authors

Tension $\sigma_r$ is equal to:

$$\sigma_r = (\sigma_r)_A + \int_r^R \left(\frac{\partial \tau_{rz}}{\partial r} + \frac{S_r - S_\phi}{r}\right) dr, \quad (44)$$

where $(\sigma_r)_A$ is the radial stress at point $A$ (Fig. 4) located on the outer surface of the workpiece.

The axial stress is:

$$\sigma_z = S_z + \sigma_r - S_r. \quad (45)$$

After substituting expressions (44), and (45) into equation (43), we obtain:

$$(\sigma_r)_A = \frac{1}{\pi R^2}\left(P - 2\pi \int_0^R (S_z - S_r + S) r \cdot dr\right), \quad (46)$$

where:

$$S = \int_r^R \left(\frac{\partial \tau_{rz}}{\partial z} + \frac{S_r - S_\phi}{r}\right) dr. \quad (47)$$

The stresses at the remaining points located on the horizontal axis of symmetry of the workpiece were determined by equation (44):

$$(\sigma_r)_i = (\sigma_r)_{i+1} + \int_{r_{i+1}}^{r_i} \left(\frac{\partial \tau_{rz}}{\partial z} + \frac{S_r - S_\phi}{r}\right) dr. \quad (48)$$

Stress $\sigma_z$ and $\sigma_\phi$ are calculated along the radius:

$$(\sigma_z)_i = (\sigma_r)_i - (S_r)_i + (S_z)_i; \quad (49)$$

$$(\sigma_\phi)_i = (\sigma_r)_i - S_r)_i + (S_\phi)_i. \quad (50)$$

The stress along other parallel radii is calculated similarly. Axis stress value $\sigma_z$ along the vertical lines is determined by integrating the second differential equilibrium equation (3):

$$(\sigma_z)_{i+1} = (\sigma_z)_i - \int_{z_i}^{z_{i+1}} \left(\frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r}\right) dz. \quad (51)$$

The stress and strain values obtained in this way are used to display the spatial directions of deformation $e_u$ ($\eta$, $m_\sigma$), as well as calculations $\beta_i$ per formula (12) i $\psi$ following the condition (40).

Figure 5 presents the dependences of the components of total stresses, namely $\sigma_z$, $\sigma_r$ and $\sigma_\phi$ on the level of deformation $e_u$ at characteristic points (Fig. 4) on the horizontal axis of symmetry of the workpiece (Fig. 4b), at $z = 0$. Analysis of the obtained dependences of the components of total stresses ($\sigma_z$, $\sigma_r$ and $\sigma_\phi$) on the level of deformation $e_u$ (Fig. 5) indicates an accurate correspondence of this theoretical calculation method to the actual deformation process. The dependencies reflect the transition from the first to the second stage of deformation. This is especially pronounced at the points furthest from the vertical axis of symmetry of the workpiece, where the level of non-monotonicity is high. Traditional calculation methods based on flow theory relations do not allow for this result. There is no sharp change like the stress-strain dependence obtained from the flow theory relations at the moment of transition from one extrusion stage to the next. The obtained result indicates the importance of considering the influence of non-monotonic plastic deformation on the patterns of stress field formation under anisotropic strengthening since the reliability of the assessment of the deformability of the workpiece depends on this.

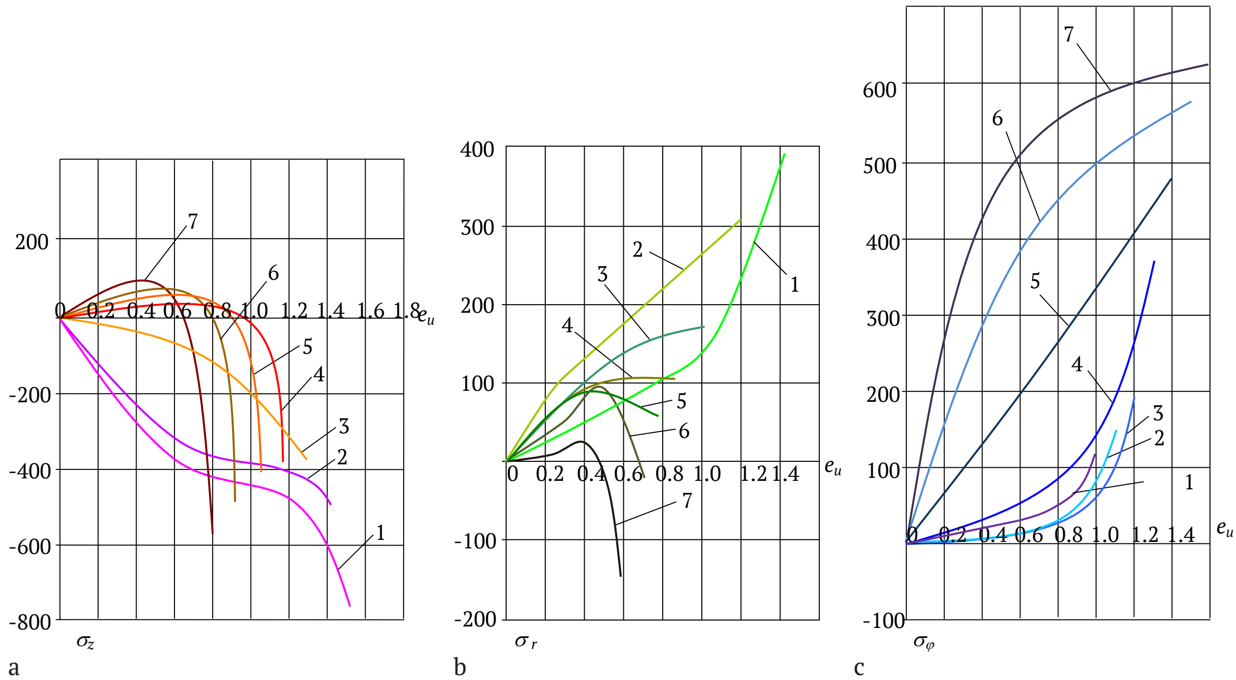


**Figure 5.** Stress depends on the degree of deformation $e_u$ at characteristic points (1-7)

**Note:** for $\rho/d_0$=0.15; a) $\sigma_z$, b) $\sigma_r$, c) $\sigma_\phi$

**Source:** compiled by the authors

The surface of maximum deformations for steel 10 is approximated by the dependence (Meyer & Menzel, 2021; Sheykin *et al.*, 2021):

$$e_p = (\eta, \mu_\sigma) = 0.68exp(0.43\mu_\sigma - 0.71\eta). \qquad (52)$$

The surface of the ultimate deformation of steel 10, as well as the deformation paths of material particles at points 3, 5, and 7 (Fig. 4b), is shown in Figure 6. Position 7 corresponds to point *A*, which was used in the stress calculation. From the analysis of the nature of the obtained spatial curves and the tendency of their formation in the selected space, it follows that increasing the radius of the die rounding $\rho$ shifts the trajectories to a convenient zone in terms of increasing the plasticity of the metal and therefore improving the deformability of the workpiece. The experience of producing parts by radial extrusion shows that macro-cracking occurs first of all at the point of the free surface of the flange, on the equatorial axis of symmetry. Contouring reduces the likelihood of fracture in the specified area of the part and provides a flange with a diameter significantly larger than the size of flanges obtained by traditional extrusion methods. In addition, the contact between the free surface of the flange and the matrix creates a region where the metal is in a favourable stress pattern. This further reduces the likelihood of fracture in the danger zone of the part, makes it possible to increase the maximum dimensions and gives the product the necessary technological continuity.

Calculations $\psi$ are shown in Table 1, for a flange with a diameter $d_{max} = 48$ mm (at $d_0 = 20$ mm), depending on the radius of the matrix rounding.

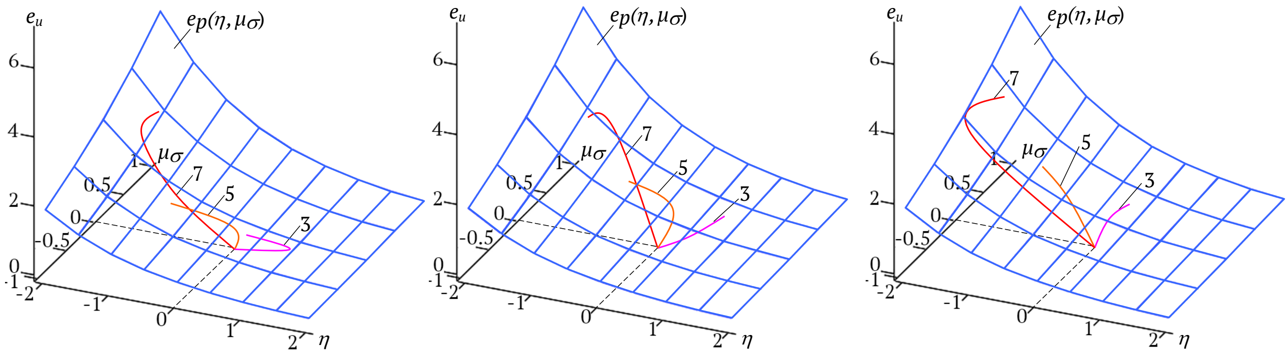


**Figure 6.** The surface of maximum deformation $e_p(\eta, m_\sigma)$ for steel 10 and the deformation paths of material particles at the points 3, 5, 7

**Note:** a) $\rho/d_0 = 0.05$; b) $\rho/d_0 = 0.10$; c) $\rho/d_0 = 0.15$

**Source:** compiled by the authors

**Table 1.** Results of calculations of the value of the used plasticity resource

| The ratio of the rounding radius of the die to the initial diameter of the workpiece, $\rho/d_0$ | Point | The amount of plasticity resource used, $\psi$ |
|---|---|---|
| 0.05 | 3 | 0.48 |
| | 5 | 0.74 |
| | 7 | 0.88 |
| 0.10 | 3 | 0.39 |
| | 5 | 0.58 |
| | 7 | 0.64 |
| 0.15 | 3 | 0.36 |
| | 5 | 0.44 |
| | 7 | 0.56 |

**Source:** compiled by the authors

The analysis of the results presented in Table 1 shows that increasing the radius of curvature $\rho$ from 1 mm to 2 mm does not affect the amount of plasticity used $\psi$ at the stress point. Only at $\rho = 3$ mm, the value of the used plasticity resource is reduced to $\psi = 0.56$. The deformation of the free surface of the flange during contact with the matrix also has a favourable effect on the amount of plasticity used. If the difference between the values of $\psi$ at points 3 and 5 is large enough, the interval at points 5 and 7 has been significantly reduced. This fact indicates a reduction in the intensity of damage accumulation in this area of the flange. The radius of curvature of the die is less than 2 mm ($\rho < 2$ mm) leading to an increase in the value of the plasticity resource at the dangerous point, compared to the value $\psi$ at $\rho = 3$ mm. At this value $\rho$, the flange diameter can reach $d_{max} = 48$ mm ($d_0 = 20$ mm), with no formation of macro cracks on the free surface. Experimental studies have established that the limit value of the flange diameter is

$d_{max}$ = 52 mm, for the ratio $\rho/d_0$ = 0.15. The results of the calculations coincide with the experimental results obtained by L. Aliieva *et al.* (2020) and V. Chukhlib *et al.* (2020).

The physical picture of the damage accumulation kinetics under non-monotonic loading has not been studied. Therefore, one of the ways to solve this problem is to apply the hypothesis of the tensor nature of damage accumulation within the phenomenological theory of deformability V. Kukhar *et al.* (2022), which estimates the used plasticity resource under non-monotonic loading. In general, L. Zhou & H. Wen (2019), and M. Brünig *et al*. (2023) used a plasticity diagram to determine the components of the damage tensor. There are no thorough studies devoted to three-dimensional load trajectories under non-monotonic deformation.

The reason for the unsatisfactory accuracy in determining the value of the used plasticity resource under non-monotonic loading is the neglect of strain anisotropy in the assessment of the stress-strain state (Hasemann *et al.*, 2019; Lakshmi *et al.*, 2020). To assess the deformability of future products and ensure the quality of finished parts, information on the deformation history of each material particle in the workpiece volume is required. M.B. Shtern *et al.* (2021) and V. Mykhalevych *et al.* (2023) proposed an original approach to assessing the stress-strain state in the plastic zone, which obtains a sufficiently reliable history of deformation of a part of the material by solving the system of differential equations of the theory of plasticity.

To study the set of stresses and strains both on the outside and inside of the workpieces, one of the most effective methods is the coordinate mesh method, which was studied by G. Faraji & H. Torabzadeh (2019) and I.S. Aliiev *et al*. (2023). The systematic set of steps for macrostructure detection and the microstructural method can also be regarded as ways in which natural grids are used for research (Beygelzimer *et al.*, 2023). The relations for calculating deformations from curved meshes are derived for cases where the original square mesh drawn on the main plane is transformed into a parallelogram after deformation. More general formulas were obtained by V. Kukhar *et al*. (2022) for the case when the initial cell has the shape of a parallelogram, which is especially important when studying the processes of shape change in a stepwise manner. Methods of this type are quite versatile, but the disadvantages include the following: increased labour intensity of measurements, low accuracy of determining small deformations and obtaining averaged results within the cell boundaries. In addition, if the sides of the cell are severely distorted after deformation, this approach leads to large errors.

Along with the direct study of the deformation of a unit cell, the quantification methodology can be based on the step-by-step measurement of the coordinates of points (grid nodes), i.e., determination of the displacement front for a given time interval and subsequent determination of the deformation velocity field. M. Brünig *et al.* (2023) determined that the flow theory relation is used to perform further stress state calculations. When determining the stress state by deformation, it is necessary to address the relations of the theory of plasticity. The desired stress field must satisfy the equilibrium equations, the plasticity condition, the flow law and the boundary conditions. When determining stresses from kinematics that do not satisfy the boundary conditions during the integration of equilibrium equations, a significant discrepancy between the solutions is observed. According to S. Yoon *et al.* (2022), in some areas, errors can reach hundreds of per cent. The main disadvantage of the considered approaches is that errors in experimental measurements of the curved dividing mesh lead to inaccuracies in the determination of stress deviators. As a result, deviators contain errors that are not always possible to detect and evaluate. The problem in the form of functions that satisfy the equilibrium equations, plasticity condition and boundary conditions can be solved using partial solutions obtained by independent integration of each expression. However, partial solutions can have very significant differences. The approach of W. Dou *et al*. (2023), based on the finite-difference representation of the equilibrium equation, is more reasonable. To accurately satisfy the equilibrium equation at the nodes of the computational grid, a certain relaxation of the requirements for fulfilling the plasticity condition is carried out. The methodology of W. Dou *et al.* (2023) complicates the use of these methods and techniques in areas with complex geometry and cannot be used for the required calculation accuracy. Therefore, when studying the plastic flow of metal, a universal approach is needed to reduce labour intensity and increase the accuracy of calculating kinematic characteristics.

Thus, the proposed complex of calculations is more optimal for determining the stress-strain state and assessing the deformability of workpieces during cold forming, since it addresses the most important indicators of technological processes, which are supplemented by non-monotonic plastic deformation.

## CONCLUSIONS

The hypotheses accepted in modern theories of deformability do not always reflect the real nature of damage accumulation under non-monotonic plastic deformation. This leads to an accumulation of errors at each stage of the calculation, from determining the deformation kinematics to estimating the amount of plasticity resource used. A high estimate of the probability of workpiece fracture during metal forming depends on reliable information about the change in the stress-strain state during plastic forming. The known methods for determining the stress-strain state do not always meet modern requirements for assessment accuracy. The value of the used plasticity resource, as one of the indicators of the technological heredity of products, significantly depends on the parameters of an arbitrary technological process. If this process is combined, the determination of this dependence is much more complicated due to the presence of non-monotonic plastic deformation. The obstacle is the reason why the application of many deformability criteria in solving certain technological problems is limited. Therefore, the method of determining the kinematic characteristics should be the starting point for improving the calculation algorithm. The next step is to determine the components of the stress deviator based on a mathematical model of an anisotropically hardened body that considers the effect of non-monotonic loading. For steel 10, the experimental dependences of the Bauschinger parameter and the hereditary function on the degree of deformation were obtained. The value of the used plasticity resource was estimated using a tensor model. The main difference between the criteria of this model and the known ones is that the surface of the boundary shape change is used instead of the plasticity diagram to approximate the functions describing the mechanical properties of the material.

The proposed sequence of calculating the value of the used plasticity resource was applied to assess the deformability of the workpiece in the process of two-stage cold combined extrusion. As a result, the peculiarities of changes in the value of the used plasticity resource at characteristic points on the horizontal axis of symmetry of the part with a flange were determined. At the same time, the stress state was determined using experimentally derived functions that consider the Bauschinger effect and the hereditary influence of the load history. The components of the strain rate tensor are determined by analytical functions based on experimental data using Lagrangian and Eulerian coordinates. The boundary strain surface was used as a characteristic reflecting the dependence of plasticity on the stress-strain pattern, and the loading history was set by trajectories in the three-dimensional space of dimensionless stress-strain parameters and accumulated strain. This addresses the effect of non-monotonic plastic deformation under bulk stress conditions. The discrepancy between theoretical and experimental values was assessed by comparing the value of the calculated maximum flange diameter $d_{max}$ and the diameter of the flange with signs of macrocracking. The error between the values was 7-9%. The present work is a continuation of research in the field of plasticity of deformed metal. Further research will be improved by refining the methods of calculating the stress-strain state, quantifying the intensity of damage accumulation, using the theory of dislocations and considering structural transformations in the deformed metal.

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None.

## CONFLICT OF INTEREST

None.

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**Роман Сивак**
Доктор технічних наук, професор
Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-7459-2585

**Володимир Куликівський**
Кандидат технічних наук, доцент
Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-4652-0285

**Василь Савченко**
Кандидат технічних наук, доцент
Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-0921-1424

**Олена Сукманюк**
Кандидат історичних наук, доцент
Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0003-2485-488X

**Віктор Боровський**
Старший викладач
Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-1759-8155

# Застосування ресурсозберігаючих технологій видавлювання і комплексного підходу оцінки пластичності металу деталей в агроінженерії

**Анотація.** Серед перспективних ресурсозберігаючих технологій виробництва деталей, з покращеними експлуатаційними характеристиками, чільне місце займають процеси об'ємного пластичного деформування виробів. Актуальність досліджуваної теми обумовлена необхідністю підвищення показників механічних властивостей деформованого металу, збільшення стійкості інструменту, отримання високоточних штампованих виробів із належним рівнем технологічної спадковості. Метою дослідження є створення необхідного рівня деформаційного зміцнення та пошкодженності деформованого металу, виробів складної конфігурації, що дозволить замінити дорогі марки сталей більш дешевими, із аналогічними службовими характеристиками. Для розрахунку компонентів тензора напружень, при немонотонному навантаженні, використана модель анізотропно-зміцнюваного тіла. На підставі теоретичних та експериментальних надбань запропоновано, для виготовлення деталей з фланцем, застосовувати способи холодного комбінованого видавлювання, які дозволяють значно збільшити граничні розміри і покращити показники технологічної спадковості виробу. В статті представлена методика визначення кінематичних характеристик пластичної течії металу аналітичними функціями, отриманими на основі експериментальних досліджень руху суцільного середовища. Тензорний підхід дозволив створити модель накопичення пошкоджень при немонотонній деформації. Представлений комплекс обчислень дозволяє достовірно і з досить високою точністю визначити напружений стан, величину витраченого ресурсу пластичної формозміни під час немонотонного об'ємного деформування, без попереднього підігріву металу. На основі інформації про напружено-деформований стан і тензорної моделі накопичення пошкоджень здійснена оцінка граничного формоутворення деталей з фланцем. Практична цінність досліджень полягає у використанні запропонованих підходів для розв'язання низки технологічних задач обробки металів тиском, коли матеріал зазнає немонотонного пластичного деформування в умовах об'ємного напруженого стану

**Ключові слова**: холодне комбіноване видавлювання; немонотонна деформація; складне навантаження; пластичність металу; об'ємне штампування

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**Ruslan Yermolenko***
PhD in Physical and Mathematical Sciences, Associate Professor
Taras Shevchenko National University of Kyiv
01033, 60 Volodymyrska Str., Kyiv, Ukraine
https://orcid.org/0009-0000-0854-4668

**Denys Klekots**
Student
Taras Shevchenko National University of Kyiv
01033, 60 Volodymyrska Str., Kyiv, Ukraine
https://orcid.org/0000-0002-4251-2958

**Olga Gogota**
PhD in Physical and Mathematical Sciences, Researcher
Taras Shevchenko National University of Kyiv
01033, 60 Volodymyrska Str., Kyiv, Ukraine
https://orcid.org/0000-0003-4108-7256

# Development of an algorithm for detecting commercial unmanned aerial vehicles using machine learning methods

**Abstract.** This study aimed to train algorithms for detecting commercial unmanned aerial vehicles using machine learning techniques. Neural network architectures YOLOv8 and MobileNetV3 were used to detect unmanned aerial vehicles in images and videos. The models used were pre-trained on the ImageNet dataset and then refined on the SimUAV dataset containing images of four types of drones (Parrot A.R. Drone 2.0; DJI Inspire I; DJI Mavic 2 Pro; and DJI Phantom 4 Pro), different sizes and in eight different background locations. The study confirmed that the combination of the YOLOv8 and MobileNetV3 architectures has significant potential for detecting commercial unmanned aerial vehicles in various types of images. The trained models demonstrated high performance in the recognition and classification of unmanned aerial vehicles, achieving an average detection accuracy (at an IoU threshold of 50%) of 0.747 and 0.909 for the MobileNetV3_Small and MobileNetV3_Large models, respectively. This demonstrates the high efficiency and accuracy of the models in detecting objects on the test data. The results of the study also included the values of the binary cross-entropy metric, which were 0.308 and 0.216, respectively, indicating the high accuracy of the models in object classification and confirming the high efficiency and reliability of these models in working with objects on the test data. During the study, the MobileNetV3_Large model showed more accurate results than MobileNetV3_Small, which indicates its higher efficiency in detecting and classifying aircraft. The obtained results confirm the prospects of applying machine learning methods in the field of monitoring and security systems, which reliably detect and track unmanned aerial vehicles in various conditions. The high performance of the trained models demonstrates their effectiveness in real-world operating conditions, making them a valuable tool for solving important control and supervision tasks

**Keywords**: convolutional neural network; object classification; YOLOv8; MobileNetV3; computer vision; binary cross-entropy

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*Corresponding author

## INTRODUCTION

The growing popularity and availability of unmanned aerial vehicles (UAVs) introduce new technologies and open many new opportunities in various industries, such as commercial activities, industrial production, and research and exploration. However, at the same time, the growth in the use of drones has also raised serious security constraints and concerns, as some drones can be used by malicious actors for illegal or harmful purposes, creating a need for improved methods of detecting and controlling them. This problem creates a need for effective solutions for fast and reliable detection of unmanned aerial vehicles, even in remote or difficult conditions. Existing methods are often insufficiently efficient or slow to effectively monitor such devices. Therefore, there is a need to develop new technologies and algorithms aimed at detecting and identifying unmanned aerial vehicles, which will ensure effective control and prevent security threats.

Machine learning methods have great potential in this area, as they can be used to automate the process of detecting and identifying objects in images. The use of machine learning algorithms can be used to create models that can analyse and interpret large amounts of data with high speed and accuracy (Pidpalyi, 2024). Such models can perform a variety of tasks, including detecting objects of different types and classes. An important aspect of using machine learning methods is their ability to adapt and learn from new data. This allows the models to continuously improve and adapt to changing environmental conditions, which is critical in the case of drone detection. In addition, the use of machine learning methods allows automation of the detection process and provides faster response times, which is important in the case of detecting potentially dangerous devices.

One of the most important areas of application of neural networks is their use in image processing, which opens wide opportunities for solving various tasks in the field of computer vision (Najjar & Baskaya, 2022). L. Chen *et al.* (2021) analysed the effectiveness of different convolutional neural network architectures for image classification and object recognition tasks, which highlighted the advantage of deep architectures over traditional machine learning methods, especially in tasks such as object recognition. Y. Wang *et al.* (2020) studied the impact of different optimisation algorithms and activation functions on the accuracy of models in image processing tasks, showing that the choice of optimal parameters can significantly affect the quality and efficiency of neural networks in image and video analysis tasks. M. Hammami *et al.* (2020) also focused on developing new data augmentation methods to improve model training in the face of insufficient image data, which improved their overall performance. However, such studies are often limited to specific aspects or contexts and do not incorporate all implementation options, which requires additional study and analysis.

The use of neural networks opens opportunities for their adaptation to new conditions and tasks, making them more flexible and versatile in various applications. A. Taherkhani *et al.* (2020) conducted a detailed analysis of the ability of neural networks to transfer learning to different tasks and datasets, identifying the key factors affecting their versatility and efficiency. M.M. Bejani & M. Ghatee (2020) addressed the impact of different regularisation methods on the overall performance and versatility of neural networks. K.M.R. Alam *et al.* (2020) analysed the possibility of using ensembles of neural networks to improve the accuracy and reliability of results. Such studies, however, focus only on certain features of the use of machine learning technologies, which may limit their applicability in real-world applications and require more detailed research.

The development of neural networks also allows them to not only reproduce existing knowledge but also learn from new data and experiences, ensuring their ability to continuously improve and adapt to changing conditions (Janulin *et al.*, 2022). S. Tishchenko & E. Kuznetsov (2024) investigated the capabilities of neural networks in the context of solving prediction and classification tasks in dynamic learning, emphasising their ability to effectively adapt to changes in the environment. N.O. Kushnir *et al.* (2022) addressed the mechanisms of neural networks' self-tuning during training, enabling automatic adjustment of their parameters to achieve optimal performance and accuracy. C.J. Lin *et al.* (2021) analysed the role of neural networks in resource-constrained learning environments, where they have shown the ability to efficiently use computing power and data, making them attractive for use in limited hardware. However, each case of using neural networks is unique and requires an individual approach, considering specific conditions, data, and the task at hand (Song *et al.*, 2018). Each research or application of neural networks has its peculiarities that should be addressed when developing and analysing models.

The study aims to investigate the effectiveness of MobileNetV3_Small and MobileNetV3_Large models in detecting commercial unmanned aerial vehicles in images, in different conditions and application modes. The main tasks will include training these models on a suitable dataset and evaluating them for object detection and classification.

## MATERIALS AND METHODS

The key algorithms used in this study were neural network architectures for detecting objects in images and videos, such as YOLOv8 and MobileNetV3 (in particular, MobileNetV3_Small_ImageNet and MobileNetV3_Large_ImageNet). To use a combination of these models, the keras_cv library was used as it provides convenient access to these models and their functionality (The YOLOV8Detector model, n.d.). These models were managed through an application programming interface (API), which ensured ease of use and integration with other system components. The model used for training was pre-trained on the widely used ImageNet dataset (ImageNet Large Scale..., n.d.), which gave it a basic understanding of the different images and patterns in the images. After the preliminary training, the model was further trained on the SimUAV dataset (n.d.), which was divided into three parts: 10% for validation, 10% for testing and 80% for training. This dataset included 29,568 colour images of four models of unmanned aerial vehicles, presented in 640×640 pixels format. The images were artificially generated in different locations and under different lighting conditions to provide diversity and versatility in object recognition for the model.

Considering the pre-training of both models, the study decided to focus on retraining only the last layers in the YOLOv8 model. This strategy implied that all layers after tf.concat_5 would be retrained while maintaining the previously trained weights for the rest of the model. This approach retained the information gained from the previous training, while also allowing the model to tune its parameters to better match the specific characteristics of the SimUAV dataset. During the retraining process, the corresponding APIs of the keras_cv library were used, which provided convenient access to the model functionality and allowed for efficient implementation of changes in model weights following the specific requirements and characteristics of the SimUAV dataset. The retraining process involved adapting the model's weights, addressing the output formats, input and output layer sizes, and optimisation parameters. This strategy has significantly reduced the time required to train the model while ensuring high-quality results and compliance with the requirements of the UAV detection task.

The task of object detection implies the presence of two output levels in the model, namely classification and regression, each of which uses a separate loss function. For the classification layer, a binary cross-entropy loss function was used to facilitate the model correctly classifying objects in the images. For the regression level, the ratio of the intersection area of the rectangles described around the object to the area of their union was used (also known as interaction over union (IoU) loss function), which allowed the model to accurately determine the boundaries of the objects. The final loss function was calculated as the sum of the loss functions of the classification and regression levels. To evaluate the efficiency and accuracy of the model, the mean average precision (mAP) metric for the threshold value of the IoU was used, thus assessing the overall ability of the model to detect objects in images. After training, the model with the best mAP was selected, evaluated on the validation dataset, and used to evaluate the metrics on the test dataset.

## RESULTS

There are many different methods and technologies used to detect drones, which can be divided into two main categories: non-optical and optical. Non-optical approaches include the use of sound, radar and radio frequency methods. Analysing the acoustic characteristics of drones' rotors can detect their presence, but this method is not always effective in noisy environments such as airports and cities. Radars are widely used to detect large aerial objects but require special modifications to detect drones and can suffer from noise. Radio-frequency methods allow drone signals to be intercepted and analysed, which is an effective way to detect over long distances.

Optical approaches, in turn, are based on image processing. Traditional methods include manual feature extraction from images, such as histograms of oriented gradients (HOG) and others. However, these methods, despite being quite fast, usually have low accuracy. In contrast, deep learning methods use neural networks to automatically extract features, which results in higher-quality object recognition in images (Rahmad *et al.*, 2020). In the research field of computer vision, there are usually three main categories of tasks: classification, detection and segmentation. The construction of a bounding box surrounding the drone in the frame requires information about what and where the object is in the image, which belongs to the object detection category.

Two-stage detectors are complex models divided into two stages for more efficient detection of objects in images. The first stage involves the creation of proposed areas where the required facilities could potentially be located. This process is carried out employing convolutional neural networks such as RCNN, Fast RCNN, and Faster RCNN (Fig. 1), which use base networks such as VGG-16 or ResNet to generate feature maps (Nguyen & Huynh, 2023).

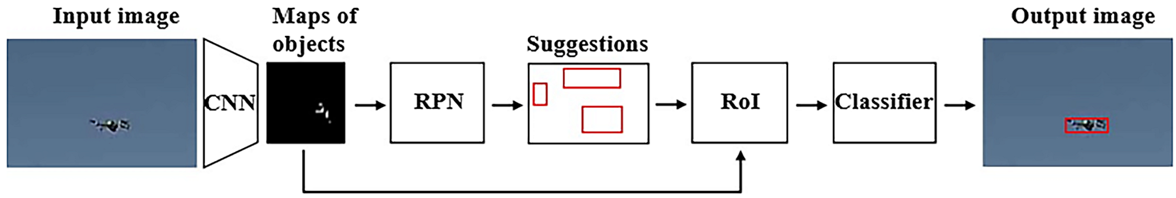


**Figure 1.** Scheme of a two-stage structure of object detection on the example of Faster R-CNN
**Source:** compiled by the authors

Then, the network responsible for generating region-of-interest (RoI) suggestions determines the locations where objects can be found. The proposed regions are then merged with the corresponding feature maps using maximum merging to create fixed-size feature maps. The obtained results are transferred to a classifier that determines the class of the object and builds a restrictive framework around it (Raja *et al.*, 2020).

Two-stage detectors usually provide higher accuracy than single-stage models, but their speed may not be sufficient for real-time applications. However, the ability to accurately detect objects makes them an important tool in the field of computer vision. One-step object detectors are innovative models that abandon the traditional two-step approach to object detection and instead provide bounding boxes and object classes simultaneously. This opens up new perspectives in the world of computer vision, allowing for faster and more efficient real-time object detection. One-stage detectors differ from their two-stage counterparts in that they operate without a phase of region proposal. Complex deep learning networks are used to simultaneously predict the position of objects and their classes. This provides faster and more efficient solutions to object detection tasks on large volumes of data. Two examples of one-step detectors are You Only Look Once (YOLO) and Single Shot Detector (SSD). Both methods use different strategies to solve object detection problems (Shuai & Wu, 2020; Jiang *et al.*, 2022). The SSD strategy relies on feature-matching functions to predict bounding boxes and object classes. On the contrary, YOLO technology divides the image into a grid of cells at three different scales, each of which is responsible for predicting anchor boxes and class probabilities (Fig. 2).

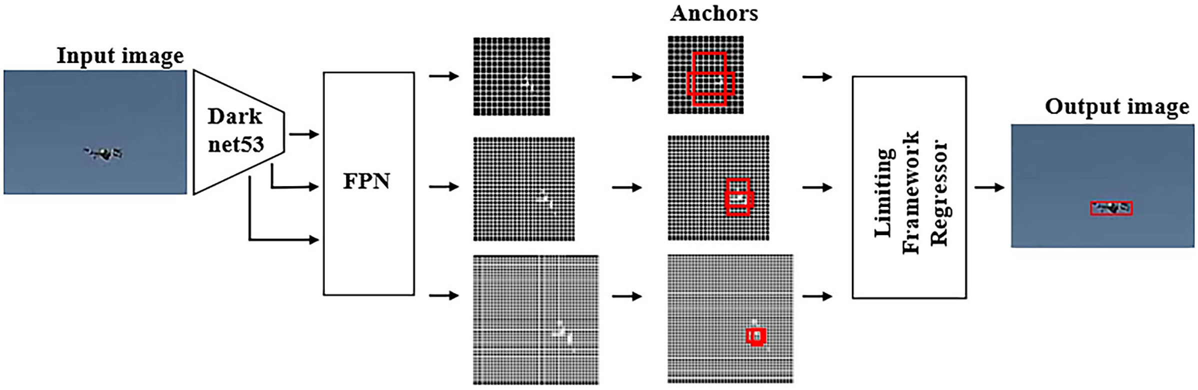


**Figure 2.** Scheme of the one-stage structure of object detection on the example of YOLOv3
**Source:** compiled by the authors

It is worth noting that YOLOv8 is an advanced model in the field of object recognition. It features a complex architecture, which includes several key components, each of which plays an important role in the data processing process (Fig. 3).

The Backbone plays a key role in extracting information from the input data in the YOLOv8 model. This model uses CSP Darknet53, which is an improved version of the previous models. Darknet53 is a basic architecture based on the idea of cross-stage partial connections (CSP). This architecture is noted for its ability to efficiently process large amounts of data and extract important features. The use of CSP Darknet53 in YOLOv8 provides faster data processing and improved object detection accuracy using advanced data processing technologies. Such a network can keep important features from the input images and transfer them for further analysis and classification of objects (Zou *et al.*, 2023).

"Neck" is used to combine features from different levels of the spine. For this purpose, the Path Aggregation Network (PANet) technology is used, which is the basis for the optimal integration of information from different levels. PANet provides adaptive feature weighting, where each feature is assigned a weight according to its importance. This allows the model to focus on the most informative features, increasing its ability to recognise objects. The panel effectively combines information from different layers of the ridge and uses it for further analysis and classification of objects in the images.

"Head" is an important component of the YOLOv8 model responsible for predicting bounding boxes and classifying objects. This model uses several heads that operate at different scales, allowing the model to accurately detect objects of different sizes and shapes. Each head predicts bounding boxes and object classes for a specific image scale. The YOLOv8 uses three heads, each responsible for a different scale: 82 layers for detecting large objects, 94 layers for medium-sized objects, and 106 layers for small objects (Diwan *et al.*, 2023).

"Auxiliary Branches" in the YOLOv8 model is a component aimed at improving the accuracy of small object detection. By starting object detection at an early stage of processing, auxiliary branches allow the model to confidently recognise even the smallest details. This is important for tasks where small objects can be critical to the accuracy and completeness of the analysis. Another important technology in the development of lightweight and efficient deep learning models for image processing on mobile devices is MobileNetV3. This series of models is designed to optimise computing resources and power consumption, delivering high performance on devices with limited specifications. The MobileNetV3 is characterised by its high performance and lightweight design, making it ideal for a variety of applications on mobile devices such as smartphones and embedded systems (Fig. 4).

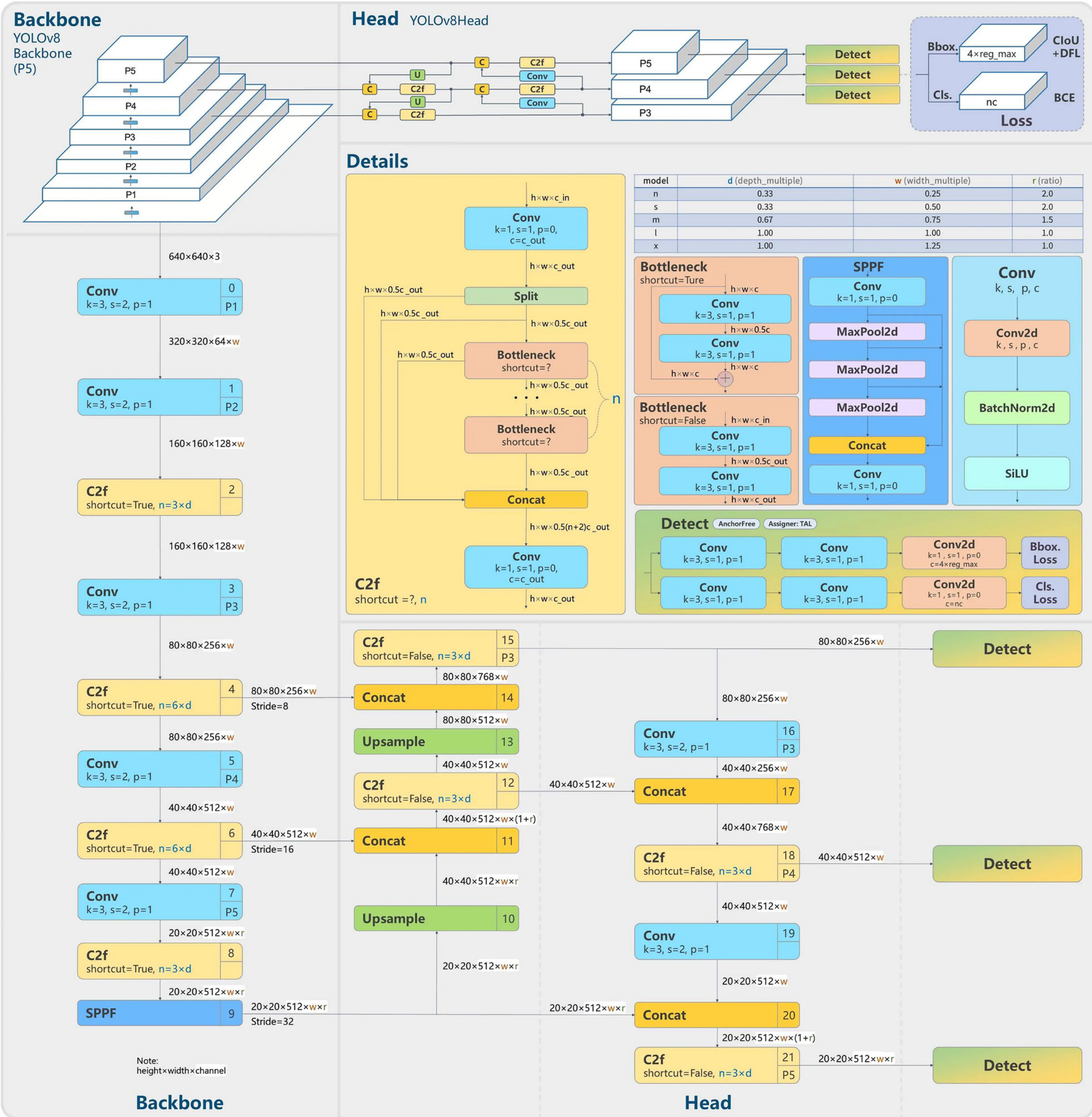


**Figure 3.** Structure of the YOLOv8 model

**Source:** PaddleYOLO (n.d.)

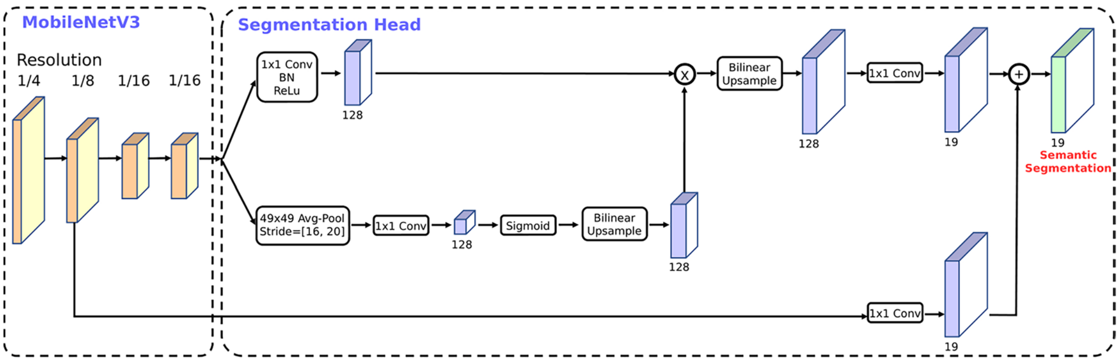


**Figure 4.** Structure of the MobileNetV3 model

**Source:** S.H. Tssng (2020)

Architectural innovations introduced in MobileNetV3 include the use of two key concepts: Squeeze-and-Excitation (SE) modules and structural adaptability modules, which allow for adaptive modification of the network architecture to meet the specifics of input data and tasks. SE modules are used to focus the network's attention on the most important features of the input data. This is achieved through two operations: "squeeze" and "excitation". The first operation performs group aggregation of features, which reduces their size and number. In the second operation, using a fully connected network, each group of features is assigned a weight that reflects its importance. Separate SE layers are used for each MobileNetV3 module, tailoring the network's attention to different contexts and details of the input images (Zhao & Wang, 2022).

The structural adaptability modules in MobileNetV3 can be used to modify to meet the requirements of a specific application. This is achieved by including different types of blocks depending on the characteristics of the input data and the expected output. For instance, for a classification task, an architecture with more connections and layers can be used, while for a segmentation task, an architecture with more layers and filters can be used. This provides greater flexibility and efficiency in a variety of use cases. In this study, a combination of the YOLOv8 and MobileNetV3 architectures was implemented and pre-trained on the ImageNet dataset. To implement this, the corresponding API of the keras_cv library was used, which provided convenient access to these models and their functionality. Due to the preliminary training of both models on a large amount of data, it was decided to retrain only some of the last layers of the YOLOv8 model (all layers after tf.concat_5).

During the retraining, the corresponding APIs of the keras_cv library were used. The retraining process involved changing the model's weights to meet our requirements and specifications, incorporating the output formats, input and output layer sizes, and optimisation parameters. This significantly reduced the time required to train the model while maintaining the high quality of the results. To improve the efficiency of the model in detecting UAVs, especially when they are small in the image, the image interlacing method can be used. This avoids missing objects on the borders of tiled images. For example, if the camera resolution is 1920×1080 pixels, and the size of the input image in the YOLOv8 model is 640×640 pixels. During operation, each image in the dataset can be cut into 8 tiles, with 2 tiles arranged vertically and 4 tiles arranged horizontally. The width and height of the tile in this case is 640 pixels, which corresponds to the size of the input image in the YOLOv8 model. The calculation of overlaps between distributed tiles is as follows:

$$l_o = \frac{nl_{tile} - l_{image}}{n-1}, \tag{1}$$

where $l_o$ – the length of the overlap; n – the number of tiles; $l_{tile}$ – the length of the tile; $l_{image}$ – the length of the original image.

The formula (1) establishes that the overlap length between vertically adjacent tiles is 200 pixels, which is a fairly optimal solution since it is an integer. However, using the same formula, the overlap length between horizontally adjacent tiles is approximately 213.4 pixels, which creates problems in practical applications due to the difficulty of achieving such accuracy. Instead, the length of the three overlaps can be manually set to 200, 200, and 240 pixels, respectively. This will make the tile grid more accurate and simplify calculations, which is critical in applications where accuracy and simplicity are important factors. After splitting the image into tiles, the coordinates of the object labels must be updated to reflect the new positions. Information about the objects in the source images is stored in the YOLO format, where each image has a corresponding .txt file with annotations, including the object class, x-y coordinates, and width and height. The x, y, w, h were calculated using formulas (2-5), addressing the pixel coordinates:

$$x = \frac{x_{min} + x_{max}}{2w_{image}}, \tag{2}$$

$$y = \frac{y_{min} + y_{max}}{2h_{image}}, \tag{3}$$

$$w = \frac{x_{max} - x_{min}}{w_{image}}, \tag{4}$$

$$h = \frac{y_{max} - y_{min}}{h_{image}}. \tag{5}$$

Each object label of the source image contains the x and y coordinates of the upper left corner of the bounding box, as well as its width (w) and height (h). The x-coordinate defines the position relative to the left edge of the image, increasing towards the right. The y-coordinate defines the position relative to the top edge of the image, increasing in the downward direction. These values are expressed as a percentage of the total width ($w_{image}$) and height ($h_{image}$) of the image (Fig. 5).

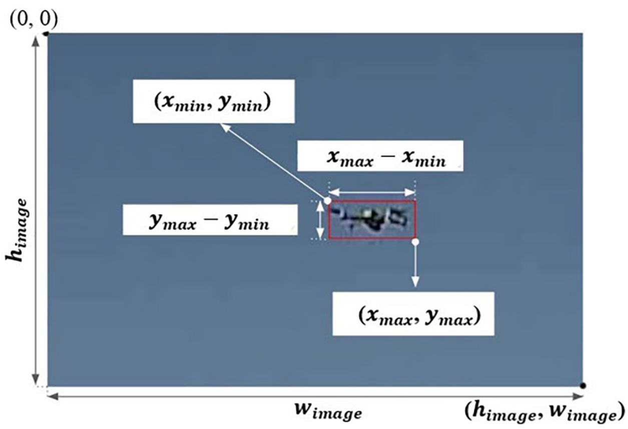


**Figure 5.** Calculation scheme in the YOLO model
**Source:** compiled by the authors

Emphasis was placed on calculating the model's performance in real-time. Since drone tracking requires the rapid processing of many images, several key performance metrics have been identified. To determine the effectiveness of the output level responsible for classification, binary cross-entropy was used, which is the optimal choice for binary classification tasks. This metric measures the distance between the predicted and actual values, addressing the probability of each class for each input sample, and is calculated using the formula (6):

$$L_{classification} = -\frac{1}{N}\sum_{i=1}^{N}(y_y * \log(p_i) + (1-y_i) * \log(1-p_i)), \quad (6)$$

where N – the number of samples in the training set; $y_i$ – the actual class label for sample i; $p_i$ – the predicted probability that sample i belongs to class 1.

The binary cross-entropy is used to assess how accurately the model classifies objects into two classes: present (in this case, a UAV) or absent. The value of this metric is minimised if the predicted and actual probabilities are the same, which means that the model correctly classifies objects. High values of binary cross-entropy indicate that the model cannot effectively separate classes, which leads to low classification accuracy. For the regression level, intersection over Union (IoU) was used (He et al., 2021; Yuan et al., 2020). This metric is calculated as the ratio of the intersection area to the area of the union of the two boundary regions: true boundary regions and predicted boundary regions (7):

$$IoU = \frac{\text{Cross-sectional area}}{\text{The area of the association}}. \quad (7)$$

The true boundaries are manually annotated based on the dataset, while the predicted boundaries are the output of the model that processes the input images (Fig. 6).

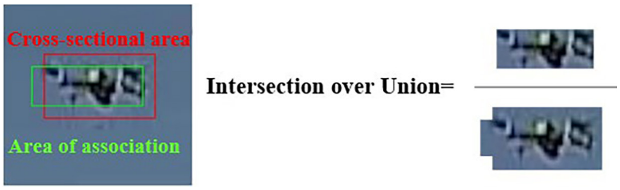


**Figure 6.** IoU calculation scheme

**Source:** compiled by the authors

This indicator determines how accurately the projected boundaries of an object coincide with the real ones. The mean average precision (MaP) was also performed, with results with an IoU value greater than 0.5 (50%) addressed. On the other hand, -ln(IoU) is used as a loss function for object detection tasks (Yu *et al.*, 2016). The final loss function was calculated as the sum of the loss functions for classification and regression (8):

$$L_{end} = L_{classification} - \ln(IoU). \quad (8)$$

While training the object classification and detection model in this study, four types of drones (Parrot A.R. Drone 2.0; DJI Inspire I; DJI Mavic 2 Pro; and DJI Phantom 4 Pro), on eight locations (street, trees, grass, mountain lake, palace, winter town, and temple), were used to train the classification part of the model. At the same time, the marked rectangle coordinates were used to train the regression part of the model, which predicts the exact location of the drones in the image. Furthermore, for training the models, the NVIDIA L4 GPU was used through Google Collab. One of the advantages of using Google Collab was the availability of a configurable development environment and pre-installed TensorFlow version 2.15. More detailed characteristics of the medium used are given in Table 1.

**Table 1.** Characteristics of the environment used in Google Collab

| Characteristic | Value |
|---|---|
| Number of virtual CPUs | 16 |
| GPU | NVIDIA L4 |
| RAM | 64 Gb |
| GPU memory | 24 GB GDDR6 |
| SSD drive | 375 GB |

**Source:** compiled by the authors

The batch size was set to 160 when training the MobileNetV3_Large_ImageNet and MobileNetV3_Small_ImageNet models. To optimise the parameters, the Adam algorithm was used as one of the most efficient for training neural networks. The learning rate parameter of the Adam optimizator was set to 0.048 during MobileNetV3_Large_ImageNet model traning and 0.024 for MobileNetV3_Small_ImageNet. These parameters were carefully selected to ensure optimal learning computation speed. Using appropriate values of the package, optimiser and training speed helped to ensure the stability of the training process and improve the quality of the resulting models. The image size was set at 640×640 pixels, ensuring a balance between detection quality and processing speed. Other hyperparameters were left by default (Bhargavi, 2021; Rui *et al.*, 2021).

During the training of the models, their state was saved at each epoch for further analysis of their performance. The so-called COCO metrics were used to evaluate the model, in particular, the mean average precision for a threshold value of the interaction over union of 50% (MaP@[IoU=50%]) (Wood & Chollet, 2022). The comparison of the MaP@[IoU=50%] level was carried out at different points using the weights of the models saved at different stages of training. The graphs in Figure 7 show the loss functions as a function of the training epoch for both models under study.

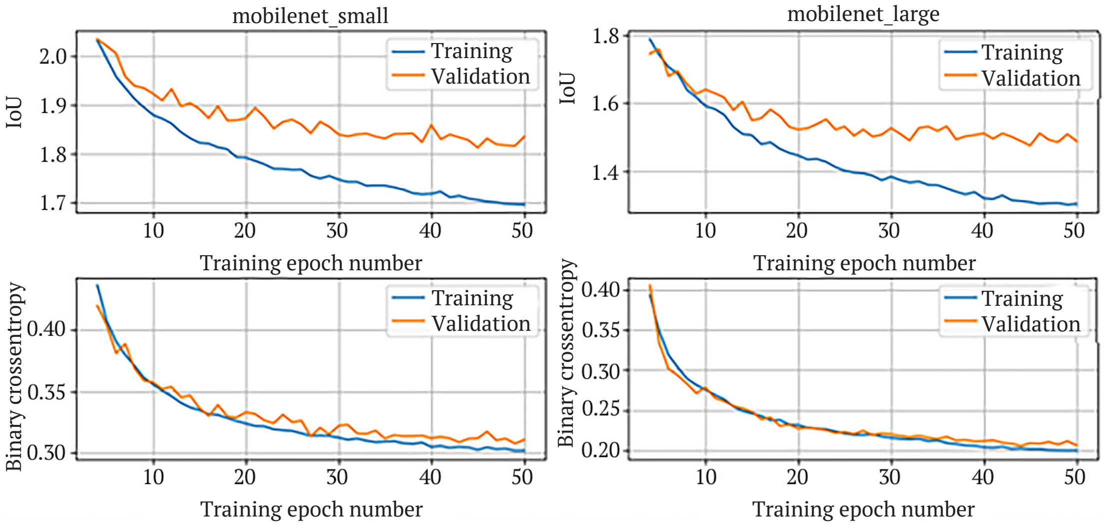


**Figure 7.** Loss functions for models with increasing number of epochs
**Source:** compiled by the authors

When determining the effectiveness of a model, it is necessary to address the difference between its training and validation performance. A graphical representation of this difference indicates that validation results may be shelved even though training performance may be improving. Figure 8, in turn, shows the dependence of the MaP@[IoU=50%] metric estimated on the validation dataset on the training epoch.

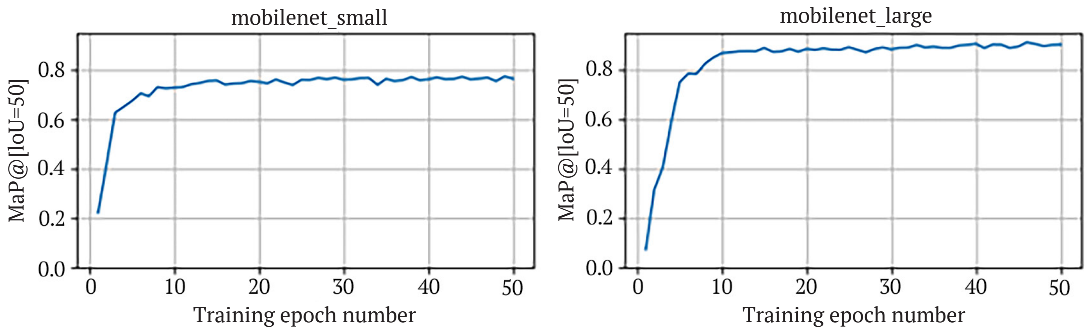


**Figure 8.** The dependence of MaP@[IoU=50%] estimated on the validation dataset on the number of training epochs
**Source:** compiled by the authors

As can be seen from the graphs in Figure 8, the accuracy of the MobileNetV3_Large model is higher. Noting these results, it should be noted that this may be the result of the greater complexity of the model itself. This can include more parameters or a more complex architecture, allowing it to better adapt to different types of data and conditions. Table 3 shows the values of the metrics evaluated on the test dataset for the models with the highest validation score of MaP@[IoU=50%]. The results of object classification on the test dataset are shown in Figure 9.

**Table 3.** Metrics for the models under study

| Metric | MobileNetV3_Small | MobileNetV3_Large |
|---|---|---|
| Binary cross entropy | 0.308 | 0.216 |
| -ln(IoU) | 1.818 | 1.529 |
| MaP@[IoU=50%] | 0.747 | 0.909 |

**Source:** compiled by the authors


**Figure 9.** Results of correct object classification using the trained model
**Source:** compiled by the authors

Several key technologies that have a significant impact on its functionality and efficiency should be considered when analysing the MobileNetV3_Large model in detail. One such technology is the mixed-depthwise convolution blocks technique, which reduces the number of computational operations and parameters while maintaining high accuracy. In addition, MobileNetV3_Large uses optimisation mechanisms such as linear bottlenecks and squeeze-and-excitation to reduce computational costs and improve model accuracy by focusing on important areas of the image. It's also worth noting the use of the Mish-activated function, which negates problems with vanishing and vanishing gradients.

Thus, the pre-training on ImageNet provided a basic understanding of the original features and common patterns in the images, but the combination of this pre-training with MobileNetV3 technologies allowed the model to show higher performance in object classification.

## DISCUSSION

Scientific research in the development and application of neural networks for image and video processing is of great importance in the rapidly evolving and advancing world of technology. Such research can open broad prospects for solving various problems in the field of computer vision. Neural networks can make significant progress in object detection, image classification, and the analysis and processing of large amounts of video data. They are an important tool that can help increase automation and efficiency in many industries. As the market for unmanned technologies such as UAVs is rapidly developing, the use of neural networks can enable their detection in images and video with high accuracy and speed, which is becoming a key factor in ensuring safety and effective airspace management. Efficient algorithms and models developed based on neural networks can be a key element in security systems, as well as in commercial applications where unmanned vehicles can be used for surveillance, research and transport needs (Zarichuk, 2023).

It is important to note that the development and application of neural networks for detecting and classifying unmanned aerial vehicles requires an individual approach to each case. Each type of drone may have its unique characteristics, such as size, shape, speed and movement patterns, which require the use of appropriate technologies to detect and identify them. This individual approach will allow for the most efficient use of resources and ensure adaptation to various usage scenarios. Given the wide range of factors that influence the detection and classification of UAVs, it is important to pay sufficient attention to creating more accurate, fast and reliable systems to ensure effective airspace management.

The results of this study show the significant potential of using the YOLOv8 and MobileNetV3 algorithms in the detection of commercial unmanned aerial vehicles in various types of images. This was confirmed by the MaP@[IoU=50%] value of 0.909 for the MobileNetV3_Large model. This demonstrates the high efficiency and accuracy of this algorithm in recognising aircraft under different conditions and in different types of images. At the same time, for the MobileNetV3_Small model, this indicator reached 0.747, which also indicates the possibility of its use in this area, given its features. The achieved aircraft detection and classification rates are high and demonstrate great potential in the application of these models for solving airspace surveillance and security tasks. YOLOv8 along with MobileNetV3 can be used to build comprehensive detection systems that provide reliable and fast real-time object recognition.

S.V. Viraktamath *et al.* (2021) also analysed the impact of various parameters of neural networks on their accuracy and efficiency in object recognition, showing that the correct selection of parameters can significantly improve model performance. A.M. Ghoreyshi *et al.* (2020) improved algorithmic approaches to processing large amounts of data, which has increased the speed of video data processing and improved the accuracy of object detection. However, it is worth noting that this study has solved some problems that remained unaddressed in the above-mentioned works. In particular, the use of YOLOv8 and MobileNetV3 has made it possible to achieve significant improvements in the accuracy of object detection and display, which is a significant achievement. In addition, this study focused on the specific tasks of detecting unmanned aerial vehicles, which allowed for a deeper understanding of their specifics and needs.

When analysing the results, it is important to note the binary cross-entropy index, which for the MobileNetV3_Large model was 0.216. This indicator indicates low training losses and high efficiency of the model in solving classification tasks. This makes the MobileNetV3_Large model perfect for image processing and object detection tasks. The value of this indicator for the MobileNetV3_Small model, which was 0.308, is also an important result. This indicator indicates lower efficiency and accuracy of the MobileNetV3_Small model compared to MobileNetV3_Large in classification tasks. Thus, the analysis of this indicator can conclude the efficiency and potential of each model in the context of solving specific image processing tasks. O.S. Bubryak & K.R. Potapova (2023) also conducted similar analyses and studies in the field of image processing, identifying and confirming the high efficiency of using neural network algorithms in object detection and classification. At the same time, the study by S. Thakur *et al.* (2021) examined various aspects of using machine learning for image analysis and processing, which is also important for the development of this field. It should be noted that these works could complement the present study, contributing to a more complete understanding of the possibilities and limitations of using neural networks in the field of image processing and object classification.

The results also demonstrated the -ln(IoU) values for MobileNetV3_Small and MobileNetV3_Large models, which reflects their accuracy in detecting and localising objects in images. The -ln(IoU) values for these models were 1.818 and 1.529, respectively. This confirms the high accuracy and efficiency of both models in solving object detection tasks. A high IoU score (which is equal to low -ln(IoU) score) indicates that the models correctly determine the size and position of objects in the image, making them very useful for applications that require accurate object localisation. N.N. Hasibuan *et al.* (2021) determined that optimising some algorithms and parameters of the YOLOv8 and MobileNetV3 models can increase the speed of image and video processing, which is a significant achievement in this area. M.Ş. Gündüz & G. Işık (2023) also added to the knowledge of the model's response to different types of images, revealing support for a wide range of image formats and sizes without significant performance loss. At the same time, W. Liu *et al.* (2022) brought new information on the impact of weather conditions and other factors on the performance of models of this series in different operating conditions, which expands the understanding of its operating limits and features. All the above research contributes to a deeper and more complete understanding of the capabilities and limitations of the YOLOv8 and MobileNetV3 models in real-world applications, ensuring their high suitability for a wide range of uses in a variety of environments.

Thus, such research using machine learning and computer vision algorithms is of great importance in the overall technological landscape. They can be used to develop and design more accurate and efficient computer vision systems that can be used for object detection, pattern recognition, motion tracking, and other tasks. The rapid development of unmanned aerial vehicles, video surveillance and monitoring systems requires continuous improvement in image and video processing techniques to ensure the highest level of safety and performance. Research in computer vision and machine learning addresses these challenges by developing new algorithms and models that can work in real-time and reliably detect objects even in difficult conditions, improving safety, efficiency and process automation in various fields of activity.

## CONCLUSIONS

The study results confirmed that the combination of YOLOv8 and MobileNetV3 algorithms has significant potential in detecting commercial unmanned aerial vehicles in images when working on a test dataset. Preliminary training of these algorithms on the ImageNet dataset, followed by refinement and training on the SimUAV dataset containing 29,568 images, achieving high accuracy in recognising and classifying UAVs of various types and sizes. The results of the study demonstrated that the MobileNetV3_Large model has better accuracy than the MobileNetV3_Small. After 50 iterations, the models achieved MaP@[IoU=50%] of 0.909 and 0.747, respectively, indicating the high efficiency and accuracy of this algorithm in detecting objects on the test data.

The study also showed that the value of the binary cross-entropy for the MobileNetV3_Large model is 0.216, confirming the low level of training losses and high efficiency of the model in solving classification tasks. Additionally, the study notes that the IoU for this model is 1.529, indicating its high accuracy in detecting and localising objects in images. Thus, the results obtained indicate the superiority of the MobileNetV3_Large model and confirm its potential in solving computer vision problems in the example of commercial UAV detection. It is worth noting that despite the high performance of the research results, it is important to consider the limited availability of the data used, which may limit the universality of the model. In addition, pre-training a model on publicly available datasets such as ImageNet can lead to the transfer of the limitations of these datasets to the resulting model, which can affect its versatility and accuracy in specific applications. All of this should be addressed in further research and consideration of applications of the model.

One of the areas for such research could be to expand the dataset for model training, which would enhance the model's ability to detect and classify various objects. It is also worth considering improving the preview and filtering algorithms that help avoid false positives and improve model accuracy. Such research will further improve such models and facilitate their application in real-world conditions.

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## CONFLICT OF INTEREST

None.

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**Руслан Єрмоленко**
Кандидат фізико-математичних наук, доцент
Київський національний університет імені Тараса Шевченка
01033, вул. Володимирська, 60, м. Київ, Україна
https://orcid.org/0009-0000-0854-4668

**Денис Клекоць**
Студент
Київський національний університет імені Тараса Шевченка
01033, вул. Володимирська, 60, м. Київ, Україна
https://orcid.org/0000-0002-4251-2958

**Ольга Гогота**
Кандидат фізико-математичних наук, науковий співробітник
Київський національний університет імені Тараса Шевченка
01033, вул. Володимирська, 60, м. Київ, Україна
https://orcid.org/0000-0003-4108-7256

# Розробка алгоритму виявлення комерційних безпілотних літальних апаратів за допомогою методів машинного навчання

**Анотація.** Дане дослідження було спрямоване на тренування алгоритмів виявлення комерційних безпілотних літальних апаратів з використанням методів машинного навчання. Під час дослідження для виявлення безпілотних літальних апаратів на зображеннях та відео були використані архітектури нейронних мереж YOLOv8 та MobileNetV3. Використовувані моделі були попередньо натреновані на датасеті ImageNet, а потім доопрацьовані на датасеті SimUAV, що містив зображення безпілотних апаратів чотирьох типів (Parrot A.R. Drone 2.0; DJI Inspire I; DJI Mavic 2 Pro; and Dji Phantom 4 Pro), різних розмірів та у восьми різних фонових локаціях. Результати даного дослідження підвердили, що поєднання архітектур YOLOv8 та MobileNetV3 має значний потенціал у виявленні комерційних безпілотних літальних апаратів на різних видах зображень. Навчені моделі продемонстрували високі показники в розпізнаванні та класифікації безпілотних літальних апаратів, досягаючи середньої точності виявлення (при пороговому значення IoU рівному 50%) на рівні 0,747 та 0,909, для моделей MobileNetV3_Small та MobileNetV3_Large, відповідно. Це свідчить про високу ефективність та точність моделей у виявленні об'єктів на тестових даних. Також результати дослідження включали в себе значення метрики бінарної перехресної ентропії, які склали відповідно 0,308 та 0,216, вказуючи на високу точність моделей у класифікації об'єктів, та підтверджуючи високу ефективність та надійність цих моделей в роботі з об'єктами на тестових даних. В ході дослідження модель MobileNetV3_Large показала більш точні результати порівняно з MobileNetV3_Small, що свідчить про її вищу ефективність у виявленні та класифікації літальних апаратів. Отримані результати підтверджують перспективність застосування методів машинного навчання в області систем моніторингу та безпеки, що дозволить надійно виявляти та відстежувати безпілотні літальні апарати в різних умовах. Високі показники натренерованих моделей свідчать про їх ефективність у реальних умовах експлуатації, що робить їх цінним інструментом для вирішення важливих завдань контролю та нагляду

**Ключові слова**: згорткова нейронна мережа; класифікація об'єктів; YOLOv8; MobileNetV3; комп'ютерний зір; бінарна перехресна ентропія

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**Vasyl Kravchenko***

PhD in Technical Sciences, Associate Professor
Uman National University of Horticulture
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0003-2334-0705

**Andrii Voitik**

PhD in Technical Sciences, Associate Professor
Uman National University of Horticulture
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0002-8196-3102

**Oleksandr Pushka**

PhD in Technical Sciences, Associate Professor
Uman National University of Horticulture
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0002-6481-8536

**Ivan Lisovyi**

PhD in Technical Sciences, Associate Professor
Uman National University of Horticulture
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0003-1480-1805

**Mykola Korobko**

PhD in Technical Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-2602-4225

# Modelling of the hydraulic scheme for loading the sowing sections of sowing machines for energy recovery

**Abstract.** One of the most promising areas for improving the energy efficiency of machines is the use of energy recovery from its source. The study aims to develop a basic hydraulic scheme of the clamping mechanism of the sowing section, which would allow to recovery of the energy of the oscillatory movement of the sowing section relative to the sowing frame. The paper considers the scheme of using hydraulic loading of sowing sections using a single-acting hydraulic cylinder. To collect the energy of the sowing section of the seeder, it is proposed to install a hydraulic motor in the existing hydraulic loading circuit to convert the hydraulic energy of the system into the mechanical energy of rotation of its output shaft and a system of check valves to redirect the working fluid in the system and ensure that the hydraulic motor shaft rotates in one specified direction. The input parameters of this system are unevenness of the soil, design features of the sowing section of the seeder, and forward speed of the seeder. The influence of the main parameters of the hydraulic cylinder,

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*Corresponding author

hydraulic accumulator and hydraulic motor of the system on the rotational speed and torque on the hydraulic motor shaft is investigated. The research shows that under certain external conditions, when modelling the system in the MATLAB Simulink software, the forced reciprocating motion of the hydraulic cylinder piston is converted into the rotational motion of the hydraulic motor output shaft, which, under certain system parameters under study, can rotate at a speed of 6-86 rpm, developing a theoretical torque of up to 22 N·m. The size of the hydraulic cylinder piston has the greatest influence on the output characteristics of the system. The hydraulic accumulator provides smoothing of pulsations, the magnitude of which, like the total pressure in the system, depends on the pressure of its pre-charging. The results of this study can be applied in agriculture to optimise energy use during the sowing process by developing efficient energy recovery systems for sowing machines, which will reduce fuel consumption and negative environmental impact

**Keywords**: seeder section, hydraulic cylinder, hydraulic accumulator, hydraulic motor, MATLAB Simulink

## INTRODUCTION

Energy vehicles with internal combustion engines that use fossil fuel energy are the main performers of all mechanised operations in the field when growing crops. Therefore, the main task of agricultural machinery developers is to improve the energy efficiency of these machines by reducing energy consumption during the performance of specified technological operations. There are many ways to improve the energy efficiency of agricultural machinery: improving the design of the working bodies of these machines, changing the operating modes of the working units, or changing the energy source from an internal combustion engine to electric drives powered by electrical energy from batteries, electrical networks, etc. A. Bonavolontà *et al.* (2019) believe that the use of energy recovery in machine operation is a very promising way to improve energy efficiency. Many researchers are working towards harnessing this energy recovery potential in various mechanisms and machines. One of the main conditions for such research is the presence of "free" kinetic or potential energy in machines and the ability to "capture" such energy. Agricultural machines also have the potential to generate renewable energy, which is mostly converted into heat and dissipated. For instance, in the case of precision seed drills with working bodies placed on separate movable sections, when the field surface is copied by individual sections, these sections move spontaneously up and down relative to the main frame of the seed drill, the energy of this movement is often lost in the clamping mechanisms of the sections and is spent on heating the springs of these loading systems.

The clamping mechanisms of the sectional working bodies of the seeders are designed to create additional pressure on the working bodies when performing operations related to penetration into the soil or cutting plant residues noted by A. Sharda *et al.* (2017) note. Springs are used to generate the downward force on the sowing section. Pneumatic or hydraulic cylinders are also used instead of springs to increase the range of clamping forces. The hydraulic pressurisation systems of the sowing sections of precision seed drills can be equipped with single or double-acting hydraulic cylinders as the main actuators. Double-acting hydraulic cylinders forcibly lower and raise the suction pressure or automatically change it depending on the soil conditions. S.S. Virk *et al.* (2021) note that the introduction of such regulations facilitates the introduction of precision farming systems, as they allow for automatic response to external changes in the system.

Similar to the processes of lifting and lowering the sowing sections of the seeders while tracing the soil surface is the movement of the vehicle suspensions, which has already been sufficiently studied in terms of energy recovery. As such, M.N.Awad *et al.* (2018) addressed hydropneumatic regenerative car suspension systems. This regenerative system contains a double-acting hydraulic cylinder, a hydraulic rectifier with a check valve system, two hydraulic accumulators in the high and low-pressure lines, an unregulated hydraulic motor designed to rotate the shaft of an electric generator, the energy from which is stored in the accumulator battery. The performance of the developed hydropneumatic scheme was compared with conventional mechanical suspension, and hydropneumatic suspension using a double-acting hydraulic cylinder and a single-acting one. The proposed suspension system allows for collecting up to 20% more energy than its counterparts, and it is concluded that the larger size of the hydraulic accumulator can significantly improve the stability of the hydraulic motor and, accordingly, the entire regenerative system (accumulators with a volume of 0.16, 0.35, 0.5 and 0.75 litres were studied).

The research into energy recovery systems is also being extended to material-handling machines such as excavators and telescopic handlers. The potential energy of the load and the actuator itself is converted into a source for energy recovery and storage when they are lowered. J. Li *et al.* (2020) found that a hydraulic cylinder designed to lift and lower loads becomes the main actuator in energy recovery. The working system can also include a hydraulic accumulator when energy is stored in the form of compressed gas, or a hydraulic motor. With the help of a hydraulic motor, through its output shaft, which can be connected to the input shaft of a generator, energy can be stored in the form of an electric current in batteries or, when the hydraulic motor shaft is connected to a flywheel, energy can be stored in the form of kinetic energy of a spinning mechanical drive.

Another example of energy production using hydraulic systems is given by Z. Fang *et al.* (2021), employing the principle of the up-and-down motion of a body floating on the water surface to convert the kinetic energy of a sea wave first into mechanical and then into electrical energy; the main actuators here are also double-acting hydraulic cylinders that create a directed flow of working fluid inside the hydraulic system, which also contains a check valve system, high and low-pressure hydraulic accumulators, and a hydraulic motor whose output shaft is connected to the shaft of the electrical energy generating plant.

Thus, there are many developments and studies of clamping systems for seeder sections, but they have not been investigated in terms of the possibility of recovering the energy of the lifting and lowering movement of the sections. Furthermore, the issue of obtaining regenerative energy from the reciprocating motion of hydraulic cylinders, which are actuators in-vehicle shock absorbers, lifting machines, etc. is sufficiently covered in the literature, but the obtained patterns need to be adapted and investigated for the operating conditions of a precision seeder.

This study aims to create a basic hydraulic scheme for the pressing mechanism of the sowing section of the seeder, which provides the possibility of using the energy arising from the vibrations of the sowing section compared to the seeder frame.

**Figure 1.** Hydraulic loading of the sowing section using a single-acting hydraulic cylinder RFX Hydraulic Planter Down Pressure System
**Source:** Precision Farming Dealer (2015)

The study of the proposed energy recovery system was carried out with the help of MATLAB Simulink software using the internal libraries of hydraulic and measuring equipment (Fig. 3).

The main actuating elements of this system were a hydraulic cylinder, the parameters of which determine the pressure and flow rate of the working fluid in the closed system of loading the sowing sections, a hydraulic accumulator that determines the rigidity of the system, and a hydraulic motor, through the output shaft of which energy was extracted from the system, the size of which can be estimated through its rotational speed and the torque generated, which represents the energy capacity of this system. A hydraulic accumulator is installed after the hydraulic

## MATERIALS AND METHODS

One of the simplest schemes of using hydraulic loading of sowing sections with the use of a single-acting hydraulic cylinder is considered. For example, such a scheme is proposed in the RFX Hydraulic Planter Down Pressure System by Dawn Equipment Company (USA), which aims to maintain a given pressure on the working bodies of the sowing section of the seeder (Fig. 1).

When using this scheme, the pressure on the sowing section is set according to the pressure gauge using a valve mechanism. The hydraulic accumulator acts as a shock-absorbing element, taking over the overloads that occur in the system due to the spontaneous movement of the sections up and down due to uneven field surfaces.

To collect the energy of the oscillatory movement of the sowing section of the seeder, it is proposed to install a hydraulic motor to convert the hydraulic energy of the section's movement into hydraulic energy in the existing hydraulic loading circuit, which contains a hydraulic cylinder as the main actuator for converting the mechanical energy of the section's movement into hydraulic energy, and a system of check valves to redirect the working fluid in the system and ensure the rotation of the hydraulic motor shaft in one given direction (Fig. 2).

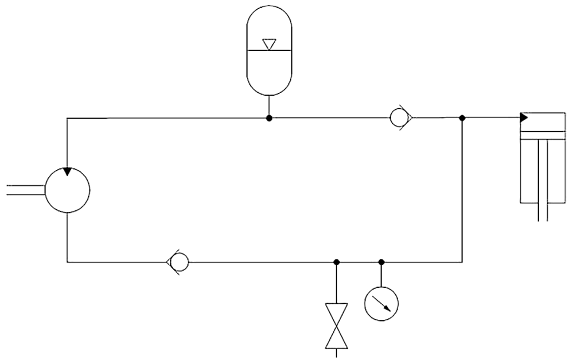

**Figure 2.** Schematic representation of the proposed system for energy recovery of the oscillatory movement of the sowing section of the seeder
**Source:** compiled by the authors

cylinder and before the hydraulic motor to smooth out the pulsations of the working fluid entering the hydraulic motor (Awad *et al.*, 2018).

The input parameters of this system were: soil irregularities, which in MATLAB are expressed as harmonic oscillations of the seeder section with a certain amplitude (responsible for the amount of change in the vertical component of the section position and the movement of the hydraulic cylinder piston (Fig. 4) ); design features of the sowing section of the seeder (a parallelogram suspension system for connecting the sowing section of the seeder to its frame was studied); the translational speed of the seeder as the main dynamic characteristic (an increase in the speed of movement leads to an increase in the supply of working fluid by the hydraulic cylinder rod) (Voitik *et al.*, 2021).

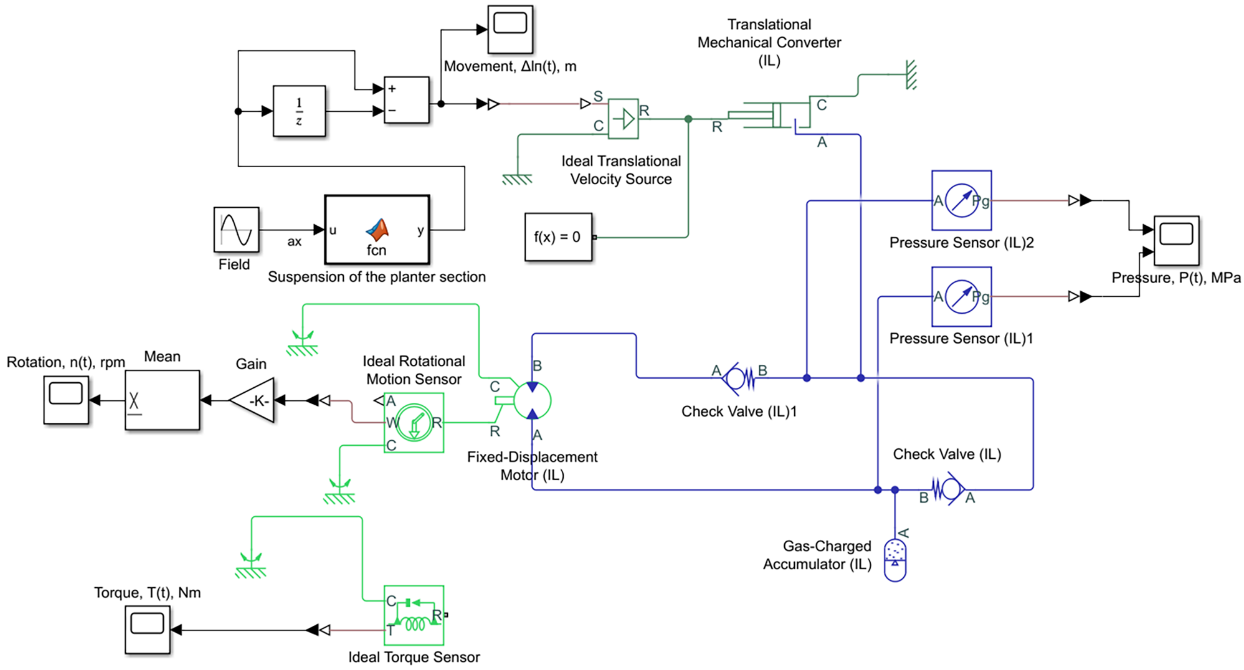


**Figure 3.** The model of energy generation from the movement of the sowing section of the seeder is compiled in the MATLAB Simulink program field

**Source:** compiled by the authors

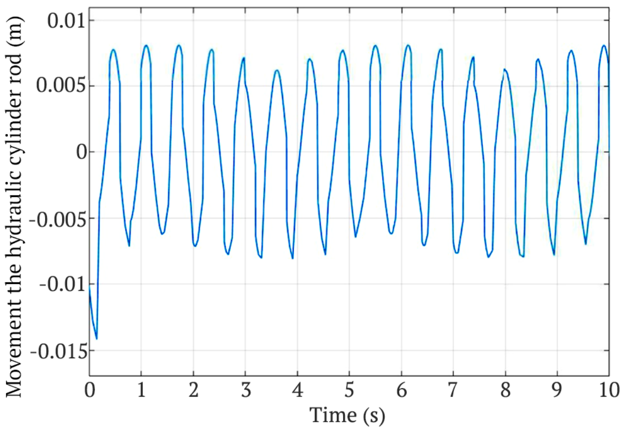


**Figure 4.** Movement of the hydraulic cylinder rod when the sowing machine is in motion

**Source:** compiled by the authors

The equation (Voitik *et al.*, 2021) was used to determine the amount of stroke of the hydraulic cylinder rod during the translational movement of the seeder within the parallelogram suspension of the sowing section:

$$\Delta l_n(\vartheta) = \sqrt{a^2 + b^2 + 2ab \cdot cos(0{,}5\pi - arcsin(\vartheta))}, \quad (1)$$

where $\Delta l_n$ – stroke length of the hydraulic cylinder rod of the parallelogram section suspension, m; $\vartheta$ – variable that determines the position of the working bodies relative to the central frame beam; $a$ – length of the short link of the suspension parallelogram, m; $b$ – length of the long link of the suspension parallelogram, m.

Next, the MATLAB Simulink internal block The Ideal Translational Velocity Source measured the velocity of the rod according to the formula:

$$\upsilon = \upsilon_R - \upsilon_C, \quad (2)$$

where $\upsilon_R$ and $\upsilon_C$ – absolute speeds at ports *R* and *C* respectively (Fig. 3).

This unit is an ideal velocity source that generates velocity in proportion to the input physical signal. A source is ideal in the sense that it is considered powerful enough to maintain a given speed regardless of the force acting on the system.

To represent the hydraulic cylinder, the Translational Mechanical Converter (IL) block was selected, which reflects the relationship between an isothermal fluid and a mechanical system, i.e. converts mechanical force into isothermal fluid pressure and vice versa. The hydraulic cylinder in this recovery system worked as a pump, acting as a converter of mechanical energy of the sowing section movement into hydraulic energy of the working fluid flow.

$$Q(t) = S \cdot h(t), \quad (3)$$

where $Q(t)$ – hydraulic cylinder supply of the hydraulic fluid, m³/c; $S$ – piston surface, m²; $h(t)$ – piston velocity, m/s. The main parameters of the hydraulic cylinder are the piston stroke, which depends on the unevenness of the field, and the piston diameter. Manufacturers of seed drills and sowing section pressing systems mainly use hydraulic cylinders with a piston diameter of 40-50 mm (Zhou *et al.*, 2023). Therefore, this size was used as a baseline for further research. To redirect the working fluid to the hydraulic motor inlet, the system is equipped with two Check Valves that allow the fluid to flow in only one direction. The locking elements of the valves started to open when there was a pressure difference of 0.5 bar in the working fluid, and the diameter of the passage hole of the selected valves was 11 mm.

When overcoming obstacles, the piston of the hydraulic cylinder must reciprocate relative to its body, while the compression movement will occur when the initial pressure set in the system is overcome, which provides the necessary downforce of the sowing section. Since the hydraulic system's working fluid is incompressible, the hydraulic accumulator plays the role of a shock absorber and volume compensator in this system. The main parameters for the study of the accumulator were its volume, which determines the amount of working fluid that it can accept to compensate for the movement of the hydraulic cylinder piston, and the precharge pressure in its gas part, which is recommended to be set at 60-90% (Dindorf *et al.*, 2023) of the set pressure in the hydraulic clamping system, but at the same time, the damping properties of the system depend on the precharge pressure of the accumulator: the greater the pre-charging pressure of the hydraulic accumulator, the stiffer the system.

The Gas-Charged Accumulator (IL) block simulates a gas-charged hydraulic accumulator in an isothermal fluid system. The battery contains a pre-charged gas chamber and a liquid chamber. The chambers are separated by a membrane. According to the description from the MATLAB Simulink library, the total volume of the hydraulic accumulator $V_T$ is divided by the membrane into a liquid chamber with a potential volume $V_L$ and a gas chamber with a potential volume $V_G$. The volume of liquid in the $V_C$ liquid chamber is always less than the total volume of the battery, so the gas volume is never zero:

$$V_L = V_T - V_G, \tag{4}$$

$$V_C = V_T - V_{dead}, \tag{5}$$

where $V_T$ – overall hydraulic accumulator volume, $V_L$ – volume of liquid in the hydraulic accumulator, $V_G$ – gas volume in the hydraulic accumulator, $V_C$ – capacity of the liquid chamber of the hydraulic accumulator ($V_T$ - $V_G$), $V_{dead}$ – the part of the gas chamber that remains filled with gas when the liquid chamber is full.

The contact pressure of the hard stop was modelled based on the specified stiffness and damping properties. The ratio of gas pressure and gas volume between the current state and the pre-charge state was polytropic, and the pressure was balanced on the membrane of the hydro accumulator:

$$P_G V_G^{ksh} = P_{pr} V_T^{ksh}, \tag{6}$$

where $P_G$ – gas pressure in the gas part of the accumulator, $P_{pr}$ – precharge pressure of the gas part of the accumulator (when there is no liquid in the liquid part of the accumulator), $k_{sh}$ – coefficient of specific heat capacity (assumed to be 1.4). Since the system considers only one sowing section with one hydraulic cylinder, a 1-litre hydraulic accumulator was used as the basis.

The actuating mechanism of the proposed system was an unregulated hydraulic motor, through the output shaft of which the hydraulic energy created by the hydraulic cylinder would be converted back into mechanical energy for further transformation. This element is represented by the Fixed-Displacement Motor (IL) block, which models an engine with a constant displacement. The main characteristic of a hydraulic motor is its displacement - the speed of rotation of its shaft and torque will depend on the displacement of the hydraulic motor (Zou *et al.*, 2017):

$$n = \frac{Q}{q}\eta_v, \tag{7}$$

$$T = \frac{\Delta P q}{2\pi}\eta_m, \tag{8}$$

where $n$ i $T$ – rotational speed and torque of the hydraulic motor output shaft, respectively; $q$ – engine displacement; $Q$ – the flow of working fluid passing through the hydraulic motor; $\Delta P$ – pressure drop between the inlet and outlet of the hydraulic motor; $\eta_V$ and $\eta_m$ – respectively, volumetric efficiency and mechanical efficiency of the hydraulic motor. According to J. Mi *et al.* (2017), a hydraulic motor with a displacement of 20 $cm^3$/rev was used as a basis. To measure the pressure upstream and downstream of the hydraulic accumulator, Pressure Sensor units with the settings to show gauge pressure were used. This block displays the physical pressure difference between the $P$ and $P_g$ sensor ports (Fig. 3). The main initial data for the study of the hydraulic model of energy recovery from the movement of the sowing section of the precision seeder in MATLAB Simulink are given in Table 1.

**Table 1.** Initial data for research

| No. | Parameter | Value |
|---|---|---|
| 1 | Length of the short link of the parallelogram, m | 0.2 |
| 2 | Length of the long link of the parallelogram, m | 0.4 |
| 3 | Driving speed of the sowing machine, m/s | 3 |
| 4 | Bump wavelength, m | 0.3 |
| 5 | Height of field irregularities, m | 0.02 |
| 7 | Hydraulic cylinder piston diameter, m | 0.04; 0.06; 0.08 |
| 8 | Hydraulic accumulator capacity, l | 1 |
| 9 | Initial charging pressure of the hydraulic accumulator, bar | 20; 30; 40 |

*Continued Table 1.*

| No. | Parameter | Value |
|---|---|---|
| 10 | Displacement of the hydraulic motor, cm³/rev | 10; 20; 30 |
| 11 | Nominal hydraulic motor pressure drop, MPa | 10 |
| 12 | Volumetric efficiency of the hydraulic motor | 0.92 |
| 13 | Mechanical efficiency of the hydraulic motor | 0.88 |
| 14 | Diameter of the valve bore, mm | 11 |

**Source:** compiled by the authors

To obtain the output parameters on the hydraulic motor shaft, the Ideal Rotational Motion Sensor and Ideal Torque Sensor blocks are used to measure the shaft rotation speed and torque, respectively. Both units operate in "ideal" conditions, without considering inertia, friction, energy losses, etc. The Ideal Rotational Motion Sensor unit measures the rotational speed in rad/s, so the Gain auxiliary unit is used to convert these revolutions to rpm, and the Mean unit is used to display the average values of the hydraulic motor shaft rotation on the oscilloscope display. During the research, these blocks were connected to the output shaft of the hydraulic motor in turn, separately from each other.

## RESULTS AND DISCUSSION

The main purpose of the proposed scheme for loading the sowing sections of precision seeders was to obtain energy from the spontaneous movement of these sections relative to the seeder frame on the output shaft of the hydraulic motor, which can be estimated by its rotational speed and the torque generated by it. Therefore, the influence of the main parameters of the system on the efficiency of the hydraulic motor, namely the parameters of the hydraulic cylinder, hydraulic accumulator and, directly, the hydraulic motor itself, was investigated.

When varying the size of the hydraulic cylinder piston, it should be borne in mind that the volume of working fluid it pushes out depends on the size of the piston stroke and its diameter, while at the same pressure, the size of the hydraulic cylinder piston diameter affects the pressing force of the sowing section, according to Pascal's law. That is, the larger the piston diameter, the lower the pressure in the system should be, and also, such a hydraulic cylinder as a pump can create a greater flow of working fluid for the same period, which was confirmed by the corresponding simulation graphs in MATLAB Simulink, which show the dependence of the rotation speed of the hydraulic motor output shaft on the size of the hydraulic cylinder piston diameter (Fig. 5a).

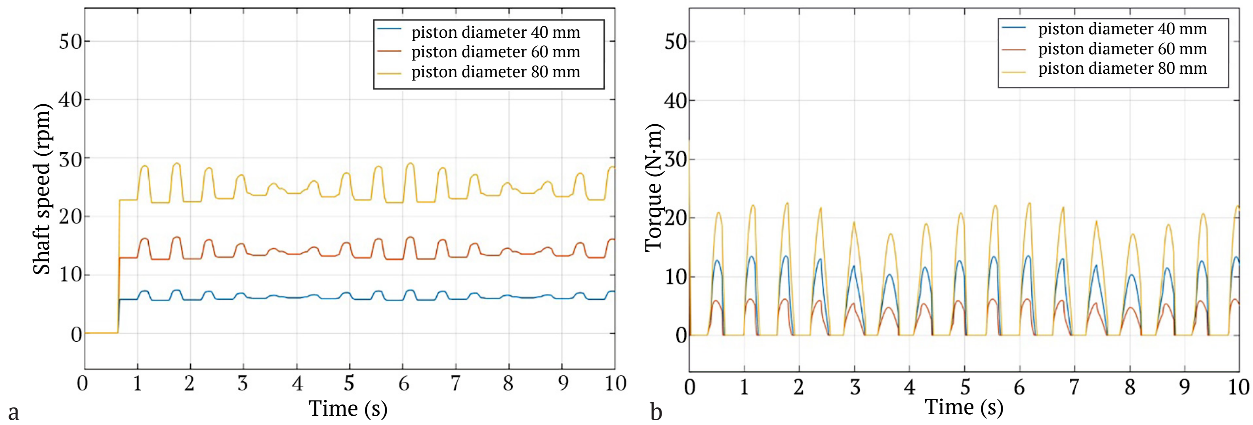


**Figure 5.** Rotational speed (a) and torque (b) on the shaft of the hydraulic motor of the clamping system
**Note:** with variable hydraulic cylinder piston dimensions a constant hydraulic motor displacement of 30 cm³/rev and a precharge pressure of 30 bar
**Source:** compiled by the authors

As can be seen from the graph (Fig. 5a), the rotational speed of the hydraulic motor shaft was on average 8, 14 and 25 rpm with the corresponding hydraulic cylinder piston diameters of 40, 60 and 80 mm. The amount of torque on the hydraulic motor shaft (Fig. 5b) also increased with increasing hydraulic cylinder piston diameter: the peak values increased from 6 N · m at a hydraulic cylinder piston diameter of 40 mm to 12 N · m at a hydraulic cylinder piston diameter of 80 mm. During the research, the nominal pressure losses at the inlet and outlet of the hydraulic motor were assumed to be 10 MPa. Similar trends can be seen in the work of P. Zheng *et al.* (2019). When determining the optimal parameters of a hydroelectric regenerative vibration damping system in car suspension systems, the effect of the piston diameter of a hydraulic cylinder that perceived the main shock loads from road irregularities was investigated. In the experiments, when the piston diameter increased from 25 to 50 mm, the rotational speed of the hydraulic motor shaft increased from 300 to 1100 rpm, and the power increased from 10 to 220 watts. Thus, it is possible to conclude that the dimensions of the hydraulic cylinder piston are one of the decisive factors influencing the efficiency of the regenerative component of the proposed energy recovery system since the rotational speed of the hydraulic motor output shaft and its torque will determine the amount of energy that this system can generate.

To analyse the effect of the hydraulic accumulator parameters on the system operation, the study investigated how changing its precharge pressure affects the kinematic and dynamic parameters of the system, namely, smoothing the fluid pressure fluctuations after the hydraulic cylinder is supplied (Fig. 6) and directly on the rotational speed and torque on the hydraulic motor shaft (Fig. 7).

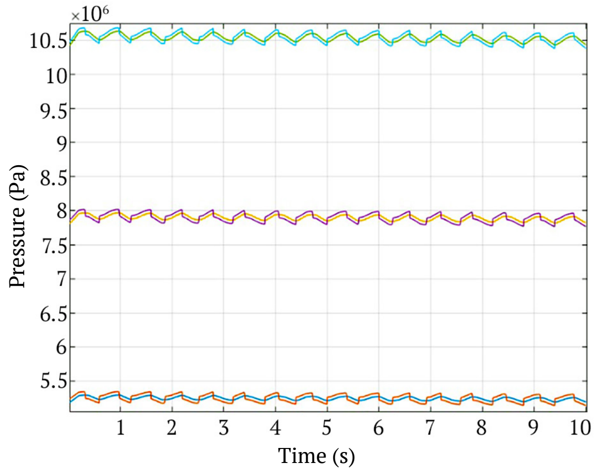


**Figure 6.** System pressure upstream and downstream of the accumulator at 20, 30 and 40 bar accumulator precharge pressure

**Note:** with a constant hydraulic motor displacement of 20 cm$^3$/rev and a hydraulic cylinder piston diameter of 60 mm

**Source:** compiled by the authors

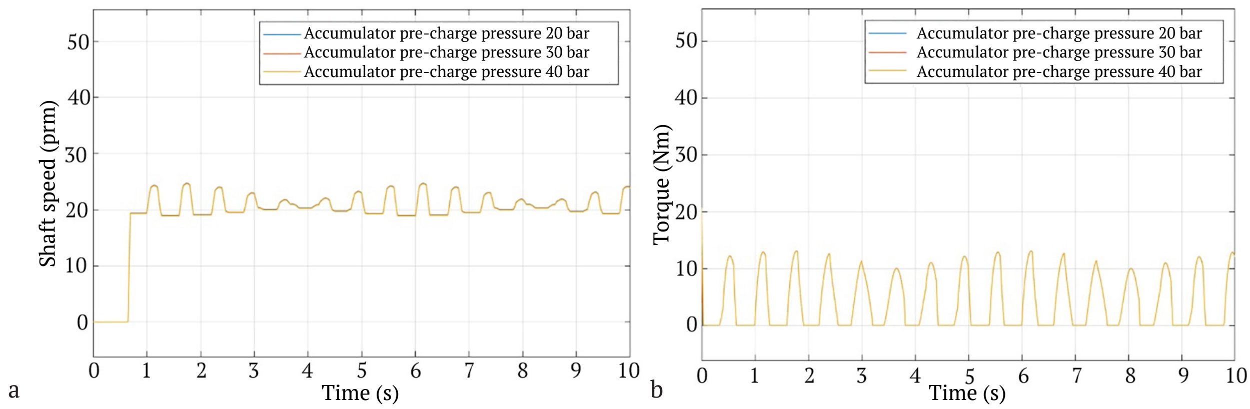


**Figure 7.** Rotational speed (a) and torque (b) on the shaft of the hydraulic motor of the clamping system

**Note:** at variable pre-charging pressure of the hydraulic accumulator and constant working volume of the hydraulic motor of 20 cm$^3$/rev and piston diameter of the hydraulic cylinder of 60 mm

**Source:** compiled by the authors

As can be seen from the graph (Fig. 6) the hydraulic accumulator acts as a pulsation smoothing device, reducing the peak fluctuations that occur when the hydraulic cylinder rod moves. This ensures more stable operation of the hydraulic motor and more even rotation of its output shaft. The lower the pre-charging pressure of the accumulator, the lower the pulsation amplitude after the accumulator. But it is also worth noting that the pre-charging pressure of the hydraulic accumulator directly affects the overall pressure of the loading system: when the pre-charging pressure of the hydraulic accumulator was doubled from 20 to 40 bar, the pressure in the clamping system also increased from 5.3 to 10.6 MPa. This factor must be addressed when designing the regeneration system, as it directly affects the downward force on the working members of the seed drill section.

After analysing the graphs (Fig. 7), it is possible to conclude that the value of the pre-charging pressure of the hydraulic accumulator, in our case, does not affect such parameters of the hydraulic motor as the speed of rotation of its output shaft and the torque on it. Similar conclusions about the role of a hydro accumulator in a regenerative system were made by P. Zheng *et al.* (2019), who traced the effect of changing the volume of the hydraulic accumulator on the kinematic and energy parameters of the hydraulic motor output shaft in such a system. They noted that changing the parameters of the hydraulic accumulator has the least impact on the average speed of rotation of the hydraulic motor shaft and its torque, although in their studies, increasing the volume of the hydraulic accumulator from 0.63 to 1 litre led to a decrease in the speed of rotation of the hydraulic motor shaft within 30 rpm and a decrease in power within 50 W, under the conditions of their experiments. The output shaft speed of the hydraulic motor is directly proportional to the flow rate of the working fluid and inversely proportional to the working volume of the hydraulic motor. The amount of torque depends on the pressure drop between the inlet and outlet of the hydraulic motor and is directly proportional to the displacement of the hydraulic motor. These facts can be seen in the graphs (Fig. 8) when performing simulations in MATLAB Simulink with changes in hydraulic motor parameters.

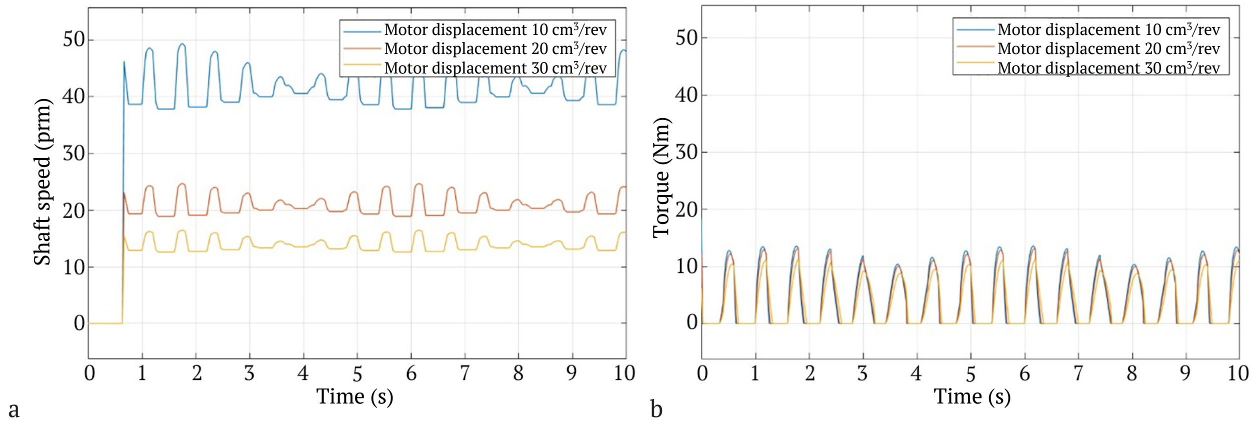


**Figure 8.** Rotational speed (a) and torque (b) on the shaft of the hydraulic motor of the clamping system
**Note:** when its working volume changes the precharge pressure of the hydraulic accumulator is constant at 30 bar and the piston diameter of the hydraulic cylinder is 60 mm
**Source:** compiled by the author based on research

Analysing the graph (Fig. 8a), it is possible to note that with a decrease in the working volume of the hydraulic motor from 30 to 10 $cm^3$/rev, the rotational speed of the hydraulic motor shaft increases at its peak values from 17 rpm to 42 rpm. A similar trend was observed by P. Zheng *et al.* (2019), in which a decrease in the working volume of the hydraulic motor from 8.94 to 5.77 $cm^3$/rev led to an increase in the speed of rotation of the hydraulic motor shaft from 600 to 1000 rpm. The effect on the torque (Fig. 8b) of the hydraulic motor displacement, in this case, is the opposite: with an increase in the hydraulic motor displacement, the torque increases from 11 to 13 Nm at its peak values. The difference is small, which can be explained by the fact that in MATLAB Simulink, in the hydraulic motor properties, the same nominal pressure drop was set for all three studies with different hydraulic motor displacements. The results obtained are in line with the studies conducted by J. Zou *et al.* (2017). When studying the regenerative vehicle suspension system, the researchers obtained clear results of the effect of the hydraulic motor displacement on the energy performance at its output shaft. By changing the working volume of the hydraulic motor from 8 to 12 $cm^3$/min in increments of 1 $cm^3$/rev, and taking into account the change in the speed of the hydraulic motor output shaft, they obtained a steady increase in power from 2200 to 5000 W on this shaft.

Recent studies have shown that the use of recuperation systems on various types of machines helps to improve their efficiency. For example, for machines with lifting mechanisms, the reduction in energy consumption due to the accumulation of electrical energy can range from 17% (Wang & Wang, 2013) to 54-58% (Minav *et al.*, 2012; Yu & Ahn, 2019). For systems with energy storage in the form of pressure up to 50-70% (Zhao *et al.*, 2017; Xia *et al.*, 2018). The use of flywheels reduces energy consumption for excavator operations by up to 44%-62% (Choi *et al.*, 2015; Li *et al.*, 2020).

The results of the research on modelling the energy generation from the oscillatory movement of the sowing section relative to the seeder frame, made in the MATLAB Simulink software, show that with predefined system parameters, it is viable and can implement the rotation of the hydraulic motor output shaft with a certain frequency and torque for further accumulation or use of the generated energy flow. Analysing the physical data obtained on Simulink oscilloscopes, it is possible to state that the actual values of rotational speed and torque have patterns similar to those obtained by other scientists in the study of car suspension systems. This can be explained by the similarity of the process, when an external disturbance causes the hydraulic cylinder to move, as well as the similarity of the equipment. However, in the studies, the values of the hydraulic motor shaft speed and power are higher than those obtained in this study. This difference can be explained by the fact that the vehicle's movement on the road has much higher speeds and, accordingly, higher dynamic characteristics compared to the movement of the seeder in the field, which contributes to a greater number of working strokes of the hydraulic cylinder rod, which is the basis of the shock absorber. In addition, all the reviewed works on energy recovery in car suspension systems use double-acting hydraulic cylinders, which makes linear movements of the hydraulic cylinder rod in both directions work. Thus, to optimize the performance of a hydroelectric regenerative vehicle suspension system, B. Gong *et al.* (2016) investigated the regenerative system of a hydraulic electromagnetic shock absorber for vehicles. The hydraulic part of this system includes a double-acting hydraulic cylinder, a hydraulic accumulator, and a system of check valves that direct the working fluid from both chambers of the cylinder to a nonreversible hydraulic motor, which directly rotates the shaft of the power generator.

## CONCLUSIONS

A basic hydraulic diagram of the clamping mechanism of the sowing section was developed, which would allow to recovery of the energy of the oscillatory movement of the sowing section relative to the sowing frame, and its operation was modelled in the MATLAB Simulink program. The research shows that under certain external conditions, namely the magnitude of field irregularities, the speed of the seeder and the design parameters of the parallelogram mechanism of the sowing section, and the pre-accepted parameters of the main structural elements, namely the hydraulic cylinder, hydraulic accumulator and hydraulic motor, this system will be able to function. When the system was modelled in MATLAB Simulink, the forced reciprocating motion of the hydraulic cylinder piston was converted into the rotational motion of the hydraulic motor output shaft, which, with certain system parameters under study, can rotate at a speed of 6-86 rpm, developing a theoretical torque of up to 22 N·m. The size of the hydraulic cylinder piston has the greatest influence on the output characteristics of the system. The rotational speed of the hydraulic motor shaft was on average 8, 14 and 25 rpm at the corresponding hydraulic cylinder piston diameters of 40, 60 and 80 mm, and the torque value increased with increasing hydraulic cylinder piston diameter: from 6 N·m with a hydraulic cylinder piston diameter of 40 mm to 12 N·m with a hydraulic cylinder piston diameter of 80 mm. However, the design parameters of the hydraulic cylinder require additional justification, as it is also the main actuating element of the pressing system of the sowing section of the seeder. The hydraulic accumulator provides pulsation smoothing, the magnitude of which, like the total system pressure, depends on the precharge pressure of the hydraulic accumulator. However, the precharge pressure of the accumulator directly affects the total pressure in the system; when the precharge pressure of the accumulator was doubled from 20 to 40 bar, the pressure in the clamping system also increased from 5.3 to 10.6 MPa. The parameters of the hydraulic motor require additional research in terms of working with a certain number of sowing sections of the seeder because the research was carried out with only one sowing section. The study determined that reducing the hydraulic motor's displacement from 30 to 10 cm $^3$/rev leads to an increase in the motor shaft speed from 17 rpm to 42 rpm, while the effect on its torque is inversely related to this parameter: as the displacement of the hydraulic motor increases, torque increases from 11 to 13 Nm. The system of further conversion, storage and use of recovered energy also requires separate research.

## ACKNOWLEDGEMENTS

None.

## CONFLICT OF INTEREST

None.

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**Василь Кравченко**
Кандидат технічних наук, доцент
Уманський національний університет садівництва
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0003-2334-0705
**Андрій Войтік**
Кандидат технічних наук, доцент
Уманський національний університет садівництва
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0002-8196-3102
**Олександр Пушка**
Кандидат технічних наук, доцент
Уманський національний університет садівництва
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0002-6481-8536
**Іван Лісовий**
Кандидат технічних наук, доцент
Уманський національний університет садівництва
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0003-1480-1805
**Микола Коробко**
Кандидат технічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-2602-4225

# Моделювання гідравлічної схеми довантаження висівних секцій посівних машин з метою рекуперації енергії

**Анотація.** Одним з перспективних напрямків підвищення енергоефективності машин є застосування рекуперації енергії створеної її джерелом. Метою даної роботи є розробка принципової гідравлічної схеми притискного механізму секції сівалки, яка б давала можливість рекуперувати енергію коливального руху висівної секції відносно рами сівалки. В роботі розглянуто схему використання гідравлічного довантаження висівних секцій з використанням гідроциліндра односторонньої дії. Для збирання енергії руху висівної секції сівалки пропонується в існуючу гідравлічну довантажувальну схему, встановити гідравлічний мотор для перетворення гідравлічної енергії системи в механічну енергію обертання його вихідного валу та систему зворотних клапанів для перенаправлення робочої рідини в системі і забезпечення обертання валу гідравлічного мотору в одному заданому напрямку. Вхідними параметрами даної системи є: нерівності ґрунту, конструктивні особливості висівної секції сівалки, поступальна швидкість руху сівалки. Досліджено вплив основних параметрів гідроциліндра, гідроакумулятора та гідромотора системи на швидкість обертання та крутний момент на валу гідравлічного мотору. Проведені дослідження показують, що за певних зовнішніх умов, при моделюванні системи в полі програми MATLAB Simulink примусовий зворотно-поступальний рух поршня гідроциліндра перетворився в обертальний рух вихідного валу гідромотора, який при певних досліджуваних параметрах системи може обертатися зі швидкістю в межах 6-86 об/хв, розвиваючи теоретичний крутний момент до 22 Н·м. Найбільший вплив на вихідні характеристики системи має розмір поршня гідроциліндра. Гідроакумулятор забезпечує згладжування пульсацій, величина яких, як і загальний тиск в системі, залежить від тиску його попереднього зарядження. Результати цього дослідження можуть бути застосовані в сільському господарстві для оптимізації використання енергії в процесі сівби через розробку ефективних систем рекуперації енергії висівних машин, що дозволить зменшити споживання палива та негативний вплив на навколишнє середовище

**Ключові слова**: секція сівалки; гідроциліндр; гідроакумулятор; гідромотор; MATLAB Simulink

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**Makhavat Dzhusupova***
PhD in Technical Sciences, Associate Professor
Kyrgyz State Technical University named after I. Razzakov
72004, 66 Ch. Aitmatov Ave., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0004-1453-1942

**Saule Kulshikova**
PhD in Technical Sciences, Head of the Department of Technological Machines and Construction
Zhezkazgan University named after O. Baikonurov
100600, 1B Alashakhan Ave., Zhezkazgan, Republic of Kazakhstan
https://orcid.org/0000-0001-5412-8454

**Aidai Talantbek kyzy**
Postgraduate Student, Lecturer
Kyrgyz State Technical University named after I. Razzakov
72004, 66 Ch. Aitmatov Ave., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0009-9461-7426

**Gulnaz Baimenova**
PhD in Technical Sciences, Senior Lecturer
Zhezkazgan University named after O. Baikonurov
100600, 1B Alashakhan Ave., Zhezkazgan, Republic of Kazakhstan
https://orcid.org/0009-0008-5095-9750

**Abdulkalyam Ospanov**
PhD in Technical Sciences, Associate Professor
Zhezkazgan University named after O. Baikonurov
100600, 1B Alashakhan Ave., Zhezkazgan, Republic of Kazakhstan
https://orcid.org/0009-0006-1224-4223

# Utilisation of industrial waste in heat and power industry

**Abstract.** The study aims to address the physical properties and chemical composition of ash and slag waste from a thermal power plant to determine the possibility of its reuse in the heat and power industry. This included classification and chemical analysis of ash and slag waste generated by the Bishkek thermal power plant to determine its composition. The received material samples were also subjected to laboratory tests to determine the particle size distribution and moisture content. Once the fractionation boundaries were established, a detailed study of the ash mass was carried out, including carbon distribution analysis and flotation experiments to determine effective methods of carbon recovery from ash and slag waste. The results confirmed the significant potential of ash and slag waste from the Bishkek coal-fired thermal power plant for reuse in the heat and power industry. Analysis of the chemical components revealed the content of unburned coal particles within 10-11%, and the content of water-soluble sulphur and sulphuric acid compounds ranged from 0.18% to 0.71%. Experimental data confirmed the importance of the fractionation of ash and slag by particle size, which makes it possible to further separate coal fractions with different physical properties. The

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*Corresponding author

fraction of less than 150 microns is characterised by a low carbon content (less than 2.5%), which makes it suitable for use in construction as a fine aggregate. However, the study noted that fractions larger than 150 microns, and especially those larger than 300 microns, are a valuable feedstock for the production of carbon concentrate with a carbon content of more than 75%, which opens up the prospects for its use in the production of water-coal fuel. Thus, the results of the study confirm the potential of ash and slag waste for reuse in the heat and power industry. This can help to reduce waste, reduce the negative impact on the environment, and create efficient and sustainable production processes in the heat and power industry

**Keywords**: ash and slag waste; flotation; coal particles; carbon concentrate; water-coal slurry; fuel processing

## INTRODUCTION

In major cities and towns of Kyrgyzstan, the main suppliers of heat and electricity are combined heat and power plants and boiler houses, which are fuelled by solid fuels. This results in the use of a significant amount of coal, contributing to the release of a significant amount of ash into the atmosphere and its storage in ash dumps. Such ash dumps are becoming a serious problem, occupying large areas of fertile land and having a negative impact on the environment. The environmental impacts of using coal for energy production also impose significant financial costs for environmental remediation and protection. Each tonne of coal used causes significant environmental damage, which leads to huge economic losses. Therefore, issues related to efficient energy management and reduction of negative environmental impact are becoming increasingly important for Kyrgyzstan.

The development of alternative energy sources and the introduction of more efficient technologies for the utilisation of industrial waste, such as ash and slag, can help mitigate this impact and make the energy sector more sustainable and environmentally friendly. Ash and slag waste can become a valuable resource if the right approaches to its disposal are used (Lyubchyk *et al.*, 2015). The integration of innovative methods of using this waste is possible in various industries, including construction, agriculture and others. However, it may be more promising to recycle and reuse them in the thermal power industry, which could make it possible to use ash and slag waste efficiently and reduce dependence on traditional energy sources, while reducing the negative impact on the environment (Orfanova, 2023).

To combat the negative effects of coal use in the energy sector, a detailed study of their composition and properties is essential. M.A. Khoshimkhanova *et al.* (2022) employed a chemical analysis method to determine the composition of ash and slag waste, which confirmed its potential as a valuable product in various industries. Z. Xue *et al.* (2022) also studied ash and slag and revealed that they can be used in the production of environmentally friendly fuels with a high degree of efficiency. O. Svietkina *et al.* (2021), in turn, highlighted that optimising waste management processes, such as ash and slag, can significantly reduce waste volumes and make the production of certain materials more cost-effective. Nevertheless, further research is required to develop technologies and methods for their utilisation, as well as to create an infrastructure for their processing and industrial application, to fully transition to the use of ash and slag waste as raw materials or fuel.

One of the key factors influencing the successful utilisation of ash and slag waste is the development of innovative technologies aimed at turning it into high-quality materials. L. Ren *et al.* (2023) demonstrated that specialised ash and slag treatment methods can produce materials with properties such as increased carbon content, which can be used in the thermal power industry. E. Liu *et al.* (2020) also confirmed the potential of ash and slag to create environmentally friendly and efficient fuels, such as water-coal fuel. However, W. Yu *et al.* (2022) state that the development of more efficient methods of waste treatment and purification is necessary to minimise the content of harmful impurities and ensure high quality of the final product. This, in turn, emphasises the importance of continuous scientific and technological development in the field of industrial waste management and the creation of innovative approaches to its processing.

The development of effective methods for controlling the quality and safety of products made from slag waste. S. Yan *et al.* (2023) addressed the environmental impact of various slag treatment processes and determined that certain processing methods can reduce emissions and improve environmental safety. J. Zhang *et al.* (2023) assessed the environmental safety of slag use in the heat and power industry and confirmed the environmental friendliness of products obtained from ash and slag processing. L. Cuicui *et al.* (2024) identified the need to improve the technologies for treating such waste to increase its popularity and applicability in the heat and power industry. Despite the progress in the study of ash and slag waste, it is necessary to study more deeply the issues related to the long-term perspective of products derived from ash and slag waste. It is also necessary to investigate the possible negative impact of these products on the environment and human health, which will allow for a more complete assessment of the environmental sustainability of such projects.

The study aims to determine the optimal methods of treatment and use of ash and slag waste from a thermal power plant, using the example of the Bishkek Thermal Power Plant (TPP), to identify the potential for its use as an important product in the production of water-coal fuel. The main objectives of the study are to analyse the chemical composition and physical properties of ash materials, determine the optimal methods of waste treatment and purification, and explore the possibilities of reusing the products in production processes.

## MATERIALS AND METHODS

The detailed study of ash and slag waste generated by thermal power plants began with a process of classification and chemical analysis to determine its composition. The fuel slag was obtained as a result of coal combustion in a pulverised form, after which its chemical composition and properties were studied. The ash and slag waste and ash from the hydraulic ash removal process were also subjected to chemical analysis and detailed study of properties and characteristics.

To study the possibility of producing coal fuel from ash and slag waste, areas were identified on the territory of the Bishkek CHP plant where a significant amount of slag crushed stone and ash mass with a minimum slag content was concentrated. Material samples were taken to a depth of 1.7 m using a hand-held drill to minimise the impact of external factors and preserve material integrity. Then, the obtained samples of ash and slag crushed stone were subjected to laboratory tests to determine the particle size distribution and moisture content. The particle size distribution was determined by sorting the particles by size, and the moisture content was measured to assess the degree of dryness of the material.

After laboratory tests, the particle size distribution limits were established. Fractions with sizes less than 300 μm were classified as "ash", fractions from 300 μm to 1 mm as "slag sand", and fractions larger than 1 mm as "slag". Hence, the data obtained was systematised and classified for further analysis and use in the study. For a more detailed study of the ash mass, samples with a high ash content were prepared. After that, a series of experiments was conducted to determine the main characteristics of the ash mass, which included detailed fractionation of ash with the definition of the boundaries of separation into fractions.

The process of studying the carbon distribution in different ash fractions included a preliminary dehydration step at 375°C to remove moisture and other volatile components from the samples that could affect the final results. This procedure was followed by an experiment in which the samples were subjected to pyrolysis at temperatures up to 900°C. During the pyrolysis, substances were lost, including carbon components, which made it possible to estimate the carbon content of the ash. Subsequent analysis of the data was used to determine specific values of carbon content in different ash fractions and to analyse its distribution depending on different sample processing conditions.

For a more thorough analysis of the efficiency of flotation methods of carbon extraction from ash and slag waste, a series of experiments were also conducted on a flotation machine using mechanical frothing. This involved the use of various chemicals including paraffin as a collector, rare glass as a mineral particle depressor, and a variety of synthetic surfactants as foaming agents.

The flotation separation process was analysed for two main fractions of ash and slag waste – fine (less than 150 microns) and coarse (more than 300 microns). For the fine fraction, the main priority was to effectively remove carbon residues to reduce the carbon content to less than 2.5%, which is critical to ensure high-quality material for further use in industrial processes. At the same time, for the fraction larger than 300 microns, it was more important to achieve a carbon concentrate with the highest possible carbon content and minimum ash content, which significantly increases its value and applicability in the thermal power industry.

## RESULTS

In Central Asian countries, including Kyrgyzstan, the use of ash and slag waste is less than 4% of the total volume, reflecting insufficient attention to waste management and inefficient use of resources. Increasing the use of ash and slag waste can reduce the amount of waste produced by the industry and reduce the negative impact on the environment.

Ash and slag waste (ASW) is an important resource in various fields, including energy, construction and others. The composition of ash and slag waste, including the content of carbon and other substances, makes it a valuable source of energy when burned. Recycling processes for ASW can be optimised to increase the efficiency of their use and reduce harmful emissions into the atmosphere. Using ASW to process and produce important products that can be used as alternative fuels in thermal power plants can reduce the consumption of coal or gas, which helps to reduce greenhouse gas and other pollutant emissions (Guo *et al.*, 2020a; Lv *et al.*, 2023). They are also a valuable component in the production of cement and concrete, due to their positive impact on the structure and properties of materials. Ash and slag waste improves the strength, deformability, frost and chemical resistance of building structures by regulating the concentration of calcium hydroxide in the curing system.

After the process of selecting, incinerating and storing fuel waste, it is classified into three main types: fly ash (FA), ash and slag mixture (ASM) and fuel slag (FS). The hydraulic ash from the Bishkek Thermal Power Plant (TPP) with a moisture content of 40 to 50% is transported to special ash pits in a fine form using a pneumatic system. The combustion of coal produces fuel slag in a dust-like form, which is a compact and durable mass. Its composition is a mixture of particles ranging in size from 0.10 to 30 mm, with some inclusions of larger particles. This material can be considered a natural combination of fine and coarse aggregates. That is why slag produced by thermal power plants is effectively used as the main aggregate in both light and heavy concrete. They can also partially replace crushed stone in the amount of 20 to 50%.

The chemical analysis of the selected samples revealed that the content of $SiO_2$, $Al_2O_3$ and $FeO$+$Fe_2O_3$ in the mixture and the ash from the hydraulic removal is identical. However, the chemical composition of the fuel slag is distinguished by a particularly high FeO+$Fe_2O_3$ content of 5.02%, including 3.96% $Fe_2O_3$. This is possibly caused by the increased content of molten particles and the formation of fuel slag (Table 1).

**Table 1.** Chemical composition of ash and slag at Bishkek TPP, %

| Waste name | $SiO_2$ | Oxide | | | | | | | | | | Unspecified components |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Al_2O_3$ | $Fe_2O_3$ | FeO | CaO | MgO | $SO_3$ | MnO | $K_2O$ | $Na_2O$ | $TiO_2$ | |
| ASM | 52.09 | 20 | 1.44 | 0.79 | 5.74 | 0.74 | 0.71 | 0.02 | 1 | 0.5 | 0.92 | 15.3 |
| FA | 52 | 21.58 | 0.97 | 1.3 | 6.47 | 1.14 | 0.21 | 0.01 | 1.7 | 0.9 | 1.05 | 12.13 |
| FS | 54.95 | 20.56 | 1.06 | 3.96 | 7.67 | 2.22 | 0.18 | 0.1 | 1.2 | 2.4 | 0.88 | 4.07 |

**Source:** compiled by the authors

When studying the chemical composition of FA and ASM, it was found that they contain no free lime. The presence of CaO is due to the presence of calcite. The chemical composition of fly ash materials is also characterised by a high content of alumina ($Al_2O_3$), which has certain properties and prospects for use in various industries requiring materials with high resistance to thermal and chemical influences. The content of unburned coal particles (UCP) in the fuel waste was about 10-11%, while the content of water-soluble sulphur and sulphuric acid compounds, converted to $SO_3$, ranged from 0.18% to 0.71%. A detailed study of the properties of various components of ash and slag reveals significant differences that prevent their direct use without prior separation.

Regulatory requirements from various industries emphasise the importance of classifying and separating ash components. For instance, the construction industry limits the content of unburned carbon, and the iron and steel industry sets a minimum iron content in ores. These limitations make fly ash unsuitable for many purposes, leaving only limited use as a substitute for aggregates or for landscape amendments. ASW, which is classified as acidic ash, is initially devoid of binding properties. But when they are incorporated into a composite cement binder, an interesting transformation takes place: they begin to interact with calcium hydroxide, acquiring the property of pozzolanic activity already at normal temperatures. This transformation is due to the formation of various firing products in the ash, including clays containing amorphous substances such as metakaolinite and aluminosilicate compounds, as well as amorphous forms of $SiO_2$, $Fe_2O_3$ and $Al_2O_3$. These components exhibit different activities when interacting with calcium hydroxide (Cheah *et al.*, 2021). Metakaolinite is particularly active due to its large specific surface area, which leads to the formation of calcium hydrosilicates and hydrogenated calcium. At higher temperatures, kaolinite decomposes, producing silica and alumina with lower activity due to their sintering and crystallisation, which results in a decrease in their specific surface area. The ash also contains aluminosilicate phases, quartz and feldspars, which are inactive under normal temperature conditions but become more reactive with increasing temperature.

The increase in hydraulic activity of amorphous clay is associated with its high specific surface area, which results from the decomposition of metakaolin ($Al_2O_3x_2SiO_2$). This process converts metakaolin into amorphous silica ($SiO_2$) and alumina ($Al_2O_3$). The increase in the specific surface area is due to the enrichment of the material with microscopic cavities and irregularities on the surface of the particles, which in turn contributes to more intensive interaction with water and other components of the concrete mix (Hay & Celik, 2023). The percentage of soluble silicic acid in the ash ranges from 1.5% to 6%. This parameter has a significant impact on the chemical properties of ash and its ability to interact with other components in the creation of building materials. The amount of free alumina, in turn, varies from 0.2% to 2.7%. An important factor is that certain components of ash and slag may represent more valuable raw materials, provided they are extracted and meet quality standards. For example, ash that has been subjected to a carbon purification process can have a value many times higher than the value of the original ash and slag material. Similarly, magnetite powder ($Fe_3O_4$) derived from ash and slag can have even higher commercial value (Li *et al.*, 2021).

Unburned coal also deserves special attention, as it stands out for its potential for more efficient use against the backdrop of production waste from coal-fired power plants. This coal, which remains after the combustion process and often has a particle size of 50 to 300 microns, is a valuable resource that can be recycled and reused. The reasons for its formation are manifold and are related to the technical complexities of the combustion process, including rapid exit from the high-temperature zone and oxygen depletion. Given the trend towards pelletized coal, which requires more careful processing, unburnt coal continues to be a relevant solution in this area. The idea of recovering and reusing unburned coal from thermal power plant ash and slag is an innovative approach to waste management and the creation of additional resources (Nesterenko & Rosokhata, 2023). This process can be of both economic and environmental importance, given its potential for wide application in various industries. During the process of temperature exposure of coal particles during combustion, a complex chemical and physical transformation takes place. Under the influence of high temperatures, the pyrolysis process takes place, as a result of which volatile components such as sulphur oxides ($SO_x$), arsenic (As) and mercury (Hg) evaporate from the coal matrix and are removed to a gaseous state. This process is accompanied by chemical reactions of disintegration and decomposition, which result in the formation of simpler chemical compounds (Zeng *et al.*, 2020; Johansson *et al.*, 2021).

The remaining coal also undergoes physical changes. High temperatures promote the recrystallization and reorganisation of carbon molecules in the coal matrix. This can lead to more stable structures and reduced porosity of the material. Increased density and structural orderliness can affect the physical and chemical properties of the remaining coal, making it more stable and less susceptible to oxidation and decomposition. As a result, the residual coal has a changed chemical composition and structure. Reduced volatile content and improved structural properties make it cleaner and more stable in terms of its applicability in various production processes. When using fine carbon obtained from coal sludge or tailings from coal plants, the high content of volatile components must be considered, requiring specialised purification technologies. The fixation of coal in composites requires the selection of binders with high viscosity. Underburnt coal forming hybrid particles also presents a challenge for separation due to differences in density and structure of the components, which can lead to the separation of concentrate with higher carbon content (up to 60%) requiring additional treatment (Wang *et al.*, 2021).

Effective separation of unburned coal from thermal power plant ash requires a two-stage procedure using specialised processing and separation methods that provide partial separation between these stages. This approach will make it possible to efficiently extract conditioned coal from thermal power plant ash with minimal losses and maximum efficiency. Another serious technical problem that has a significant impact on the combustion processes in TPP boilers is the lack of volatile substances in coal particles present in coal ash. This aspect has a critical impact on the efficiency and stability of energy systems. Since coal particles do not contain volatile components, this slows down the ignition process. This is due to the absence of the formation of hot gas columns necessary to maintain stable combustion. Furthermore, such particles can act as a heat source when interacting with oxygen, tending to initiate and maintain combustion. Thus, the combustion process is less intensive and less stable, which can lead to uneven heat generation and reduced efficiency of the TPP boiler.

One solution to this problem is to add unburned coal to the main fuel of TPPs. This method involves adding a small percentage (about 10-20%) of unburned coal to the main fuel before it is burned in the boilers. This process can increase the calorific value and thermal efficiency of the fuel mixture, which can lead to more efficient use of energy when burned in boilers. This, in turn, can reduce fuel consumption and reduce the operating costs of thermal power plants. However, this method has its limitations and drawbacks. Unburned coal contains high levels of ash and sulphur, which can lead to flue gas pollution and the release of harmful substances into the environment. This creates the need for additional flue gas treatment systems and can increase operating costs for maintenance and waste disposal (Turgunov *et al.*, 2024). In addition, the addition of unburned coal only temporarily increases the efficiency of the combustion process in thermal power plants but does not eliminate the root causes, such as insufficient combustion temperature or improper air distribution in the boiler. This method can only be considered as a temporary solution that requires additional research and development of more effective methods to combat the problem of under-combustion (Wei *et al.*, 2023).

When studying the process of utilisation of unburned coal from thermal power plant ash and slag, products made from ultra-carbon coal are preferable, as they represent an ideal solution due to their characteristics. First, it does not require additional grinding of the feed sulphur for effective demineralisation, which saves time and resources. In addition, it is not critically sensitive to the volatile compounds in the fuel, making it versatile and adaptable to different operating conditions. It should be noted that coal briquettes and pulverised coal fuel (PCI) do not meet all of the above criteria cumulatively. They either require additional processing or have limitations in terms of applicability to different types of thermal power plants. In contrast, water-coal fuel (WCF) has a high compliance with these parameters, which makes it more attractive for use in technical processes of utilising waste coal. Water-based fuels are a complex system involving finely dispersed carbonaceous materials such as coal, coke and graphite that are dispersed in water to form a stable and viscous slurry. This process forms a heterogeneous system similar in viscosity to fuel oil or crude oil. One of the main properties of water-coal fuel is that its quality depends significantly on the size of coal particles. The reduction in size from 300 to 30 microns is accompanied by a noticeable decrease in their ignition temperature. For example, for PCI, such a change in particle size leads to a decrease in this indicator from 560 to 420°C (Xi *et al.*, 2020). Despite this, there is no data on the entrainment temperature for particles smaller than 30 μm due to the complexity of dry grinding coal to this size. However, when using an aqueous medium, the effective grinding limit of coal is much lower and amounts to a few microns. This opens the possibility of relatively simple methods for removing coal with particles smaller than 10 microns.

The process of introducing water into coal fuel, and transforming it into water-coal fuel, has a significant impact on its chemical and thermal properties, leading to significant changes in combustion conditions. One of the key changes is a reduction in the ignition temperature of coal particles, which can range from 70 to 200°C, depending on the type of coal and particle size. It is noted that the ignition temperature for WCF produced based on anthracite coal with a low content of volatile particles (4-5%) is reduced to 500-560°C. At the same time, the ignition temperature for a WCF made from gas-coal with a high content of volatile particles (40-50%) is 400-440°C. For lignite-based WCF, this figure is even lower and amounts to 300-350°C

(Nussupbekov *et al.*, 2022). Comparing these results with the ignition temperature of PCI, it should be noted that the combustion temperature is significantly lowered when using WCF. For example, the ignition temperature for anthracite-based PCS is 950-1000°C, for gas coal it is 650-700°C, and for lignite it is 380-400°C. Such changes indicate a significant change in the thermal characteristics of coal fuel when it is modified into hydrocarbon fuel, which affects the possibility of its use in energy processes.

Comparative data for PCI and WCF based on different coal grades show that the dependence of the ignition temperature on the volatile content is much weaker for WCF than for PCI. This indicates that the process of combustion of the water-coal slurry is less sensitive to changes in the content of volatile substances compared to traditional methods of coal combustion. Predictions of the ignition temperature for WCF based on micron-sized coal particles suggest that it will be comparable to the ignition temperature of diesel fuel, which is 260-300°C. This indicates the potential for using CCS as an alternative and efficient energy source in various industrial sectors, including power plants and manufacturing plants. Also, one of the advantages of coal-based fuels is the use of wet milling in the production of WCF, which differs from the dry milling process used in the production of PCI. Wet grinding produces finer particles or significantly reduces energy consumption for the same energy input. This is because, in the water environment, coal particles are crushed more efficiently. An important aspect of wet grinding is the ability to efficiently distribute intoxicants in the medium. This makes it possible to control and improve the quality and properties of the produced WCF. Moreover, the process of water formation itself facilitates particle oscillations. This is due to an effect based on the unique properties of water's surface tension. It contributes to a more uniform and stable distribution of particles in the water medium during grinding, which affects the quality and characteristics of the resulting coal fuel (Miao *et al.*, 2020).

WCF is also unique in its ability to significantly reduce nitrogen oxide ($NO_x$) emissions compared to pulverised coal. This is due to such factors as lowering the flame temperature and maintaining a reducing environment. This leads to a 30-60% reduction in nitrogen oxide generation during WCF combustion compared to the process of combustion of PCI to produce the same amount of heat. The average ignition temperature of the WCF, which is 200-250°C lower than that of the PCI, significantly simplifies the design of the burner and reduces its service life, as less heat energy is required to maintain combustion. The lower ignition temperature also contributes to a more efficient combustion of the fuel, which increases the energy efficiency of the process and reduces the amount of harmful emissions. The uniqueness of water-coal fuel is also manifested in its environmental safety and ability to respond effectively to emergencies, especially in the event of leaks. The WCF consists of a mixture of safe and environmentally friendly materials – water and heat-treated coal. The latter has high thermal conductivity and adsorption capacity, which makes it an effective sorbent. This shows that even in the event of a spill into the environment, its components contribute to the purification of the surrounding water rather than pollution. Thanks to these factors, water-coal fuel does not pose a threat to the environment in the event of an emergency.

To study the possibility of producing WCF from ash and slag waste at Bishkek TPP, areas where slag crushed stone and ash mass with a minimum slag content were concentrated was determined. Samples of these materials were taken at a depth of 1.7 m using a hand-held drill to minimise the impact of external factors. These samples of ash and slag crushed stone were subjected to laboratory tests to determine the particle size distribution and moisture content. After the analysis, the particle size distribution was established. Fractions with sizes less than 300 μm were classified as "ash", fractions from 300 μm to 1 mm as "slag sand", and fractions larger than 1 mm as "slag". The detailed results of this analysis are presented in Table 2.

**Table 2.** Characteristics of granulometric composition and moisture content of ash and slag waste from Bishkek TPP

| Characteristic | Sample number | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Type of waste | slag. rubble | slag. rubble | ash mass | slag. rubble | slag. rubble | ash mass |
| Humidity, W, % | 7.8 | 6.6 | 26.8 | 7.4 | 9.7 | 27.5 |
| More than 1 mm, % | 85.2 | 79.9 | 22.1 | 83.2 | 80.8 | 15.3 |
| From 300 microns to 1 mm, % | 3.9 | 7.3 | 5.7 | 4.4 | 10.1 | 2.4 |
| Less than 300 microns, % | 10.9 | 12.8 | 72.2 | 12.6 | 9.1 | 82.3 |

**Source:** compiled by the authors

After careful analysis, it was found that the slag content of the mixture varied in a wide range from 15 to 85%, while the moisture content varied from 6.6 to 27.5%. Samples with high ash content were prioritised due to their potential importance and applicability in the context of further research.

Addressing that the effectiveness of the strategy for further processing of raw materials is determined by the completeness of information on the properties of the feedstock, a series of experiments was conducted to determine the main characteristics of the ash mass. As part of this research, detailed fractionation of ash was carried out, the boundaries of separation into fractions were determined and the properties of each fraction were analysed. An example of such an analysis is the particle size distribution of sample No. 6, details of which are presented in Table 3.

**Table 3.** Detailed characteristics of sample No.

| Parameter | Fraction size (microns) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Number of particles, %, weight | less than 40 | 40 | 90 | 125 | 150 | 300 | 1 mm | more than 1 mm |
| Differential | 42 | 14.2 | 6.2 | 1.6 | 2.6 | 2.1 | 3.5 | 12 |
| Integral | 42 | 53.3 | 77.2 | 82.9 | 84.4 | 85.5 | 88 | 100 |

**Source:** compiled by the authors

The results of the analysis of various waste fractions show that there are no slag particles in the fine fractions, the size of which does not exceed 90-125 microns. However, when moving to larger fractions, starting from the specified size, the presence of slag particles becomes visually noticeable. This process is accompanied by an increase in slag concentration as the fraction size increases. When studying the fractions larger than 150 microns, particles of unburned coal were observed in the form of coarse particles that stand out from the rest of the material. For a more in-depth analysis of the carbon distribution in different ash fractions, the loss of substances during pyrolysis at high temperatures of up to 900°C was studied. This experiment was carried out after preliminary dehydration of the samples at 375°C, which helped to eliminate moisture and other volatile components that could affect the results (Table 4).

**Table 4.** Results of substance loss in the pyrolysis process

| Fractional size (μm) | less than 50 | 50-150 | 150-200 | 200-300 |
|---|---|---|---|---|
| PCI, %, weight | 2.12 | 2.48 | 4.15 | 5.94 |

**Source:** compiled by the authors

As a result of classification by particle size (less than 150 microns), a clean ash fraction with a pulverised coal content of less than 2.5% was obtained. This product is becoming a valuable resource that can be used as an active additive or aggregate in concrete mixtures and concretes, opening up prospects for creating materials with improved strength and stability characteristics. However, the fraction larger than 150 microns is noteworthy. This coarse fraction has a higher carbon content, which makes it more promising for the extraction of carbon concentrate with a carbon content of more than 75%. This concentrate can be safely used as a fuel, ensuring efficient combustion and minimising emissions of harmful substances.

The fraction larger than 300 microns consists of slag sand with an increased PCI content of up to 8%. To optimise the use of this fraction, it is advisable to carry out carbon removal procedures to a level of less than 2.5%. This can be achieved through various methods such as leaching or other methods. After cleaning procedures, the material becomes more suitable for use and can be successfully used in various industries. A detailed analysis of the composition of the ash and slag waste revealed the presence of coal particles and composite carbon-mineral compounds. These particles have similar physical properties to ash particles, which opens prospects for their separation. Embedded in thin layers of waste, coal particles represent a valuable source of carbon that can be extracted for further use. To investigate flotation methods of carbon recovery from ash, an experiment was conducted on a flotation machine using mechanical frothing. The experiment tested various chemical reagents, including paraffin as a collector, rare glass as a mineral particle depressor, and various synthetic surfactants as foaming agents. The flotation separation process was analysed for two different fractions of ash and slag waste – fine (less than 150 microns) and coarse (more than 300 microns). For the fine fraction, the main priority was to remove carbon residues to reduce its content to less than 2.5%. This aspiration is driven by the need to refine the material and ensure its high quality for further use in production processes. In contrast, for the fraction larger than 300 microns, the main objective was to produce a carbon concentrate with the highest possible carbon content and minimum ash content. The properties of the products obtained as a result of the experiment are presented in Table 5.

**Table 5.** The main characteristics of the products obtained

| Characteristic | Ash output | Concentrate | Tails |
|---|---|---|---|
| <150 μm | | | |
| Mass, g | 100 | 7.1 | 92.4 |
| PCI, %, weight | 2.86 | 30.2 | 0.84 |
| >300 μm | | | |
| Mass, g | 100 | 6.5 | 93.1 |
| PCI, %, weight | 6.9 | 73.4 | 1.9 |

**Source:** compiled by the authors

From the analysis of the data presented, a variety of ash fractions show potential for flotation treatment, which opens the way to the production of high-carbon foam products as well as carbon-free residues. The following results can be achieved with the correct flotation process settings: fractions with particles smaller than 150 microns remain as low-carbon mineral residues after processing, which can be used as fine aggregates in the production of construction materials. At the same time, fractions with particles larger than 300 microns allow us to isolate carbon concentrates with a high carbon content (73.4%) suitable for use as fuel. In addition, the foam concentrates from the fine ash treatment, enriched in carbon (30.2%), can be further processed to produce high-carbon concentrates.

Thus, carbon concentrate, obtained from particles larger than 300 microns using various separation methods, is an important intermediate product in the WCF production process. Its high carbon content and low ash content render it desirable for use in the thermal power industry. This confirms the potential of ash and slag waste as an alternative fuel source that can mitigate energy dependence and reduce the negative impact on the environment.

## DISCUSSION

Research into the production and recycling of environmentally friendly products based on fuel waste plays a key role in the heat and power industry. They reduce the negative environmental impact associated with the emission and storage of solid waste, including ash and slag, produced by thermal power and industrial enterprises. Environmental issues are becoming increasingly important in the thermal power industry, and the recycling of fuel waste for reuse offers promising ways to reduce the negative impact on the environment. Research in this area also contributes to the development of new technologies and production methods that allow efficient use of fuel waste as a product in the creation of efficient fuel materials. This includes the development of specialised methods for waste treatment and purification, optimisation of material separation processes, and research into their physical and chemical properties to achieve optimum results. Such technologies create industrial products with improved technical characteristics and environmental sustainability. Another important factor is that the utilisation of fuel waste in the heat and power industry can contribute to reducing the costs of heat and power generation, increasing the economic efficiency of the industry (Stoliarov, 2024). This is associated with the possibility of using available and cheap sources of raw materials, such as ash and slag, as the main component to produce fuel products. Thus, research in this area is not only of environmental but also economic importance to the industry.

The chemical analysis of the ash and slag waste samples carried out in this study revealed that the content of coal particles was approximately 10-11%. However, the chemical composition of the fuel slag is distinguished by a particularly high $FeO+Fe_2O_3$ content of 5.02%, including 3.96% $Fe_2O_3$. This is determined by the increased content of molten particles and the formation of fuel slag, which confirms its specific chemical properties. The study by Hariana *et al.* (2021) also determined that the structural characteristics of waste slag have a significant impact on its physicochemical properties and potential applications in various industries. Y. Wang *et al.* (2022), addressed the processes of slag formation and revealed that an important factor is the temperature regime of the fuel combustion process and the composition of the feedstock. Compared to the results of the above-mentioned works, which focused on fuel slag, this study focused on the properties of ash and slag materials and their application in the heat and power industry, which opens new prospects for the efficient use of slag waste in the production of environmentally friendly fuels.

It should also be noted that an important result obtained during this study is the detection of an increased carbon content in the ash and slag mixture, which makes it more promising for the extraction of carbon concentrate with a carbon content of more than 75%. This indicates the potential for using these materials in various technological processes and applications in the heat and power industry, ensuring efficient combustion and minimising emissions of harmful substances into the environment (Lyubchik *et al.*, 2008). At the same time, C. Wu *et al.* (2024) studied the properties of ash in the context of sustainable heat and power and determined that the use of this component allows it to be used as one of the main products in the production of water-coal fuel. L.J. Nunes (2020) also addressed the possibilities of using ash materials and the quality of such products, as a result of which the data obtained supplemented and confirmed the conclusions. However, this study is of particular importance, as it examines in detail not only the chemical composition of ash materials but also their physical and mechanical properties, especially when used in the thermal power industry. Unlike the above-mentioned studies, this research delves deeper into the analysis of the physical and mechanical properties of ash materials, which presents a more complete picture of their potential reuse in the heat and power industry. Thus, the findings of this study are an important contribution to the understanding of the capabilities of fly ash materials in the industry, as well as their potential for various technological applications.

Innovative methods, including high-temperature pyrolysis and flotation, were used in this study to thoroughly examine the carbon distribution in different fractions of the ash and slag waste. The pyrolysis experiments were carried out after preliminary dehydration of the samples at 375°C to remove moisture and other volatile components that could affect the results. Flotation analysis of fractions of different sizes (150 μm and 300 μm) was used to determine the optimal methods of carbon extraction to ensure maximum efficiency and quality of material processing. W. Wang *et al.* (2020) also used the flotation separation method, which confirmed the results of the study and increased the understanding of the physical properties and structural composition of ash materials. Z. Xue *et al.* (2023), in turn, addressed similar aspects, but focused on other types of ash residues and their potential applications. Nevertheless, this study has contributed to the knowledge of the structure and properties of ash residues, which is important for their further use in various areas of the heat and power industry and technologies. It also provided valuable information on the thermal properties of the ash residues. The analysis of thermal characteristics determines the temperature intervals in which changes in the composition and structure of materials occur. This is important for optimising their processing and subsequent use in various industries. The data obtained on the properties of ash and slag allow for more precise control over the processing and formation of final materials based on ash residues, which contributes to an increase in production efficiency and the quality of the products (Bieliatynskyi *et al.*, 2022).

The data presented in this study also confirms that different ash fractions have the potential to be processed through flotation, which opens prospects to produce high-carbon and carbon-free products. Different results can be achieved by adjusting the flotation process: fractions with particles smaller than 150 microns remain low-carbon and can be used in the production of construction materials as fine fillers. At the same time, fractions with particles larger than 300 microns allow us to produce carbon concentrates suitable for fuel with a high carbon content (73.4%). In addition, the carbon-enriched (30.2%) foam concentrates from the treatment of fine ash provide an opportunity for additional processing to produce high-carbon concentrates. F. Guo *et al.* (2020b) also investigated pyrolysis processes to analyse changes in ash composition at high temperatures, providing a deeper understanding of chemical transformations and the potential for carbon products. O. Kon and S. Caner (2021) covered the analysis of the efficiency of different filtration methods for coal waste treatment, demonstrating their applicability in practical conditions. The results of these studies add to the general understanding of coal waste treatment and utilisation, offering a more complete picture of its potential and applications. The results demonstrate the effectiveness and prospects of using innovative approaches to coal waste treatment and disposal, which opens up new horizons for creating sustainable and environmentally friendly technologies in the coal industry.

It should be noted that, in general, all such studies play an important role in the development of the heat and power industry and in increasing the sustainability of infrastructure projects. The data obtained can optimise materials and technologies in the waste management process, as well as economic efficiency and environmental sustainability. Understanding the physical and chemical properties of ash and slag materials at a detailed level allows for the development and use of more optimised technologies, which have a positive impact on process efficiency and environmental safety.

## CONCLUSIONS

This study confirmed that ash and slag waste from coal-fired thermal power plants, using the example of Bishkek TPP, has a significant potential for reuse in the heat and power industry. This underscores their importance as a valuable resource that can ensure efficient and sustainable production of water-coal fuel while reducing the negative impact on the environment and reducing the need for primary energy resources.

Chemical analysis of the components showed that the content of unburned coal particles in the fuel waste is about 10-11%, and the content of water-soluble sulphur and sulphuric acid compounds, converted to $SO_3$, ranges from 0.18% to 0.71%. The results of the experiments demonstrate the importance of separating ash and slag from coal-fired thermal power plants into fractions depending on the particle size. This approach enables the subsequent differentiation of coal fractions into components with different physical properties, which is of fundamental importance for further use. The fraction of less than 150 microns is distinguished by its low carbon content (less than 2.5%), which opens prospects for its use in the construction industry as a fine filler or additive. The additional processing of this fraction through the flotation process results in an even more significant reduction in carbon content (less than 1%), making the resulting product even more in demand in various construction and technical applications. On the other hand, fractions larger than 150 microns, especially those larger than 300 microns, are valuable feedstocks to produce carbon concentrate with a high carbon content (over 75%). The resulting carbon concentrate is a promising product to produce hydrocarbon fuel, which reflects the significant potential of this material in the energy industry. It should be noted that this study has a limited scope of analysis, covering only one thermal power plant. This means that the results may not be fully representative of other stations, requiring additional research. In addition, it is necessary to address the influence of process characteristics on the characteristics of ash and slag waste, which can also affect the accuracy of the study results.

For further research, it is recommended to study in more detail the impact of various technological processes on the chemical composition and physical properties of ash and slag waste from a particular TPP. It is also necessary to investigate the effectiveness of different waste treatment methods to produce products with high value and purity. This will optimise the processes of utilisation and reuse of ash and slag waste, as well as increase production efficiency in the thermal power industry.

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## CONFLICT OF INTEREST

None.

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**Махават Джусупова**
Кандидат технічних наук, доцент
Киргизький державний технічний університет ім. І. Раззакова
72004, просп. Ч. Айтматова, 66, м Бішкек, Киргизька Республіка
https://orcid.org/0009-0004-1453-1942
**Сауле Кульшикова**
Кандидат технічних наук, завідувач кафедри технологічних машин і будівництва
Жезказганський університет ім. О. Байконурова
100600, просп. Алашахана, 1Б, м. Жезказган, Республіка Казахстан
https://orcid.org/0000-0001-5412-8454
**Айдай Талантбек кизи**
Аспірант, викладач
Киргизький державний технічний університет ім. І. Раззакова
72004, просп. Ч. Айтматова, 66, м Бішкек, Киргизька Республіка
https://orcid.org/0009-0009-9461-7426
**Гульназ Байменова**
Кандидат технічних наук, старший викладач
Жезказганський університет ім. О. Байконурова
100600, просп. Алашахана, 1Б, м. Жезказган, Республіка Казахстан
https://orcid.org/0009-0008-5095-9750
**Абдулкалям Оспанов**
Кандидат технічних наук, доцент
Жезказганський університет ім. О. Байконурова
100600, просп. Алашахана, 1Б, м. Жезказган, Республіка Казахстан
https://orcid.org/0009-0006-1224-4223

# Використання техногенних відходів у теплоенергетичній промисловості

**Анотація.** Дане дослідження було спрямоване на вивчення фізичних властивостей і хімічного складу золошлакових відходів теплової електростанції, для визначення можливості їх повторного застосування в теплоенергетичній промисловості. Це передбачало класифікацію і проведення хімічного аналізу золошлакових відходів, отриманих в результаті роботи Бішкекської теплової електростанції, для визначення їхнього складу. Отримані зразки матеріалів також були піддані лабораторним випробуванням для визначення гранулометричного складу і вологості. Після встановлення меж поділу на фракції проводилося детальне вивчення зольної маси, включно з аналізом розподілу вуглецю та експериментами з флотації для визначення ефективних методів вилучення вуглецю із золошлакових відходів. Отримані результати підтвердили значний потенціал золошлакових відходів Бішкекської теплової електростанції, що працює на вугіллі, для повторного використання в теплоенергетичній промисловості. Аналіз хімічних компонентів виявив вміст незгорілих вугільних частинок у межах 10-11 %, а вміст водорозчинних сірчистих і сірчанокислих сполук варіювався від 0,18 % до 0,71 %. Експериментальні дані підтвердили важливість фракціонування золи та золошлаків за розмірами частинок, що надає можливість для подальшого розділення вугільних фракцій з різними фізичними властивостями. Фракція розміром менше 150 мкм характеризується низьким вмістом вуглецю (менше 2,5 %), що робить її придатною для використання в будівництві як тонкодисперсний наповнювач. Однак, було відзначено, що фракції розміром понад 150 мкм, і особливо ті, що перевищують 300 мкм, є цінним вихідним матеріалом для виробництва вуглецевого концентрату із вмістом вуглецю понад 75 %, що відкриває перспективи його використання у виробництві водовугільного палива. Таким чином, результати дослідження підтверджують потенціал золошлакових відходів для повторного використання в теплоенергетичній промисловості. Це може сприяти зменшенню обсягів відходів, зниженню негативного впливу на навколишнє середовище, а також створенню ефективних і стійких виробничих процесів у теплоенергетичній промисловості

**Ключові слова**: золошлакові відходи; флотація; вугільні частинки; вуглецевий концентрат; водовугільна суспензія; переробка палива

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**Milot Lubishtani**
Doctor of Geodesy, Director
Private Sector for Geodesy and Cadaster "Geo Noar"
70000, Deshmoret e Kombit Str., Ferizaj, Republic of Kosovo
https://orcid.org/0000-0002-4055-2438

**Fitore Bajrami Lubishtani***
Doctor of Geodesy, Professor
University of Prishtina
10000, 31 George Bush Str., Pristina, Republic of Kosovo
https://orcid.org/0000-0002-4998-8617

# Using geodetic data to optimize the distribution of solar and wind energy installations

**Abstract.** This study was aimed at identifying the optimal locations for solar and wind power plants in the Republic of Kosovo using geodetic parameters and evaluation criteria. The study used global publicly available data, including an elevation model, geographic coordinates, a land cover database, and information on solar radiation and wind characteristics, which were processed in GRASS GIS software. The analytic hierarchy process was used to calculate the weights of the criteria, which provided an integrated assessment of the suitability of the territories. The study found that 61.8% of the territory of the Republic of Kosovo is suitable for utilizing sunlight, indicating the country's significant potential for solar energy production. However, in the case of wind energy installations, the study found that only 32.5% of the territory could be considered optimal for solar power plants. This difference in percentages demonstrates the importance of considering many factors in the planning and construction of energy installations to ensure their stable and efficient operation. The study also confirmed that the F1 model, which uses all the criteria with their respective weights, provides the most reliable results for determining the optimal locations for energy installations. Sensitivity analysis showed that this model was the most effective in classifying suitable locations compared to other rasters such as F2 and F3. This confirms the importance of taking into account various parameters and their impact on the selection of optimal locations for power plants. The results open up possibilities for optimizing the use of solar and wind potential in the Republic of Kosovo, confirming the possibility of using geodetic data and geoinformation data to identify optimal locations for energy installations

**Keywords**: alternative energy; renewable resources; geographical information systems; hierarchy model; weighting coefficients

## INTRODUCTION

The global spectrum of climate change and growing demands for sustainable development pose an urgent challenge to societies to develop and implement alternative energy sources. Solar and wind energy are among the most promising sources of renewable energy, but their optimal distribution requires comprehensive approach and accurate analytics. The use of geodetic data can be a key tool in solving this problem, allowing to effectively identify the most favourable locations for solar and wind power plants. Due to population growth and industrialization, society may face increasing energy needs, which threatens the stability of energy supply and natural ecosystems.

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*Corresponding author

Therefore, the problem of finding efficient energy sources that not only meet the needs of the present, but also ensure sustainability and environmental values is becoming extremely relevant. The use of solar and wind power plants in this regard is one of the most promising areas. It should be noted that the issue of practical use of geodetic data to ensure the optimal distribution of solar and wind energy installations is still open. Accurately identifying the locations with the greatest potential for their installation, as well as analysing the impact of various factors on their efficiency, requires the integration of geodetic data with information on climatic conditions and local topography (Shtohryn *et al*., 2023). A thorough study of these aspects can help to optimize the use of renewable energy sources and ensure the sustainability of energy supply in the future.

The potential of using alternative energy sources depends on various parameters and criteria that can be taken into account when applying geographic information systems (GIS). A study by S. Lajqi *et al.* (2020) investigated the use of renewable energy potential in the energy sector of the Republic of Kosovo using GIS, which confirmed the effectiveness and accuracy of geographic information systems in this area. The work of Y. An *et al.* (2023) also studied in detail the impact of wind flows on the efficiency of wind farm installation, using GIS to analyse geographic data, also confirming the potential of geographic information systems. The study by S. Izeiroski & B. Idrizi (2023) focused on analysing the impact of geographical features on the efficiency of renewable energy sources, which became the basis for developing strategies to optimize the distribution of energy installations. Thus, the integration of geographical information systems in research has led to significant conclusions and recommendations for the further use of alternative energy sources.

The global horizontal irradiance (GHI), which measures the intensity of solar radiation on the Earth's surface, can be used to determine solar radiation (Komisova *et al*., 2023) The study by D. Kumar (2020) on the distribution of solar radiation to determine the potential for solar energy use confirmed the effectiveness and versatility of this indicator. The study by O.K. Overen & E.L. Meyer (2022), in turn, was aimed at investigating the impact of terrain on the distribution of solar radiation, in particular, how altitude and other parameters affect the intensity of solar insolation. W. Liu *et al.* (2021) also analysed the impact of soil cover and other conditions on solar radiation potential, partly focusing on the use of geodetic data. At the same time, it is important to take into account the interaction of many factors to accurately determine the solar and wind potential of an area, which will allow for more efficient use of alternative energy sources in general.

The parameters of wind speed, direction and seasonal variations can be used to assess the potential for wind energy installations. In the work of C. Jung & D. Schindler (2022), the authors examined the influence of topography on local wind conditions, in particular how mountain ranges and valleys can affect wind speed and direction. The study by A. Rezaeiha *et al.* (2020) also focused on the research of seasonal variations in wind speed and their changes throughout the year in different regions. Meanwhile, S. Deep *et al.* (2020) analysed the impact of wind conditions on electricity generation and its variability depending on seasonal changes in wind speed. However, to fully understand the potential of wind energy use, it is necessary to take into account the complex impact of various factors on the distribution of renewable energy and the efficiency of such power plants.

The purpose of this study is to assess the potential for solar and wind energy use in the territory of the Republic of Kosovo, using geodetic data and geographic information systems. The main objective of the study is to determine the optimal locations for solar and wind power plants, taking into account various conditions. The second objective is to analyse the sensitivity of the models to various parameters and weighting factors to better understand the impact of various factors on the suitability of the territory for the installation of energy facilities.

## MATERIALS AND METHODS

The study area is the territory of the Republic of Kosovo, located on the Balkan Peninsula (Fig. 1). The country covers an area of approximately 10,908 km². Kosovo is noted for its unique geographical location and climate, which creates favourable conditions for the use of renewable energy sources.


**Figure 1.** Location of the study
**Source:** compiled by the authors

To determine the basic parameters, this study used a variety of geodetic data sources, the vast majority of which are global and publicly available. To establish the basic parameters, we used the Global Digital Elevation Model (GDEM) from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of approximately 50 m (1 arc-second) from 2020. The Harmonized World Soil Database (HWSD) (Food and Agriculture Organization..., 2008) was used to determine the land cover, including its main characteristics. The digital classification sample (DCS) was created using remote sensing classification methods based on optical satellite images and covers a minimum mapping area of 30 ha. Additionally, the averaged global horizontal irradiance (GHI) data with a resolution of 50×50 m were calculated using the risen module.

The accuracy of the GHI was verified using data from weather stations and compared with commercial solar radiation data obtained from the PVGIS web portal. In this study, the average daily GHI value for the period from 2018 to 2020 was used. The three-year period was chosen to exclude the influence of extreme atmospheric conditions, as well as to ensure better data quality and reliability. All raster data were resampled to a spatial resolution of 50×50 m, as SRTM GDEM and GHI data have the same spatial resolution. Information on wind gusts, wind speed, and seasonal variations was obtained from the Global Wind Atlas database, which provides detailed data on wind resources with a spatial resolution of 1 km. These data were adapted to the local conditions of the Republic of Kosovo by using data from regional meteorological stations, which ensured their accuracy and relevance to real conditions.

In order to determine the optimal location of solar power plants and wind turbines, this study selected the analytic hierarchy process (AHP) as the most adapted and effective method to take into account all important factors and solve complex energy planning problems. This included a hierarchy creation process where the problem was broken down into objective, criteria, sub-criteria and alternatives, which allowed structuring the problem and clarifying all its aspects. One of the key steps in the AHP method was a pairwise comparison of the elements at each level of the hierarchy based on their importance. For this purpose, the Saaty comparative scale was used (Table 1), which allowed us to assess the importance of each element in comparison with other elements at the same level of the hierarchy.

**Table 1.** Comparison of importance indicators

| Intensity of importance | Value of the indicator |
|---|---|
| 1 (equal importance) | Both types of activity contribute equally to the achievement of the goal |
| 3 (moderate importance) | Experience gives a certain advantage to one type of activity over another |
| 5 (highly important) | A big advantage of one type of activity over another |
| 7 (very highly important) | Experience gives a very strong preference to one type of activity over another |
| 9 (extremely important) | Evidence that favours one type of activity over another has the highest level of weight |
| 2, 4, 6, 8 (intermediate values) | In the reverse comparison between elements, the inverse intensity values are given importance |

**Source:** compiled by the authors based on Y.E. Coruhlu *et al.* (2022)

When comparing individual pairs of alternatives at the appropriate level of the hierarchy, local weights of criteria and sub-criteria were determined. These weights were expressed in integers and recorded in matrix (1), where the values of the elements are inversely related. In other words, each value in the matrix reflects the degree of importance of one element compared to another, opposite to the intensity. This approach allowed us to systematically evaluate and rank the alternatives, taking into account their relationships at different levels of the hierarchy:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}. \quad (1)$$

Each alternative in this context is denoted by $A_i$ where i varies from 1 to n, which corresponds to the total number of alternatives. The weights between pairs of alternatives are given in each element of the matrix A, denoted as $a_{ij}$ and expressed as follows (2):

$$a_{ij} = \frac{w_i}{w_j}, \quad (2)$$

where i and j correspond to specific alternatives; $w_i$ and $w_j$ are the weights of the respective alternatives $A_i$ and $A_j$.

Each value $a_{ij}$ represents how much more important one alternative is compared to the other, and these values have reciprocal inverse correspondences in the matrix, i.e., $a_{ji} = \frac{1}{a_{ij}}$, which made it possible to systematically analyse the relative importance of each alternative in the context of multi-criteria decision-making.

GRASS GIS software was used to visually demonstrate the optimal locations for solar and wind power plants, providing powerful tools for detailed analysis and mapping. In particular, version 7.8.5 was chosen for its ability to process large amounts of data with high accuracy. The analysis also included normalization of the data, where pixel values ranged from 0 to 1, indicating the suitability of the area for power plants. Pixels with a value of 1 indicated the best locations for construction, while pixels with a value of 0 were unsuitable.

## RESULTS

The peculiarities of energy planning, which often involves numerous conflicting goals and constraints, encourage the use of hybrid methods of multi-criteria decision-making. In this context, the AHP method is particularly effective, as it allows taking into account a variety of factors and criteria, and provides a qualitative and quantitative assessment of alternatives (Witt & Klumpp, 2021; Zayat *et al.*, 2023).

To determine the optimal locations for the construction of solar and wind power plants in the Republic of Kosovo, it is first necessary to determine the exact parameters required. These parameters have been classified into two groups: those that are critical for accurate siting, and those that improve the quality of the final result. Thus, the following categories of parameters were identified for energy planning:

- critical parameters include solar radiation levels, the number of sunny days per year, wind gusts, wind direction, seasonal variations in wind speed, average annual temperature and other data that affect the efficiency of solar panels and wind farms;
- additional parameters that enhance the quality of the result include terrain topography, altitude, slope, and orientation of the surface, and geographic coordinates. These parameters are also important for the optimal location and performance of power plants.

Critical parameters were analysed to determine the optimal locations for solar and wind power plants due to their direct impact on the efficiency and sustainability of energy production. The level of solar radiation is a key indicator for assessing the potential of solar power plants. High solar radiation and a significant number of sunny days ensure maximum productivity of solar panels, contributing to their efficient operation (Bhowmik *et al.*, 2020). For wind power plants, it is critical to analyse the average wind speed and seasonal variations. High and stable wind speeds allow wind turbines to operate at full capacity, while knowledge of seasonal variations helps to optimize maintenance and operation schedules (Prema *et al.*, 2021).

In turn, the analysis of additional parameters that improve the quality of the result also plays an important role in determining the optimal locations for power plants. Topography, altitude, slope, and orientation of the surface determine not only the technical feasibility of installing equipment, but also its efficiency. For example, solar panels located on southern slopes receive more sunlight during the day, which increases their productivity (Altintas & Utlu, 2021). For wind turbines, altitude, and open spaces without significant obstacles, such as mountains or forests, provide the best conditions for capturing wind energy. Latitude and longitude allow us to determine the exact location of the site on the Earth's surface, which is necessary for analysing solar radiation, the length of the sunny day, and wind characteristics (Ojeda Avila *et al.*, 2021). The main parameters used in this study are detailed in Table 2.

**Table 2.** Main research parameters

| Parameter name | Parameter type | Requirements for the parameter |
|---|---|---|
| GHI | Critical | 0-1 |
| Wind gust speed | Critical | 0-1 |
| Wind direction | Critical | 0-1 |
| Seasonal variations in wind | Critical | 0-1 |
| Geographical coordinates | Additional | Latitude=0-1<br>Length=0-1 |
| Tilt level | Additional | No more than 30% of the total |
| Orientation (azimuth) | Additional | North, south=0-1<br>West, east=0-1 |
| Height above sea level | Additional | No more than 300 m<br>100-500 m |

**Source:** compiled by the authors

Various parameters were taken into account in the study, but the GHI and wind characteristics proved to have the greatest impact on decision-making regarding solar and wind power plants. It is worth noting that the level of distribution of wind resources and solar radiation is uneven throughout the Republic of Kosovo, and this is important when considering the use of such alternative energy. The GHI parameter was chosen because of its critical impact on the assessment of the solar potential of a particular area, as it measures the total amount of solar energy incident on a unit area of horizontal surface. This value includes both direct solar radiation and diffuse radiation, which is important for a full understanding of the solar energy potential of a particular location. GHI data is available at high temporal (annual, monthly, daily values) and spatial resolution (up to 1 km or less), which allows for detailed modelling of the energy potential in different areas and under different conditions. The use of GHI allows creating accurate models for predicting the energy productivity of solar installations throughout the year, taking into account seasonal and climatic changes, which is especially important for countries with variable weather, such as Kosovo (Mohammadpour *et al.*, 2022).

The parameters of wind gust speed, wind direction and seasonal wind variations have been selected for several technical reasons that are crucial for optimizing the siting of wind turbines. Wind gust speed is a key parameter as it affects the efficiency and stability of wind turbines. High wind gust speeds can provide a higher level of electricity generation, but also create significant loads on turbine structures (Akçaba & Eminer, 2022). This requires consideration of maximum wind speeds in the design and siting of turbines to ensure their durability and reliability. Wind direction is another critical parameter, as it determines the optimal orientation of wind turbines to maximize energy capture. Understanding the dominant wind directions in a given area allows the turbines to be positioned correctly so that they can efficiently utilize the available wind resource, which is particularly important in difficult terrain where wind flows can vary depending on the topography. Seasonal variations in wind, in turn, are taken into account to understand changes in the wind resource throughout the year. This allows forecasting electricity production in different seasons, which is important for ensuring a stable energy supply (Wang *et al.*, 2020). In some regions of Kosovo, there can be significant changes in wind speed and direction throughout the year, which requires additional attention when assessing the performance of wind turbines. Taking into account seasonal variations helps to plan the distribution of energy resources and determine the most appropriate periods for maintenance and optimization of turbine performance.

Orientation (azimuth) also has a significant impact on the efficiency of alternative energy sources, especially in the context of generating electricity from solar panels. The technical aspects of orientation can be illustrated by the example of azimuth, which is measured in degrees from north (0°) in a clockwise direction. For solar panels, the most efficient orientation depends on the geographical latitude and climatic conditions (Selvakumar *et al.*, 2024). In the Northern Hemisphere, the optimal orientation is usually south (180°), as this maximizes the solar energy capture during the day. In contrast, in the Southern Hemisphere, the optimal orientation is north (0°). When solar panels are oriented to the south (180°), their efficiency is highest in the Northern Hemisphere. In this case, solar radiation reaches its maximum during the day, providing the maximum amount of captured energy. The performance factor in this orientation is 1, which means 100% optimal performance. On the other hand, the north orientation (0° azimuth) is the best for the Southern Hemisphere, as it also allows for maximum solar radiation during the day with a productivity factor of 1. Orientation to the east (90°) and west (270°) is less efficient compared to the southern azimuth. East-facing solar panels capture the maximum amount of solar radiation in the morning, while west-facing panels capture it in the evening. The performance factor for the east and west azimuth is approximately 0.8-0.9, which corresponds to 80-90% of the optimal performance.

For wind turbines, orientation is also important, but more so in relation to the direction of the prevailing winds. The orientation of the turbine should ensure maximum wind energy capture throughout the year. If the dominant winds are from the north (0°), the efficiency of the turbine will be high because the maximum amount of wind energy is captured. Similarly, orientation to the south (180°), east (90°) or west (270°) will be effective if the dominant winds are from the respective directions. The efficiency factor for wind turbines varies depending on local conditions and the prevailing wind directions. The study also selected requirements for the altitude parameter, with a limit of no more than 300 m. This ensured the selection of areas that do not exceed critical altitudes that could have a negative impact on the efficiency of solar and wind energy. Altitudes above 300 m may be less attractive in terms of accessibility, technical complexity and efficiency in terms of energy collection and transportation. At the same time, the range from 100 to 500 m takes into account a variety of geographical conditions and energy use potential. Altitudes in this range provide optimal conditions for collecting energy from the sun and wind, taking into account both minimum and maximum altitude requirements for the efficient operation of solar and wind power plant (von Krauland & Jacobson, 2024).

Analysing geographical coordinates such as latitude and longitude helps in determining the optimal location of solar panels and assessing wind resources. Latitude has a significant impact on the angle of incidence of the sun's rays and the length of a sunny day, as in areas closer to the equator, the sun's rays fall more directly, which increases the intensity of solar radiation. Longitude, in turn, affects local time and, accordingly, the timeframe of maximum solar activity. In addition, the analysis of geographical coordinates helps to identify areas with the best wind conditions, where the wind frequency and speed are optimal for the installation of wind turbines. The slope requirements, which are set at 30%, are also important for the efficiency of power plants. The slope of the site affects the angle of incidence of the sun's rays, as well as the wind speed and direction, which affects the efficiency of solar panels and wind turbines (Stoliarov, 2024). Setting a requirement of 30% slope can ensure an optimal relationship between the angle of solar radiation and the surface of solar panels. In addition, the slope of the land affects the distribution of wind. Rises and slopes can contribute to the formation of turbulence, which increases the efficiency of wind turbines. A slope requirement at a certain level can provide optimal conditions for collecting wind energy and maximizing its production (Nazir *et al.*, 2020).

The terrain analysis in the study was performed using a raster model with normalized pixel values. Each pixel was assigned a value indicating its suitability for construction, taking into account slope and orientation. A value of "1" was assigned to areas with a perfect zero slope, making them the best for construction, while a value of "0" indicated areas with a slope greater than 30%, making them less suitable. Using the parameter analysis described above, a hierarchy model was developed (Fig. 2).

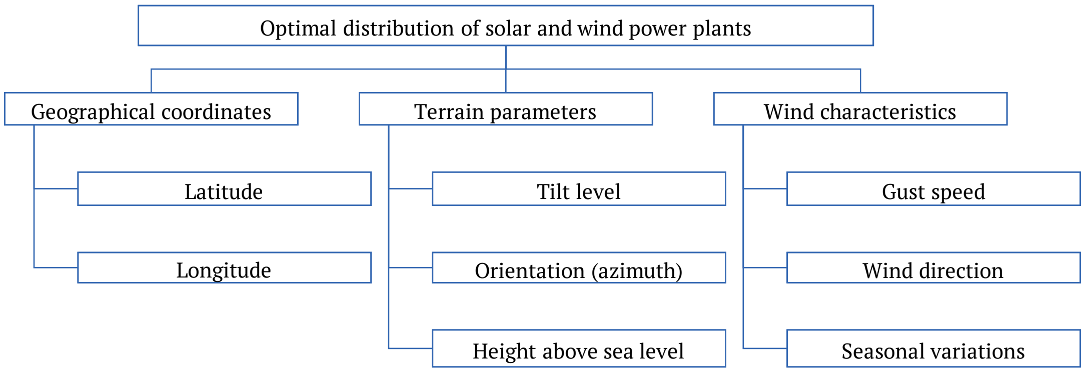


**Figure 2.** Hierarchy model

**Source:** compiled by the authors

This model is based on criteria and sub-criteria based on a detailed analysis of the various aspects that influence the selection of optimal power plant locations. Each criterion and sub-criterion have been carefully defined based on its contribution to the decision-making process and its importance for achieving the objective. This approach allows creating a more accurate and informed model that takes into account all relevant factors in determining the optimal locations for solar and wind power plants. The importance of the main parameters (Tables 3 and 4) was assessed using the method of pairwise comparisons, with the use of the Saaty scale for each pair of parameters. Then, local weights were calculated for these key parameters using the of AHP, which allowed taking into account the individual contribution of each parameter to the selection of optimal locations for solar and wind power plants, providing a more objective assessment and a better understanding of their role in the decision-making process.

**Table 3.** Indicators of importance of the main parameters (for solar panels)

| Indicator | GHI | Geographical coordinates | Terrain parameters | Weight indicators |
|---|---|---|---|---|
| GHI | 1 | 2 | 3 | 0.478 |
| Geographical coordinates | 0.3 | 1 | 2 | 0.213 |
| Terrain parameters | 2 | 0.5 | 1 | 0.309 |
| $\lambda = 5.162$; $CI = 0.058$; $CR = 0.065$ | | | | |

**Source:** developed by the authors

**Table 4.** Importance of key parameters (for wind turbines)

| Indicator | Wind performance | Geographical coordinates | Terrain parameters | Weight indicators |
|---|---|---|---|---|
| Wind performance | 1 | 2 | 3 | 0.443 |
| Geographical coordinates | 0.25 | 1 | 0.5 | 0.185 |
| Terrain parameters | 0.5 | 2 | 1 | 0.372 |
| $\lambda = 5.504$; $CI = 0.033$; $CR = 0.047$ | | | | |

**Source:** compiled by the authors

Using the AHP, calculations were performed, and weighting factors were assigned to the rasters. The total sum of all these raster data creates a final raster indicating the optimal locations for the construction of solar and wind energy installations in the Republic of Kosovo. To calculate this final raster, a mathematical expression was used, which in the case of solar power plants had the form (3):

$$F1 = 0.478 \ast R_1 + 0.213 \ast R_2 + 0.309 \ast R_3, \quad (3)$$

where $R_1$ is the value of the GHI weighting factor; $R_2$ – geographical coordinates; $R_3$ – terrain parameters.

At the same time, in the case of wind power plants, this expression looks like (4):

$$F1 = 0.443 \ast R_1 + 0.185 \ast R_2 + 0.372 \ast R_3, \quad (4)$$

where $R_1$ is the value of the weighting factor of wind characteristics; $R_2$ – geographical coordinates; $R_3$ – terrain parameters.

In order to verify the accuracy and objectivity of the results obtained through multi-criteria analysis in the context of determining the optimal locations for solar and wind power plants, the study conducted a sensitivity analysis. This analysis includes consideration of the impact of changing the weights of the criteria in three scenarios. The first scenario (F1) uses the criteria and weights described in the study. In the second scenario (F2), all criteria have the same weighting. The third scenario (F3) examines the impact of changing the weighting, where less weight is given to certain criteria, such as geographical parameters. This analysis allows assessing how sensitive the results are to changes in the weighting factors and helps to understand the impact of different weightings on the final decisions on the optimal locations for solar and wind power plants. The sensitivity assessment helps to identify the most important criteria and their weighting in decision-making, and provides a more objective assessment of the analysis results. To analyse in detail the results of the three scenarios with locations suitable for both solar and wind power plants, histograms were created for each of the final rasters (F1, F2 and F3), as shown in Figure 3. They allow visualizing the distribution of suitable locations in different scenarios, as well as understanding how changing the weighting factors affects the number and quality of potential locations.

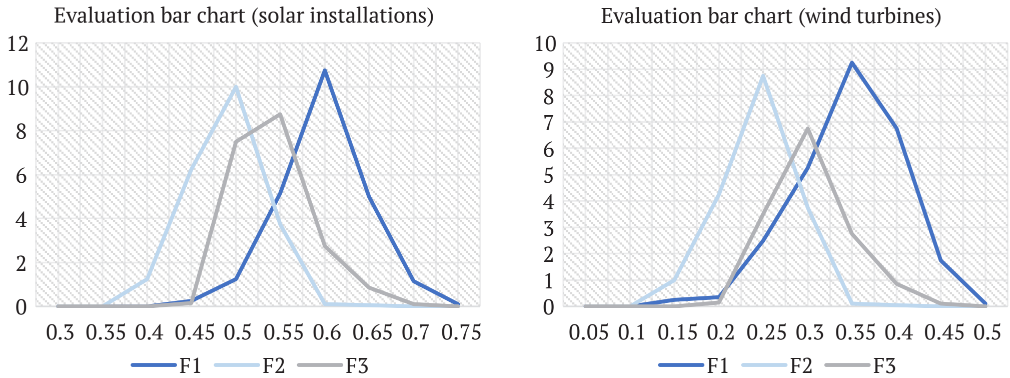


**Figure 3.** Evaluation histograms for optimal placement of power plants
**Source:** compiled by the authors

In addition, for each of the three scenarios, the relevant statistical indicators were calculated and presented in Table 5. For wind power plants, the calculation was carried out similarly (Table 6). This allowed for a comprehensive assessment of the impact of changes in the weighting factors on the distribution of optimal locations for both solar and wind power plants.

**Table 5.** Statistical indicators for optimal placement of energy installations (solar panels)

| Indicator | F1 result | F2 result | F3 result |
|---|---|---|---|
| Pixels in total | 42,906,590 | 42,906,590 | 42,906,590 |
| Correct pixels | 37,474,062 | 37,474,062 | 37,474,062 |
| Incorrect pixels | 5,432,528 | 5,432,528 | 5,432,528 |
| The lowest value, % | 0.4105 | 0.4018 | 0.3750 |
| The largest value, % | 0.8253 | 0.7933 | 0.7535 |
| Arithmetic mean value, % | 0.6179 | 0.5975 | 0.5642 |
| Standard deviation, % | 0.0475 | 0.0422 | 0.0418 |

**Source:** compiled by the authors

**Table 6.** Statistical indicators for the optimal location of energy installations (wind turbines)

| Indicator | F1 result | F2 result | F3 result |
|---|---|---|---|
| Pixels in total | 42,906,590 | 42,906,590 | 42,906,590 |
| Correct pixels | 37,474,062 | 37,474,062 | 37,474,062 |
| Incorrect pixels | 5,432,528 | 5,432,528 | 5,432,528 |
| The lowest value, % | 0.2366 | 0.2105 | 0.2120 |
| Highest value, % | 0.4123 | 0.3992 | 0.3713 |
| Arithmetic mean value, % | 0.3244 | 0.3048 | 0.2916 |
| Standard deviation, % | 0.0525 | 0.0479 | 0.0467 |

**Source:** compiled by the authors

A detailed analysis of the scenarios for the location of solar and wind power plants represented by rasters F1, F2 and F3 showed that in both cases, raster F1 contains the largest number of suitable locations for the construction of energy facilities. The histogram in Figure 3 shows that raster F2 has the smallest spread of values and lower mean values, indicating that the multi-criteria decision-making method applied to F2 provides more accurate results than the equal weighting scenario. Raster F1 has a wider range of values and a higher percentage of the most suitable locations for the construction of solar power plants than F3, which makes it more optimal. The statistical indicators presented in Tables 5 and 6 confirm these conclusions: in both cases, the F3 raster showed the worst results among all three scenarios. The maximum and average values for the F1 raster were higher, indicating a better classification of suitable locations for solar and wind power plants. Thus, the results of the analysis clearly demonstrate that the F1 raster provides the most accurate and reliable results for power plant locations, outperforming both the equal weighted raster (F2) and the raster with less weighting of geographic coordinates (F3). This conclusion is supported by visual analysis of the histograms as well as statistical data indicating that the F1 raster is more efficient and accurate in identifying optimal locations for power plants. Based on the results of the calculations and the analysis of solar and wind potential, the optimal locations for solar and wind power plants were identified (Fig. 4, 5). All analyses were performed in GRASS GIS software version 7.8.5 with a spatial resolution of 50×50 m in the official coordinate system of the Republic of Kosovo, which ensures the reliability and adequacy of the results.

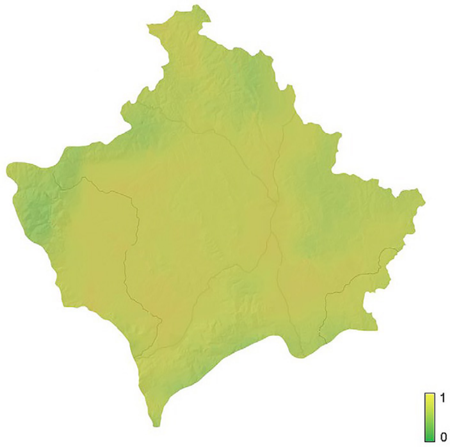


**Figure 4.** Map of the optimal location of solar energy installations in the Republic of Kosovo
**Source:** compiled by the authors

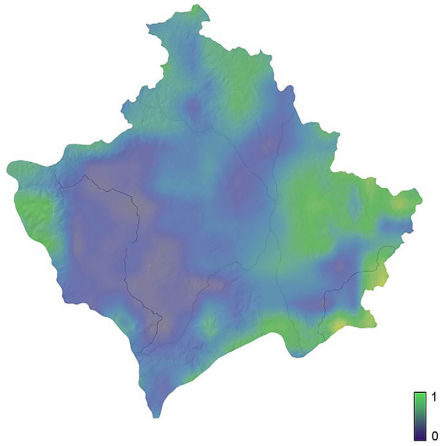


**Figure 5.** Map of the optimal location of wind power plants in the Republic of Kosovo
**Source:** compiled by the authors

The analysis of the data obtained allows concluding that, based on numerous parameters and criteria, 61.8% of the surface of the territory of the Republic of Kosovo is suitable for the use of solar potential. At the same time, this figure is about 32.5% for the placement of solar power plants. Thus, the approach considered in this study shows that although a significant part of the territory has the potential for solar energy generation, the actual suitability for the installation of solar power plants is significantly lower due to various additional requirements and limitations. The obtained results confirm the prospects of using geodetic data to analyse and determine the potential of renewable energy sources, in particular solar and wind energy. This allows effectively determining the optimal locations for the installation of solar and wind power plants, as well as taking into account various factors affecting their operation.

## DISCUSSION

Exploring the potential for using alternative forms of energy, such as solar and wind, is becoming increasingly important in the search for sustainable and environmentally friendly sources. Growing global demand for energy and increasing environmental challenges have led to the need to study and use renewable energy sources, which contributes to the development of modern technologies and research in this area. Such research is becoming critically important for developing effective strategies for energy security, reducing dependence on traditional energy sources and reducing greenhouse gas emissions. The integration of alternative energy sources into the energy system contributes to the stability, diversification, and sustainability of energy production, which are critical elements of modern energy planning (Rubino *et al.*, 2017). In addition, the efficient use of alternative energy can contribute to the development of innovative technologies and increase the country's competitiveness in the international market. The development of effective methods for assessing and using alternative energy sources can stimulate industrial development, create new jobs and contribute to economic growth. Such research is an important step towards creating a sustainable and environmentally friendly future.

In this study, a multi-attribute decision-making methodology (MADM) was applied to systematize and evaluate the various criteria and alternatives that influence the choice in the context of optimizing the distribution of solar and wind power plants. The use of this methodology allowed for a comprehensive analysis of various aspects, including parameters for assessing solar resources as well as wind resources, which is an important factor for making informed decisions. This approach helps not only to identify optimal solutions, but also to take into account potential consequences and risks, which helps to ensure a more sustainable and efficient distribution of energy resources. The study by R. Rathi *et al.* (2020) also analysed the impact of changing decision-making criteria on the final results, which allowed for a better understanding of the importance of each criterion and its impact on the selected alternatives. The work of M.L. Kamari *et al.* (2020), which focused on the development of a model for predicting the energy potential of solar installations, allowed for future forecasts and more accurate planning of energy infrastructure development. In addition, the study by M. Şahin (2021) examined the impact of various solar and wind energy development strategies on economic, environmental and social aspects, which is important for developing effective policies and strategies in the field of alternative energy sources. The results of the above-mentioned works complement the findings of this study, providing additional support for the development of strategies and policies aimed at balancing the use of solar and wind energy, taking into account various parameters and factors.

The use of the AHP in this study proved to be extremely useful for systematizing and evaluating the various criteria that influence decision-making in optimizing the distribution of solar and wind energy installations. This method allowed taking into account various aspects such as altitude, slope, orientation and establishing their relative importance. The hierarchical structure of the AHP method allowed for the ranking of criteria and alternatives based on their hierarchical interconnectedness, which helped to conduct an objective analysis and select the best solutions. Additionally, the AHP provided a convenient and clear tool for taking into account the weight of each criterion, which contributed to informed and balanced decision-making. The use of this method can contribute to a more efficient use of energy resources, as well as to the achievement of the set objectives in the context of sustainable development. The work of J.A. Romero-Ramos *et al.* (2023), which focused on analysing the impact of geodetic and geographical conditions on the distribution of solar power plants, allowed a detailed assessment of the solar energy potential depending on various factors. The results of the work of L. Albraheem & L. Alabdulkarim (2021), which focused on the impact of climatic conditions on the efficiency of solar power plants, also provided important conclusions regarding the optimal placement of such plants. However, in comparison with the results of the above studies, it was found that the consideration of various criteria and alternatives, the use of a hierarchical approach and the sound analysis conducted in this study make it completer and more relevant for making effective decisions in the field of energy technologies.

An important part of this work was also the use of three different rasters (F1, F2 and F3) to assess the suitability of the territories of the Republic of Kosovo for solar and wind energy installations. The F1 raster took into account all the criteria with appropriate weights, which allowed for the most accurate and reliable results. The analysis showed that F1 demonstrates the highest efficiency in classifying suitable locations, with maximum accuracy in showing the optimal areas for the placement of installations. The histograms and statistical indicators obtained in the course of the work confirmed that F1 has the largest number of pixels with high suitability values, which indicates its superiority over other rasters. Raster F2, which used the same weights for all criteria, turned out to be less accurate and showed a much smaller spread of values. This indicates that an equal distribution of weights does not take into account the actual importance of each criterion, which leads to less accurate results. At the same time, raster F3, where the weights for certain criteria were reduced, showed the worst results among the three, confirming that underestimating the importance of certain criteria negatively affects the overall assessment of the suitability of territories. The study by S.A. Memon *et al.* (2021) examined the impact of various criteria on the selection of locations for wind and solar power plants, which confirmed the importance of accurately setting the weighting coefficients for each parameter. In turn, S. Rekik & S. El Alimi (2023) focused on the impact of climatic and environmental factors on the selection of optimal locations for solar and wind power plants, which also emphasized the importance of an integrated approach in multicriteria analysis. Thus, the results of this study, in conjunction with the above-mentioned works, demonstrate that the correct consideration of weighting factors is critical to accurately determine the optimal locations for energy installations. This confirms the need for a systematic approach and the use of reliable analysis methods to make informed decisions in the renewable energy sector.

The results of the study showed that 61.8% of the territory of the Republic of Kosovo is suitable for the use of solar potential, which indicates a significant potential for the development of solar energy in the country. However, when additional requirements for the siting of solar energy installations are taken into account, the suitability of the territory decreases to 32.5%. This decline indicates that there are numerous technical, climatic and other constraints that need to be taken into account when planning the placement of solar panels. This means that although the country has significant potential for solar energy generation, its effective use requires detailed planning and the removal of obstacles such as the lack of necessary infrastructure, difficult terrain or environmental restrictions (Rubino *et al.*, 2023). These findings highlight the importance of conducting detailed analyses and preparing strategies to maximize the use of the available potential, which can significantly increase the region's energy independence and stability. The study by M.R. Elkadeem *et al.* (2022) focused on analysing the technical barriers and opportunities for integrating solar energy systems into existing infrastructure, which helped to identify the main obstacles and ways to overcome them. At the same time, the work of Z. Ullah *et al.* (2021) considered the possibility of using and optimal strategies for combining several sources of alternative energy when placing solar and wind installations. However, in comparison with the results of this study, the above-mentioned works did not cover such a wide range of criteria and parameters that allow a more comprehensive assessment of the suitability of territories for the placement of solar panels and wind turbines in the Republic of Kosovo, which makes this study unique and more comprehensive.

Thus, research in this area is extremely important for the sustainable development of the energy sector in different regions of the world. They help to determine the optimal locations for solar and wind power plants, taking into account various factors. Such studies help support the transition to renewable energy sources, contributing to increased energy independence and reduced environmental impact, which are key factors for sustainable development and improved quality of life.

## CONCLUSIONS

As a result of the study, a comprehensive approach was developed that included the use of geodetic data to determine the optimal locations for solar and wind power plants in the Republic of Kosovo. Using a multi-criteria analysis based on hierarchy analysis and GRASS GIS software, the study identified sites with the highest potential for efficient use of renewable energy sources. The study included the analysis of numerous parameters, such as critical parameters (solar radiation intensity and wind characteristics), as well as additional parameters (altitude, slope, orientation, geographical coordinates). The use of the SRTM global digital elevation model (GDEM) with a spatial resolution of 50×50 m and data from other open and publicly available sources ensured high accuracy of the analysis and quality of the results.

A detailed analysis of the obtained indicators led to the conclusion that 61.8% of Kosovo's territory is suitable for the use of solar potential. At the same time, in the case of wind energy installations, only 32.5% of the territory was optimally suitable for the installation of solar power plants. This difference indicates the need to consider many factors to ensure the stable and efficient operation of energy facilities. The sensitivity analysis showed that the F1 model, which takes into account all the criteria with appropriate weights, provides the most reliable results. The histograms and statistical indicators demonstrated that the F1 raster was the most effective in classifying suitable locations for energy installations compared to other rasters, such as F2 (with the same weights) and F3 (with less weight for the geographical coordinates' indicator). It is worth noting that the global models and databases used in this study, such as GDEM SRTM and HWSD, may not reflect some local features that are important for accurately determining the optimal locations for energy installations. In addition, the AHP involves subjective expert judgements, which may also affect the final results. In addition, this study considered a limited number of parameters and criteria, which may not provide a complete picture of the suitability of the areas.

Further research in this area could focus on the use of more parameters and factors, which would allow for a more qualitative and comprehensive assessment of the suitability of areas for energy installations. Another important area for research could be to expand the study area to other regions, which would allow for comparisons and adaptation of the methodology to different geographical and climatic conditions.

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None.

## CONFLICT OF INTEREST

None.

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**Мілот Лубіштані**

Доктор геодезії, директор
Приватний сектор геодезії та кадастру «Geo Noar»
70000, вул. Дешморет е Комбіт, м. Феріжай, Республіка Косово
https://orcid.org/0000-0002-4055-2438

**Фіторе Байрамі Лубіштані**

Доктор геодезії, професор
Приштинський університет
10000, вул. Джорджа Буша, 31, м. Приштина, Республіка Косово
https://orcid.org/0000-0002-4998-8617

## Використання геодезичних даних для оптимізації розміщення сонячних та вітрових електростанцій

**Анотація.** Це дослідження було спрямоване на визначення оптимальних місць розташування сонячних і вітрових електростанцій у Республіці Косово з використанням геодезичних параметрів і критеріїв оцінки. У дослідженні були використані глобальні загальнодоступні дані, зокрема модель рельєфу, географічні координати, база даних ґрунтового покриву та інформація про сонячну радіацію і характеристики вітру, які були оброблені за допомогою програмного забезпечення GRASS GIS. Для розрахунку вагових коефіцієнтів критеріїв було використано метод аналізу ієрархій, що дало змогу отримати інтегровану оцінку придатності територій для розміщення сонячних і вітрових електростанцій. Дослідження показало, що 61,8 % території Республіки Косово придатні для використання сонячного світла, що свідчить про значний потенціал країни для виробництва сонячної енергії. Однак, при розміщенні вітрових енергетичних установок, дослідження показало, що лише 32,5 % території можна вважати оптимальними для сонячних електростанцій. Така різниця у відсотках демонструє важливість урахування багатьох факторів при плануванні та будівництві енергетичних об’єктів для забезпечення їх стабільної та ефективної роботи. Дослідження також підтвердило, що модель F1, яка використовує всі критерії з відповідними ваговими коефіцієнтами, дає найбільш достовірні результати для визначення оптимальних місць розташування енергетичних установок. Аналіз чутливості показав, що ця модель є найбільш ефективною для класифікації відповідних місць розташування порівняно з іншими растрами, такими як F2 та F3. Це підтверджує важливість врахування різних параметрів та їх впливу на вибір оптимальних місць для розміщення електростанцій. Отримані результати відкривають можливості для оптимізації використання сонячного та вітрового потенціалу в Республіці Косово, підтверджуючи можливість використання геодезичних та геоінформаційних даних для визначення оптимальних місць розташування енергетичних установок

**Ключові слова**: альтернативна енергетика; відновлювані ресурси; геоінформаційні системи; модель ієрархій; вагові коефіцієнти

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**Dmytro Mykhalevskiy***
Doctor of Technical Sciences, Professor
Vinnytsia National Technical University
21021, 95 Khmelnytske Shose, Vinnytsia, Ukraine
https://orcid.org/0000-0001-5797-164X

**Volodymyr Vasylyshyn**
Doctor of Technical Sciences, Professor
Ivan Kozhedub National Air Force University
61023, 77/79 Sumska Str., Kharkiv, Ukraine
https://orcid.org/0000-0002-5461-0125

**Vladyslav Riabkov**
Master, Student
Ivan Kozhedub National Air Force University
61023, 77/79 Sumska Str., Kharkiv, Ukraine
https://orcid.org/0009-0002-6765-1492

**Ruslan Myronenko**
Master, Student
Ivan Kozhedub National Air Force University
61023, 77/79 Sumska Str., Kharkiv, Ukraine
https://orcid.org/0009-0007-9037-2009

**Dmytro Bryl**
Master
Vinnytsia National Technical University
21021, 95 Khmelnytske Shose, Vinnytsia, Ukraine
https://orcid.org/0009-0009-6359-5156

# Method for improving the coverage efficiency of wireless sensor networks based on UAVs

**Abstract.** The purpose of this study was to adaptively optimise sensor networks using unmanned aerial vehicles to reduce information losses and ensure the minimum possible technical performance of information transmission channels in the face of a considerable number of architectural obstacles. In this study, experiments were conducted on data transmission via a wireless channel using Wi-Fi technology, where the access point was placed on an unmanned aerial vehicle. The study was conducted in complex architectural settings, using the 2.4 GHz and 5 GHz frequency bands to investigate the behaviour of radio channels and assess their effectiveness in real-world conditions. As a result of the study, a new method for estimating and optimising the energy parameters of radio channels was proposed, which accommodates the influence of a range of factors to improve the coverage efficiency of wireless sensor networks based on unmanned aerial vehicles. This method helped to partially solve the problem of information losses through adaptive optimisation of network coverage

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*Corresponding author

when influencing factors occur. The experimental models developed in this study allow estimating the signal distribution in space for sensor networks based on unmanned aerial vehicles, considering the influence of external factors, using fluctuation coefficients. The study also developed a mechanism for using a control device that allows measuring signal strength at any distance from the base station, providing flexibility and accuracy of assessment. The results showed a prominent level of measurement accuracy, with 95% reliability for an observation period of 20 seconds and an error of up to ±0.5 dBm. The total error of the methodology does not exceed 5%, which confirms the high reliability of the results and their compliance with real operating conditions. Thus, the findings of this study contribute to improving the efficiency and reliability of wireless sensor networks based on unmanned aerial vehicles, providing stable and high-quality connection in various operating conditions

**Keywords**: wireless sensor networks; wireless channel; energy parameters; throughput; model; UAV; statistical analysis; information loss

## INTRODUCTION

Wireless Sensor Networks (WSNs) play a significant role in technological systems, enabling continuous monitoring and data transmission in a variety of environments. The introduction of unmanned aerial vehicles (UAVs) into these networks opens new opportunities to increase their efficiency and flexibility. As a result, UAVs can serve as mobile base stations, enabling rapid network deployment in areas where the installation of fixed infrastructure is difficult or uneconomical. The use of unmanned aerial vehicles to create coverage for wireless sensor networks provides added benefits, such as the ability to respond quickly to changing conditions and reduce the cost of network maintenance and deployment. However, the introduction of UAVs into wireless sensor networks faces a range of challenges that limit coverage efficiency and connection stability. One of the main problems is the presence of architectural obstacles that affect signal propagation. Multi-storey buildings, walls, and other structures can considerably degrade signal quality, making it difficult to ensure reliable and stable connection between sensors and base stations. A method to improve the coverage efficiency of UAV-based wireless sensor networks can significantly help solve the problem of architectural interference. Thanks to the adaptive tuning capability of unmanned aerial vehicles, signal transmission routes can be optimised to avoid interference and minimise data loss (Seidaliyeva *et al.*, 2024). This approach also accommodates the impact of external factors, which helps ensure stable and reliable connection. The use of special algorithms to optimise the parameters of radio channels allows for efficient use of resources and high-quality coverage even in difficult conditions.

Internet of Things (IoT) devices have become widespread for offline data exchange and storage. The architecture of such networks is based on the use of various types of sensors or sensors to track and convert certain physical quantities into information signals for further processing. P. Karlin (2021) examined the impact of architectural solutions on the performance of IoT networks by investigating a modified method of interaction between IoT nodes. A. Sangaiah *et al.* (2020) also investigated the possibilities of optimising data exchange in IoT networks, considering the use of different types of sensors and sensors. V. Kryzhanovsky & S.P. Sergienko (2020) focused on the investigation of energy-efficient devices and their impact on the Internet of Things. However, despite the progress made, further research in this area is needed to further improve IoT networks and ensure their stable and efficient operation.

Considering the widespread use of wireless network technologies such as Wi-Fi, Bluetooth, and 4G/5G massive data systems, it is important to consider their diversity and application possibilities. M. Mollah *et al.* (2020) investigated the effectiveness of various wireless technologies in terms of their bandwidth, transmission range, and interference resistance, showing their advantages and disadvantages. Y. Zhuang *et al.* (2022) analysed the use of Bluetooth technologies in home automation systems, where it is important to ensure stable connection and low energy consumption. Q. Khanh *et al.* (2022) explored the potential for 4G/5G technologies to connect smart transport systems and infrastructure, confirming the significance of ensuring high data rates and low latency. However, it should also consider integrating other wireless technologies to create integrated and efficient data collection and processing systems that will ensure more efficient use of resources.

Another important factor is that wireless technologies can be used in various industries and households. P. Malik *et al.* (2021) considered the effectiveness of wireless technologies in production processes and their impact on increasing the productivity of industrial plants. A. Utsav *et al.* (2021) experimented with the implementation of wireless monitoring systems in military operations to optimise command and control processes and respond to military threats. S. Routray *et al.* (2020) also explored the possibilities of using wireless technologies for military purposes, to improve monitoring systems on the battlefield. At the same time, it is vital to continue research to improve the efficiency of wireless technologies in various areas, which will facilitate their rapid development and spread, as well as improve their functionality and reliability in general.

The purpose of this study was to develop and implement a new method for optimising sensor networks using UAVs to reduce information losses and increase data transmission efficiency in the face of a considerable number of architectural obstacles. The main objective of this study was to develop adaptive algorithms for estimating and optimising the energy parameters of radio channels, which accommodate the influence of various factors, to improve network coverage, and ensure stable connection. Another important task of the study is to develop experimental models for estimating the signal distribution in space and studying the influence of external factors, which will improve the accuracy of the estimation and ensure the reliability of the results in real-world operation.

## MATERIALS AND METHODS

A range of experimental studies were conducted to develop a method for estimating and optimising the energy parameters of radio channels. This study developed a methodology that involved the organisation of wireless information transmission channels using Wi-Fi technology. This technology was chosen as the main tool for data transmission due to its popularity among drone manufacturers thanks to its low power consumption and high efficiency.

Within the framework of the experiment, the Wi-Fi access point was placed on a UAV and acted as a model of an intermediate base station, which is important for creating an effective wireless network. During the research, a mobile measuring device was used, which moved within the network coverage area and simulated the sensor field. This helped to investigate the behaviour of radio channels in real conditions. To ensure maximum representativeness of the experiment, the study was conducted in two frequency bands: 2.4 GHz and 5 GHz, which made it possible to assess the efficiency of data transmission in different scenarios. Based on the findings obtained, two types of data transmission channels were created: between two unmanned aerial vehicles (UAV-UAV) and between an unmanned aerial vehicle and a sensor (UAV-sensor).

The studies were conducted in areas with complex architectural buildings, where significant architectural obstacles, such as buildings, walls, and other structures, could affect signal propagation. This helped to investigate the behaviour of wireless channels under real architectural constraints, which is important for the further development of networks that should function effectively in urban or similar environments. Furthermore, a variety of equipment for the channel between unmanned aerial vehicles was used for research. This included testing with different types of devices to get generalised results on the behaviour of the signal on different surfaces. This approach made it possible to detect signal fluctuations depending on the type of equipment used. Analysing such fluctuations helps to better understand the impact of different devices on the stability and quality of connection, which can be useful when planning and deploying networks.

Based on the proposed methodology, a series of studies of signal coverage from the intermediate base station used on UAVs were conducted, which provided important data on the efficiency of data transmission in real conditions involving unmanned aerial vehicles. To evaluate the properties of the radio channel in different frequency bands, the study first considered the results in the 2.4 GHz frequency band, which is typical for further analyses due to its general significance and analogous nature to other bands. Analogous studies were also conducted in the 5 GHz frequency band, including its upper 5.8 GHz part, which made it possible to examine the properties of the radio channel at higher frequencies in greater detail and assess its ability to ensure connection stability.

## RESULTS

The architecture of sensor networks can be represented as a four-tiered model that includes the sensor layer, data links, data processing layer, and application layer (Fig. 1).

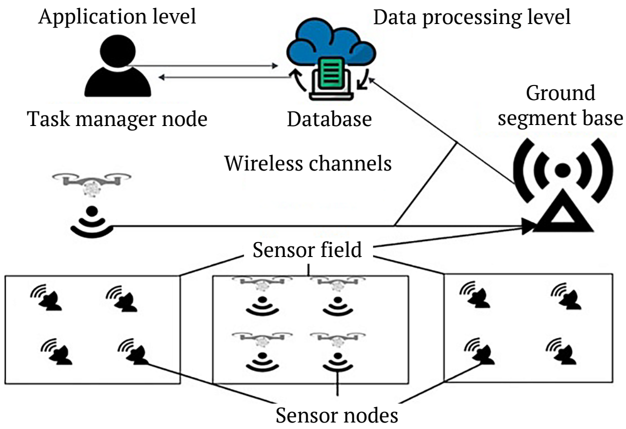



**Figure 1.** Structure of the sensor network
**Source:** developed by the authors of this study

The first is the sensor layer, which is responsible for monitoring certain environmental parameters. This layer consists of a variety of sensors combined into sensor nodes that can measure various physical quantities such as temperature, humidity, pressure. The capabilities and parameters of these sensors determine the purpose and type of the entire network. The next level is the information transmission channel, where the collected data is transferred from sensor nodes to central nodes or base stations. These channels can be either wireless or wired, depending on the specifics and requirements of the network. It is important to ensure the reliability and speed of information transmission for the effective functioning of the entire system (BenSaleh *et al.*, 2020).

The data processing layer is also a vital component of sensor network architecture, where the collected data is processed and analysed for further use. This involves filtering, aggregating, and interpreting data to extract useful information from raw measurements. Data can be processed both on-site, in sensor nodes, and in centralised computing systems (Cai & Shi, 2020). The fourth layer is the application layer, which is responsible for creating various services based on the processed data. Thus, the basic component of sensor networks is the sensor layer, which combines various sensors as part of sensor nodes. Sensor nodes form a so-called sensor field, which can be autonomous, directly subordinated to ground stations, or use intermediate base stations to collect and transmit data. Such stations can be either stationary or mobile. Fixed stations are usually located in fixed locations and provide continuous data collection and transmission. However, mobile stations that can be deployed on unmanned aerial vehicles offer much greater flexibility and efficiency (Kopetz & Steiner, 2020; Laghari *et al*., 2021).

UAV-based mobile stations act as repeaters, allowing for efficient coverage of large and hard-to-reach areas. This approach is known as clustering, where unmanned aerial vehicles act as mobile network nodes. Due to their mobility, unmanned aerial vehicles can quickly change their position, providing the optimised location for data collection and transmission. This is crucial in environments where a rapid response is required, such as natural disasters or military conflict zones. Additionally, the integration of sensors directly on the UAV opens new opportunities for monitoring. Such sensors can be used to create an entire UAV-based sensor field that can move and adapt to changes in the environment. In military applications, UAVs with sensors can be used for reconnaissance, battlefield surveillance, detection of enemy movement, and other important tasks (Tertyshnik *et al*., 2024). Mobile sensor networks based on UAVs allow for rapid deployment and reconfiguration of the network depending on the operational situation, which considerably increases the efficiency of military operations.

After converting the physical value into a digital code, the sensor transmits the information to the base station via a wireless channel created by the transceiver pair. This channel has several key parameters that determine its effectiveness. The main ones are the signal strength of the transmitters of both the sensor and the base station. Power defines coverage areas, with radii denoted as $r_1$ for the sensor and $r_2$ for the base station. To ensure efficient and symmetrical data transmission, the signal strength at the receiving end, denoted as Pm, must be sufficiently high. This is to avoid asymmetries that could lead to data loss or connection failures. A channel with a bandwidth of V must be available within the coverage area (denoted as ABh) to allow the transmission of data frames without delay to the base station of the terrestrial segment. The average value of the parameter Pm can be estimated by the following formula (1):

$$P_m \approx \frac{1}{T}\int_0^T P_m(t)dt \approx \frac{1}{n}\sum_{i=1}^{n} P_{m.i}, \tag{1}$$

where T – the observation period; n – the number of monitoring cycles.

The process of estimating $V_{pl}$ can be expressed as follows (2):

$$V_{pl} \approx \frac{1}{T}\int_0^T V_{pl}(t)dt \approx \frac{1}{n}\sum_{i=1}^{n} V_{pl.i}, \tag{2}$$

where $V_{pl.i}$ – the measurement of throughput during one monitoring cycle; n – the number of monitoring cycles during the observation period T to obtain the required reliability.

A range of experimental studies have been conducted to develop a method for estimating and optimising the energy parameters of radio channels with regard to influencing factors. A special methodology was created for this purpose. Wireless information transmission channels are often organised using Wi-Fi technology. This technology is popular among drone manufacturers because of its low cost and low power consumption of radio modules (Ertam *et al*., 2020). The use of Wi-Fi can substantially reduce the material costs of manufacturing UAVs, while maintaining high efficiency. Wi-Fi provides high-performance data links with low latency video streaming, high image quality, and interference resistance, which are critical requirements for special purpose networks (Chen *et al*., 2020). Within the framework of the experiment, the access point was placed on a UAV and served as a model of an intermediate base station. A mobile measuring device that moved within the coverage area simulated the sensor field, allowing for a detailed study of the behaviour of radio channels in real-world conditions. Two frequency bands were used for the research: 2.4 GHz and 5 GHz. This allowed for two types of data links to be created: one between two UAVs (UAV-UAV) and one between a UAV and a sensor (UAV-sensor), as presented in Figure 2.

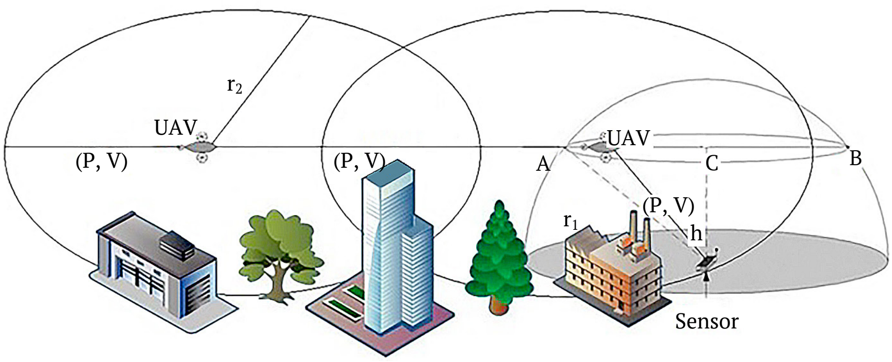
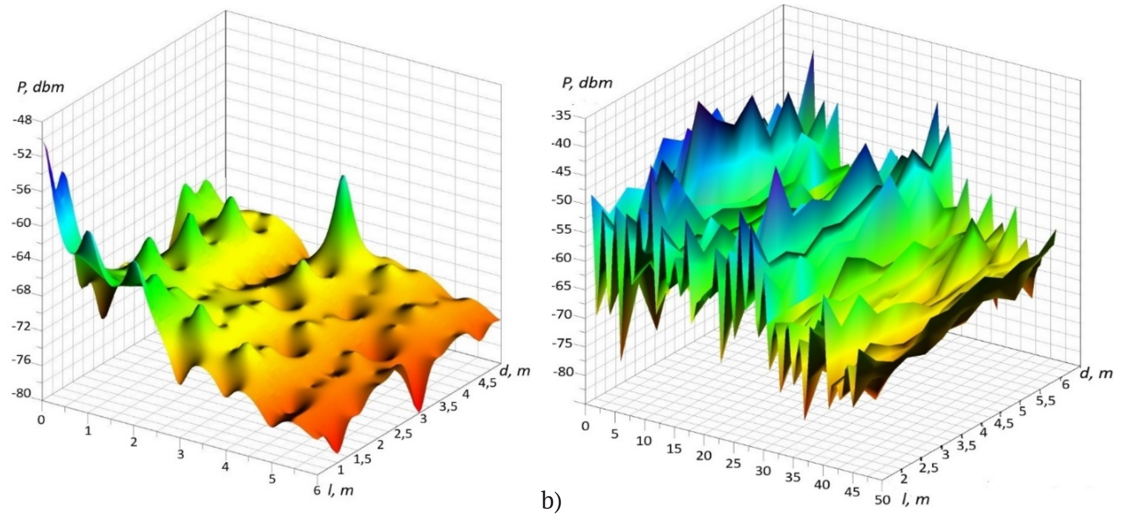



**Figure 2.** Structure of experimental studies of UAV-based network coverage in conditions of complex architectural obstacles

**Source:** developed by the authors of this study

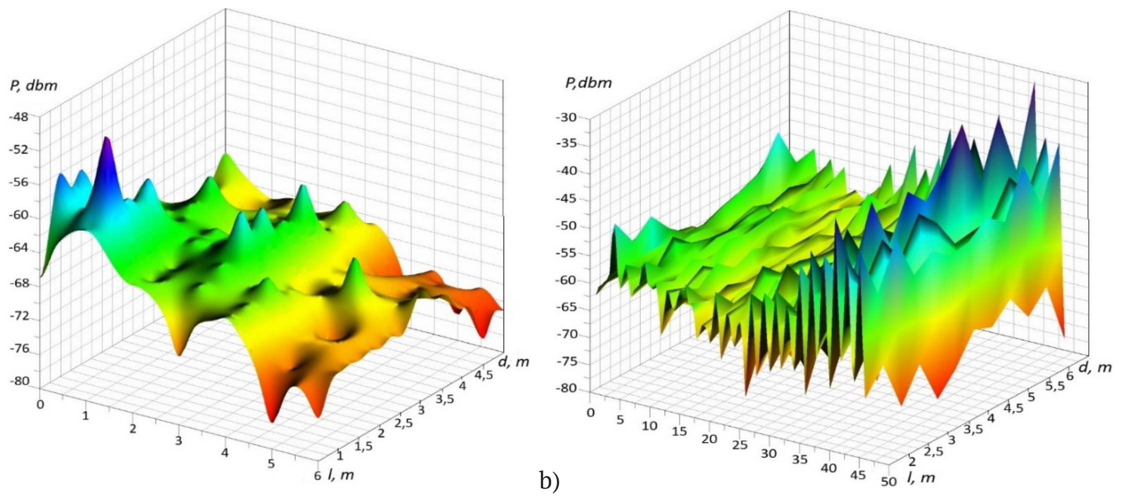
Based on the proposed methodology, a series of studies of signal coverage from an intermediate base station based on unmanned aerial vehicles were conducted. The results of the studies in the 2.4 GHz frequency band should be considered first, since they are typical for other bands and have an analogous nature. The signal power distribution for the channels between the UAV and the sensor, as well as between the two UAVs, is presented in Figure 3.




a) b)

**Figure 3.** Signal power distribution for the 2.4 GHz frequency band
**Note:** a) UAV-sensor channel; b) UAV-UAV connection diagram
**Source:** developed by the authors of this study

As Figure 3a shows, the UAV–sensor channel shows characteristic signal peaks and troughs near architectural obstacles. That is, when the signal crosses any architectural elements such as walls or poles, it can experience a considerable increase or decrease in power. For instance, when a signal passes through a building wall, it can lose some of its power due to absorption by the wall material or reflection. On the other hand, when a signal passes through an open area, its power can increase. As for Figure 3b, there is a difference between the different devices in terms of the constant attenuation factor. This means that different devices can have different levels of signal loss when passing through the same architectural obstacles. Such a difference in attenuation coefficients can lead to an increase in the jitter interval of up to 15 dBm. In some places, the signal may be significantly weaker or stronger than in other places, creating uneven connection quality. Analogous studies have also been conducted in the 5 GHz frequency band, specifically, its upper 5.8 GHz. Studies in this range allow examining the properties of the radio channel at higher frequencies, which can affect the ability to transmit data in demanding conditions and ensure connection stability. The data obtained are presented in Figure 4.




a) b)

**Figure 4.** Signal power distribution for the 5 GHz frequency band
**Note:** a) UAV-sensor channel; b) UAV-UAV connection diagram
**Source:** developed by the authors of this study

In this case, there is a different distribution of signal peaks and troughs compared to the previous results, as well as a higher attenuation coefficient, which may be due to the physics of wave propagation in this particular frequency range. Furthermore, for the UAV-UAV channel, there is a significant maximum between the two stations, where signal fluctuations can reach up to 20 dBm. Such indicators may indicate intensive interaction between devices and possible interference in the signal path, which affects its stability and reliability of data transmission (Saeed *et al.*, 2021). As such, channels in the 2.4 GHz band are proving to be more appropriate in terms of stability and range, due to their ability to penetrate obstacles such as walls and ceilings with less signal loss than higher frequencies. They can provide reliable connection at a distance and in conditions of limited line of sight between devices. However, 2.4 GHz channels have a rather narrow bandwidth, which can limit the data transfer rate, especially when there are many connected devices. Furthermore, this frequency band is also subject to significant interference and noise from other wireless devices, microwaves, Bluetooth devices, and other sources, which can result in signal loss and reduced data transmission efficiency.

The 5 GHz frequency band has a wider frequency spectrum compared to 2.4 GHz, which opens the possibility of creating a much larger number of frequency channels. These channels can be continuous or have a wide bandwidth, making them attractive for high-performance multimedia transmissions with minimal chance of architectural interference. The use of the 5 GHz band can be recommended for data exchange between UAV intermediate stations, where high bandwidth and reliability are important. However, one should consider the possibility of architectural interference, which can lead to signal loss and reduced data transmission efficiency. If sensor networks are used for bandwidth-constrained tasks, such as low-intensity data collection, it is more appropriate to use the 2.4 GHz band with narrowband channels. This can provide greater connectivity stability and less vulnerability to architectural interference and interference, which can be critical for data reliability in such scenarios (Shahraki *et al.*, 2020; Abdulsahib *et al.*, 2024).

To obtain an experimental model of the signal power distribution, it is important to consider the spatial aspect, which can be represented by two coordinates: l and d. However, in this case, a simplified model was used, where only the l coordinate corresponding to the line of sight was used. This simplification can introduce a certain error in the results, as it does not accommodate other factors, such as the distance d from the signal source. The results of the signal power distribution studies for the 2.4 GHz and 5 GHz frequency bands are presented in the form of graphs presented in Figure 5.

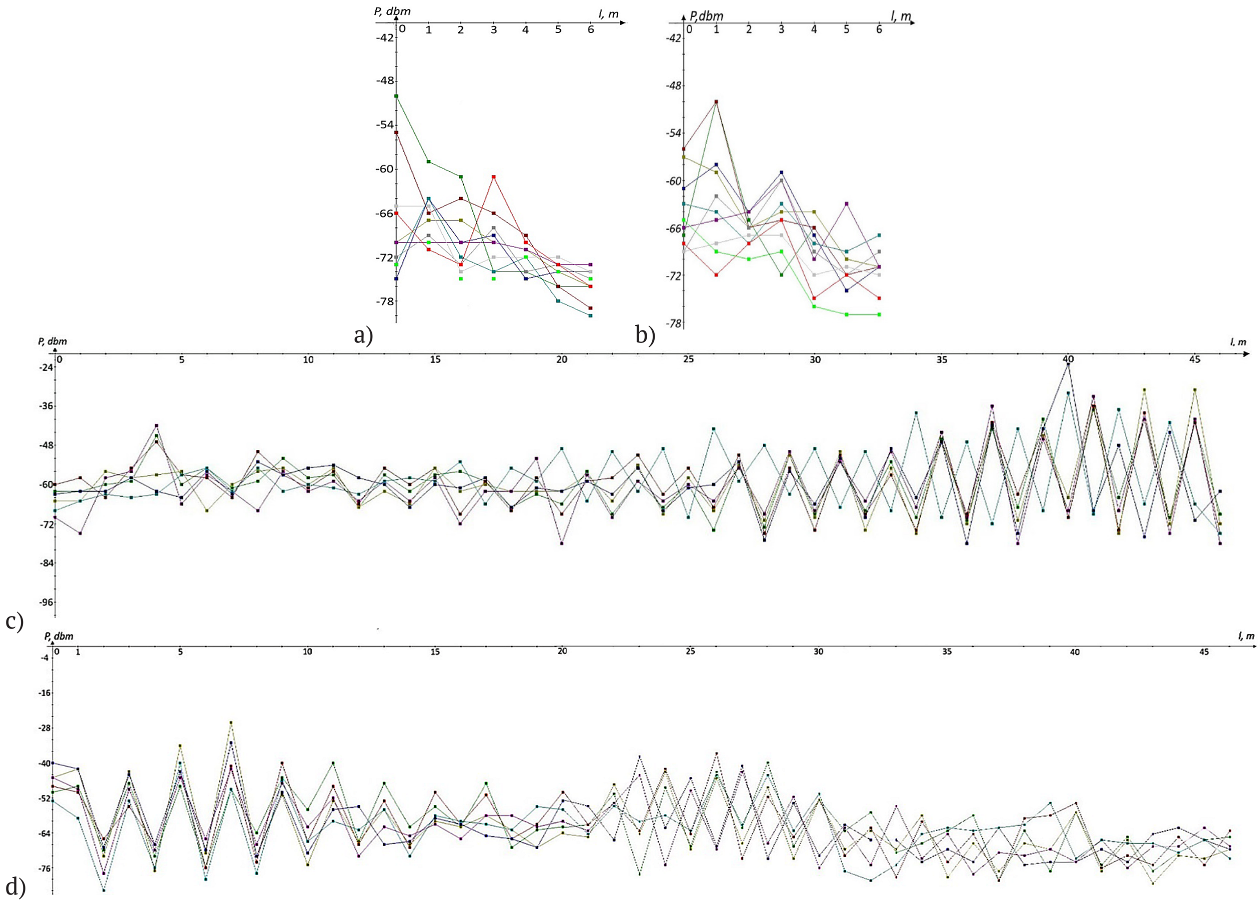



**Figure 5.** Research results for the 2.4 GHz band by line-of-sight coordinate
**Note:** a) 2.4 GHz “UAV-sensor”; b) 2.4 GHz “UAV-UAV”; c) 5 GHz “UAV-sensor”; d) 5 GHz “UAV-UAV”
**Source:** developed by the authors of this study

The analysis of Figure 5 suggests that the UAV-sensor channel is characterised by a quadratic fading law, which is typical for channels with a considerable influence of external factors. Specifically, this may include obstructions or other sources of interference that may cause harmful interference to signal transmission. To build a model of the signal power distribution (3) in space for the UAV-sensor channel, a regression analysis based on the line-of-sight coordinates can be used:

$$P_{US} = (a \pm \Delta a)l^2 + (b \pm \Delta b)l + k \pm \Delta k, \tag{3}$$

where a, b – the signal attenuation coefficients along the line-of-sight coordinate; k – the initial level; Δa, Δb, and Δk – the fluctuation parameters of the respective attenuation coefficients.

When analysing the UAV-UAV channel and separating the results into individual devices, it can be established that the signal power distribution model can be simplified to a linear nature as follows (4):

$$P_{UU} = (d \pm \Delta a)l + k \pm \Delta k, \tag{4}$$

where d – the signal attenuation coefficient along the line-of-sight coordinate.

By applying statistical analysis to the results presented in Figure 5, the attenuation and fluctuation coefficients for formulas (3) and (4) were determined, which indicate how the signal changes with distance or depending on other factors of influence. The obtained values of the attenuation and fluctuation coefficients were summarised and presented in Table 1.

**Table 1.** Attenuation coefficients

| | UAV-sensor | | | | | | UAV-UAV | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Coefficient | a | Δa | b | Δb | k | Δk | d | Δd | k | Δk |
| 2.4 GHz | 0.002 | **±0.002** | -0.2 | **±0.1** | -65 | **±5** | 0.13 | **±0.03** | 62 | **±2** |
| 5 GHz | 0.005 | **±0.003** | -0.5 | **±0.3** | -55 | **±5** | 0.3 | **±0.5** | 55 | **±2** |

**Source:** developed by the authors of this study

Thus, formulas (3) and (4) provide a means to assess and predict the level of signal coverage, accommodating a range of factors of influence, by using fluctuation intervals. They allow accommodating the influence of various variables, such as the distance between devices, architectural obstacles, and other factors that can affect signal stability. Based on models (3) and (4), which reflect the signal distribution in space for the sensor field and the intermediate station, a new method for estimating and optimising the energy parameters of radio channels was developed, considering the influence of a range of factors. This method includes several stages, which will be discussed in greater detail below.

At the first stage, the software and hardware of the receiving device are used to estimate the signal power at the receiver input ($P_m$). The evaluation is carried out based on the average statistical value of the parameter $P_m$, which is calculated according to formula (1). To obtain this value, an observation period of 5 seconds and a monitoring cycle of 1 second are used. This stage allows collecting data on signal strength and creating a basis for further analysis and optimisation of radio channel parameters.

At the second stage, the network coverage area is determined based on mathematical models (3) and (4), which consider the signal distribution in space. For this, a control sensor is used, which is placed at a certain distance from the base station, but within the coverage area. This distance can be set arbitrarily and is denoted as $l_0$. The control sensor records the signal strength it receives when it is located at a certain distance from the base station. The data received from the control sensor allows applying mathematical expressions to describe the distribution of the signal in space, making it possible to accurately determine the zone where the signal values fluctuate from minimum to maximum, and providing the necessary signal strength for stable and reliable connection. The resulting formula (5) based on model (3) allows quantifying the network coverage area, considering the factors of influence:

$$P_{US} = (a \pm \Delta a)(l^2 - l_0^2) + (b \pm \Delta b)(l - l_0) + P_m + \Delta P, \tag{5}$$

where ΔP – the level of signal power fluctuations, which is defined as follows (6):

$$\Delta P \approx \frac{1}{2}\left(\frac{1}{n}\sum_{j=1}^{n} \max\{P_{m.i}\}_j - \frac{1}{n}\sum_{j=1}^{n} \min\{P_{m.i}\}_j\right), \tag{6}$$

where n – the number of observation periods for obtaining experimental characteristics $P_m(l)$.

For instance, the calculations for the UAV-sensor channel based on the measurement of the control sensor are considered. A fragment of the calculation is presented in Figure 6. Thus, one can analyse the level of maximum and minimum signal values based on fluctuation intervals, which allows predicting the impact of various factors on the signal. This approach involves the use of a pre-built database, which helps to predict and analyse the impact of factors on radio communications more accurately.

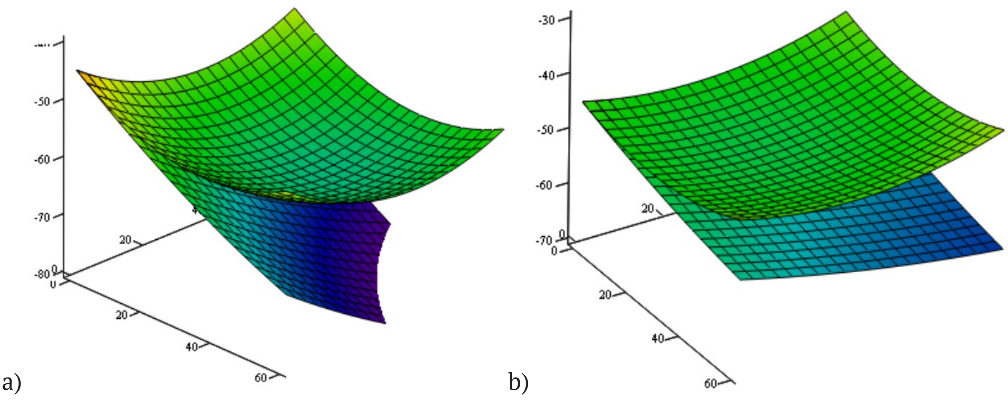


**Figure 6.** Fragment of network coverage based on reference measurement for the UAV-sensor channel
**Note:** a) for the 2.4 GHz band; b) for the 5 GHz band
**Source:** compiled by the authors of this study

The third stage involves assessing the bandwidth, which is a key indicator of the radio channel's efficiency. For this, one can use statistical matching coefficients, which reflect the degree of correspondence between the estimated and factual channel capacity. Statistical coefficients accommodate a range of factors such as interference, signal fading, and other specific channel characteristics. The use of statistical relationships makes it possible to make predictions about the possibility of data transmission in specific conditions and to adjust the radio channel to achieve optimised throughput (Mykhalevskiy, 2020). The static relationship can be expressed as follows (7):

$$V_{pl}(l) \approx K(P_{БС} \pm \Delta P) + S_0 \pm \Delta V, \qquad (7)$$

where K – the correlation coefficient between the signal power at the receiver input and the bandwidth; $S_0$ is the initial coefficient; ΔV – the bandwidth fluctuation interval, which is defined as follows (8):

$$\Delta V \approx \frac{1}{2n}\sum_{i=1}^{n}\left(\max\{V_{m.i}\}_j - \min\{V_{m.i}\}_j\right), \qquad (8)$$

The results of experimental studies of the throughput for the UAV-sensor channel are presented in Figure 7.

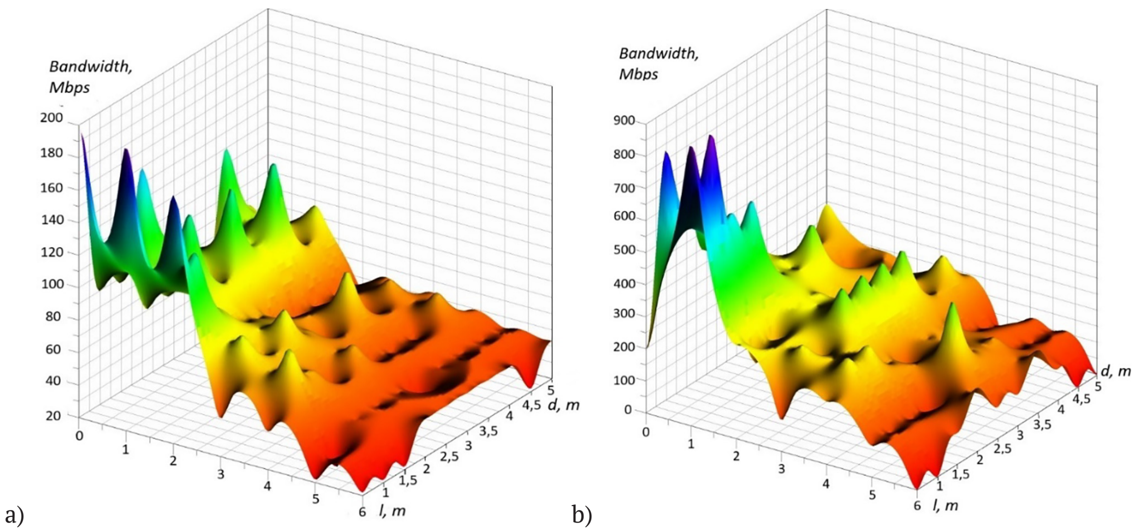



**Figure 7.** Measurement results of throughput values for the UAV-sensor channel
**Note:** a) for the 2.4 GHz band; b) for the 5 GHz band
**Source:** developed by the authors of this study

The obtained results and the expression of the statistical relationship (7) allow establishing a correspondence between the radio channel bandwidth and the required minimum signal power level.

This process is carried out considering the fluctuation interval, which is allocated to ensure that information loss in the network is minimised. This analysis helps to determine exactly what signal power values are required to ensure optimised channel throughput under different connection conditions, which allows for efficient radio channel management and minimises data loss during transmission.

At the fourth stage, the need to adjust the coverage area to ensure the minimum required channel capacity is assessed, including an analysis of the signal power fluctuation intervals (ΔP) and bandwidth (ΔV). The correction interval, denoted as Δl, is defined as the minimum signal power value that allows maintaining the required channel bandwidth. This stage involves detailed signal modelling and analysis to identify the points where changes need to be made to ensure stable and efficient connection. Based on the data obtained, the coverage area can be optimised to minimise signal loss and provide the required throughput even in areas with high fluctuations. An example of determining the correction interval Δl is presented in Figure 8.

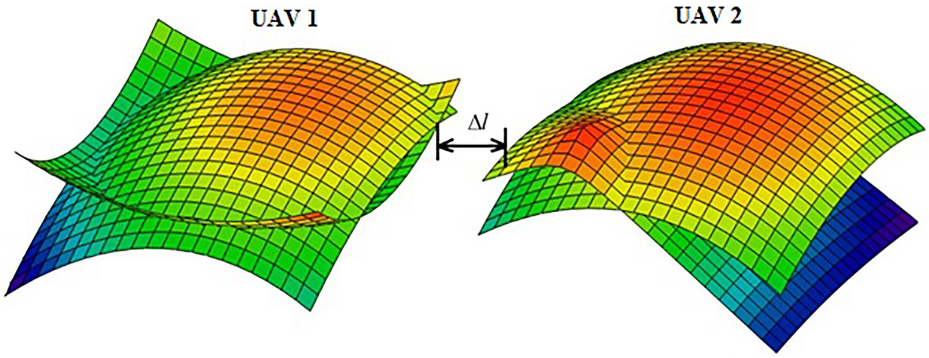



**Figure 8.** Estimating the adjustment interval
**Source:** developed by the authors of this study

As Figure 8 shows, between the coverage areas created by UAV1 and UAV2, there is an area with insufficient signal strength, denoted by the length Δl, where the signal strength is lower than the minimum required. In this zone, information losses may occur, such as delayed video stream transmission, errors in information frames, added transmission cycles, and other problems. Therefore, in such a situation, it is necessary to adjust the coverage area to ensure a stable signal strength and minimise information loss, which is crucial for maintaining the efficient operation of the network.

The fifth stage involves deriving the estimation results, considering the fluctuation intervals specified in formulas (6) and (8), as well as measurement errors. At this stage, the error minimisation operation and coverage optimisation are performed. This is achieved by adjusting the Δl parameter, which defines the area with insufficient signal strength. Due to the mobility of UAVs, their position can be adjusted to ensure that the minimum required channel capacity is set (Meng *et al.*, 2022). Thus, this stage involves the dynamic adjustment of the position of unmanned vehicles to achieve optimised network coverage and ensure stable and reliable data transmission, minimising the impact of negative factors.

The proposed method is relatively simple and affordable, since it is based on the control measurement of the energy parameter Pm using the sensor's software and hardware or a subscriber device. The parameter $P_m$ is estimated within the range of coverage from the UAV, using the parameter $l_0$ within the sensor field. This involves placing sensors at different points in space to measure the strength of the signal reaching them from the base station to the UAV, enabling the creation of a detailed picture of the signal distribution in space. The reliability of the results used to create the experimental surfaces with an observation period of 20 seconds is 0.95 with an error of up to σP±0.5 dBm, confirming their accuracy and reliability. Even when the observation period is reduced to 5 seconds, the error stays within σP±1 dBm, which ensures an error of no more than 5%. This level of accuracy is sufficient for most practical applications. The accuracy of the measurement of the parameter $P_m$ also depends on the characteristics of the sensor receiver and the parameter database of the statistical connection model $V_{pl}$ for different devices, which indicates the significance of having such a base for correct evaluation and optimisation. Thus, this method allows collecting reliable data on the energy parameters of radio channels used in the network and ensure their optimisation, accommodating the influence of a range of factors. This helps to increase the efficiency of the wireless sensor network by ensuring stable and high-quality data transmission, minimising losses, and improving overall system performance.

## DISCUSSION

Research in the field of wireless sensor networks based on unmanned aerial vehicles is of significant importance for technological development. Such networks are critical to ensure continuous monitoring and data collection in a variety of environments, from small urban areas to remote areas. The detailed investigation of wireless sensor networks can make a considerable contribution to the development of modern technologies, allowing to optimise the efficiency and reliability of such networks, and ensuring stable connection even in challenging conditions. The development of new methods for assessing and optimising the energy parameters of radio channels will help reduce information losses and ensure efficient data transmission (Lavdanskyi *et al.*, 2022). In addition, new advances in this area may contribute to the development of innovative technologies that will automate and optimise processes in these industries. They will improve data collection and processing, which will open new opportunities for efficient use of resources and provide generally more accurate and prompt decisions.

The experiment carried out within the framework of this study drew attention to the study of radio channels in real conditions. The access point placed on the UAV acted as a model of an intermediate base station, creating unique conditions for connection analysis. Particular attention was paid to the use of two frequency bands – 2.4 GHz and 5 GHz, which made it possible to obtain comprehensive data on the efficiency of signal transmission in different frequency spectra. Comparing the results in both bands helped to understand how frequency affects the quality of connection and helped us determine the optimised parameters to improve network efficiency. Z. Al Aghbari *et al*. (2020) also addressed significant aspects of the efficiency of wireless sensor networks, including their adaptive optimisation and reduction of information loss. T. Vaiyapuri *et al*. (2022) focused on improving methods for analysing radio channels in different operating conditions, which ultimately contributed to increasing the reliability and stability of connection. J. Bhola *et al*. (2020) developed new network optimisation strategies to maximise performance and speed, which proved to be a major step in the development of wireless sensor networks. However, when comparing the findings of the cited studies with the results of the present study, it should be noted that the latter allowed considering a wide range of factors, including the impact of different frequency bands, external interference, and other factors affecting the quality of connection. Quick progress has also been made in developing new methods for assessing and optimising the energy parameters of radio channels, which makes it possible to increase the network's resilience and efficiency (Sabibolda *et al*., 2022). This analysis opens new prospects for further research and development of wireless sensor networks based on UAVs.

It should also be emphasised that the experimental results indicate that the channels in the 2.4 GHz band are more appropriate in terms of stability and wave propagation range. Their ability to penetrate obstacles such as walls and ceilings with less signal loss than higher frequencies enables reliable connection over distance and in conditions of limited line-of-sight between devices. However, 2.4 GHz channels have limited bandwidth, which can limit data rates and increase vulnerability to interference from other wireless devices. At the same time, the 5 GHz frequency band has a wider frequency spectrum, which opens the possibility of creating more frequency channels. Such channels can be either continuous or have a wide bandwidth, making them attractive for high-performance multimedia transmissions with minimal architectural interference (Kabdoldina *et al*., 2022). The use of the 5 GHz band is recommended for data exchange between UAV intermediate stations, where high bandwidth and reliability are significant. However, considering the possibility of architectural interference that can affect the quality of connection, it is important to choose this range with special attention. H. Khan *et al*. (2020) also analysed the impact of various data transmission parameters on the performance of wireless sensor networks depending on the selected frequency range, which revealed key factors for optimising parameters to achieve maximum data transmission efficiency in concrete operating conditions. K. Qureshi *et al*. (2020) investigated the impact of network configuration and node location on connection efficiency in wireless sensor networks, allowing to identify optimised strategies for node location and network configuration to achieve the best performance and reliability of connection. Thus, the findings of these studies can complement the present study, expand its scope, and improve the understanding of the processes occurring in wireless sensor networks based on UAVs, accommodating various aspects of their operation and optimisation.

As a result of the present study, the proposed method proved to be effective and easy to use. It is based on the control measurement of the energy parameter $P_m$, which is important for evaluating the performance of radio channels in wireless sensor networks. The use of sensor hardware and software or a subscriber device simplifies the process and allows measurements to be carried out without significant difficulty. The estimation of the parameter $P_m$ takes place within the range of coverage from UAVs, which ensures the reliability and accuracy of the obtained findings. The use of the $l_0$ parameter within the sensor field, which allows obtaining detailed information about the distribution of the signal in space, should be highlighted. Placing sensors at separate locations allows detecting variations in signal strength and identifying optimised solutions to improve network efficiency, making it possible to accommodate real-world conditions and adapt the system to changes in the environment. S. Chatterjee *et al*. (2021) also investigated the impact of adaptive network coverage optimisation on the resistance to interference from other wireless devices, which revealed valuable findings for reducing the impact of interference and improving connection reliability. J. Akram *et al*. (2022) focused on the use of adaptive sensors to optimise target coverage in wireless sensor networks, helping to determine the optimised configuration of the network and its parameters to maximise performance and minimise signal loss. Comparison of the findings of the present study with the results of the cited studies suggests that the proposed method is effective in comparison with other strategies for optimising a network based on unmanned aerial vehicles. The identified differences in approaches and results offer a better insight into how different parameters and strategies affect network performance in different operating conditions. This analysis helps us to determine the optimised parameters and optimisation methods to improve connection quality and ensure network reliability.

It is also worth emphasising the reliability of the findings of the present study, which helped to draw significant conclusions to ensure the reliability and accuracy in assessing the energy parameters of radio channels. Based on the data obtained during the observation period of 20 seconds, it was found that the reliability is 0.95, with an error of up to ±0.5 dBm. This demonstrates the high accuracy and reliability of the findings obtained, which makes them credible for further use in practical applications. Even when the observation period is reduced to 5 seconds, the error stays within ±1 dBm, which ensures an overall error of no more than 5%. This elevated level of accuracy is important given the wide range of applications for this data. Notably, the accuracy of the measurement of the Pm parameter also depends on the characteristics of the sensor receiver and the availability of a database of parameters of the model of statistical connection $V_{pl}$ for various devices. This indicates the significance of having and using such a database correctly to ensure adequate evaluation and optimisation of radio channels. Correctly selected parameters of the statistical link model play a key role in ensuring high accuracy of energy parameter estimation, which is an essential aspect for ensuring the efficiency and reliability of wireless networks (Bloshchynskyi & Klyatchenko, 2023). M. Nguyen *et al*. (2021) examined the process of data collection using UAVs in wireless sensor networks, opening new opportunities for understanding the interaction between radio channels. M. Nomikos *et al*. (2020) investigated the dynamics of changes in energy parameters during the movement of sensor devices, which provided valuable information on the adaptation of wireless networks to changes in operating conditions. However, the findings of the present study, in comparison with the cited research, helped to analyse the impact of external factors on the parameters of radio channels in greater depth and develop effective strategies to optimise their operation in a changing environment.

Thus, achievements and developments in this area are important for the development of wireless sensor networks based on unmanned aerial vehicles, helping to understand and optimise energy parameters and dynamics of changes in different conditions. They contribute to the creation of more efficient and reliable data transmission systems, which is of significant importance in the digital world, ensuring high performance and resilience of such technologies to external influences.

## CONCLUSIONS

As a result of this study, a new method for estimating and optimising the energy parameters of radio channels was proposed, which accommodates the influence of a range of factors to improve the coverage efficiency of wireless sensor networks based on UAVs. This method is aimed at partially solving the problem of information loss by adaptively optimising network coverage when influencing factors occur. During the research, experimental models were obtained that allow estimating the signal distribution in space for sensor networks based on UAVs. These models accommodate the impact of external factors using fluctuation coefficients. Specifically, a mechanism was developed to use a control device that allows measuring signal strength at an arbitrary distance from the base station, providing flexibility and accuracy of assessment.

The reliability of the findings was confirmed by the prominent level of measurement accuracy. For an observation period of 20 seconds, the reliability is 95%, with an error of up to ±0.5 dBm. For shorter observation periods, such as 5 seconds, the error increases to ±1 dBm. The total error of the methodology does not exceed 5%, which ensures high reliability of the findings and their compliance with real operating conditions. This approach ensures efficient optimisation of sensor network coverage, considering both spatial and energy parameters, which significantly improves connection quality and reduces information loss. Thus, the new method helps to increase the efficiency and reliability of wireless sensor networks based on UAVs, providing stable and high-quality connection in various operating conditions. Notably, the study focused mainly on standard environmental conditions, which may not consider all possible variations in real field conditions. Furthermore, the use of specific UAV models and sensors may affect the universality of the results obtained, which also requires added attention and study.

Areas for further research could include extending the analysis to more diverse environmental conditions and further investigating the impact of different UAV models and sensors on the findings. It is also worth exploring the possibilities of applying the methods to a wider range of applications, including security, environmental monitoring, and intelligence, which will allow for further improvement of unmanned vehicle systems and wireless sensor networks for more accurate and efficient use in various industries.

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## CONFLICT OF INTEREST

None.

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**Дмитро Михалевський**
Доктор технічних наук, професор
Вінницький національний технічний університет
21021, Хмельницьке шосе, 95, м. Вінниця, Україна
https://orcid.org/0000-0001-5797-164X

**Володимир Василишин**
Доктор технічних наук, професор
Харківський національний університет Повітряних Сил імені Івана Кожедуба
61023, вул. Сумська, 77/79, м. Харків, Україна
https://orcid.org/0000-0002-5461-0125

**Владислав Рябков**
Магістр, студент
Харківський національний університет Повітряних Сил імені Івана Кожедуба
61023, вул. Сумська, 77/79, м. Харків, Україна
https://orcid.org/0009-0002-6765-1492

**Руслан Мироненко**
Магістр, студент
Харківський національний університет Повітряних Сил імені Івана Кожедуба
61023, вул. Сумська, 77/79, м. Харків, Україна
https://orcid.org/0009-0007-9037-2009

**Дмитро Бриль**
Магістр
Вінницький національний технічний університет
21021, Хмельницьке шосе, 95, м. Вінниця, Україна
https://orcid.org/0009-0009-6359-5156

# Метод підвищення ефективності покриття безпровідних сенсорних мереж на базі БПЛА

**Анотація.** Дане дослідження спрямоване на адаптивну оптимізацію сенсорних мереж із використанням безпілотних літальних апаратів для зменшення інформаційних втрат і забезпечення мінімально можливих технічних показників каналів передачі інформації в умовах значної кількості архітектурних перешкод. В ході роботи було проведено експерименти з передачі даних через безпровідний канал за допомогою технології Wi-Fi, де точка доступу була розміщена на безпілотному літальному апараті. Дослідження проводилися в умовах складної архітектурної забудови, з використанням частотних діапазонів 2.4 ГГц та 5 ГГц, щоб детально вивчити поведінку радіоканалів та оцінити їх ефективність у реальних умовах. В результаті дослідження було запропоновано новий метод оцінювання та оптимізації енергетичних параметрів радіоканалів, який враховує вплив різних факторів для підвищення ефективності покриття безпровідних сенсорних мереж на основі безпілотних літальних апаратів. Даний метод дозволив частково вирішити проблему інформаційних втрат через адаптивну оптимізацію покриття мережі під час виникнення впливових факторів. Експериментальні моделі, розроблені в ході дослідження, дають можливість оцінювати розподіл сигналу в просторі для сенсорних мереж на базі безпілотних летальних апаратів із врахуванням впливу зовнішніх факторів, завдяки використанню коефіцієнтів флуктуацій. Також в роботі було розроблено механізм використання контрольного пристрою, що дозволяє вимірювати потужність сигналу на будь-якій відстані від базової станції, забезпечуючи гнучкість та точність оцінювання. Отримані результати показали високий рівень точності вимірювань, з достовірністю 95 % для періоду спостереження в 20 секунд і похибкою до ±0.5 дБм. Загальна похибка методики не перевищує 5 %, що підтверджує високу надійність результатів та їх відповідність реальним умовам експлуатації. Таким чином, результати дослідження сприяють підвищенню ефективності та надійності безпровідних сенсорних мереж на базі безпілотних летальних апаратів, забезпечуючи стабільний і якісний зв'язок у різних умовах експлуатації

**Ключові слова**: безпровідні сенсорні мережі; безпровідний канал; енергетичні параметри; пропускна здатність; модель; БПЛА; статистичний аналіз; інформаційні втрати

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**Iryna Hrytsiuk***
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0003-4472-306X

**Vladyslav Volynets**
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-9192-2785

**Nataliia Komenda**
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-5944-8665

**Yurii Hrytsiuk**
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-6463-3910

**Andrii Hadai**
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-4195-7218

# Modelling the optimal switching scheme of the Ukrainian power grid during blackout (Volyn region)

**Abstract.** The relevance of the study, in particular, in the Volyn region, is due to the need to ensure the reliability and efficiency of the energy infrastructure in the face of growing challenges associated with the war between Russia and Ukraine, technological development and ensuring the country's energy security. The purpose of the study is to develop a model of the optimal switching scheme for the Volyn region's power grids during blackout to minimize the negative consequences and ensure priority power supply to critical facilities. The methods used include mathematical modelling, simulation, optimization, sensitivity analysis, and others. The study optimized the power grid switching scheme under the risk of war and other crisis situations, including a thorough analysis of various options in the event of a blackout. Taking into account additional aspects of grid safety and reliability, the optimal routes for power transmission, placement of backup power sources were identified and effective algorithms for grid management were developed. By optimizing the grid switching

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*Corresponding author

scheme, the damage caused by blackouts can be minimized, and power supply can be restored quickly. The results confirmed that an optimal switching scheme can significantly reduce blackout time and its impact on the economy and the lives of the population. The development of optimal switching schemes for power grids is an important step towards increasing the resilience of Ukraine's electricity system to crisis situations. The study has highlighted the importance of developing such models to ensure energy security and resilience of the power grid under the threat of blackouts, which affects the practical aspects of power supply management and economic development. The practical significance of the study is to improve strategies for managing the power grid in blackout conditions, contributing to the resilience of energy systems and economic development

**Keywords**: stability of electricity supply; emergencies; consumption measurement schedule; load analysis; blackout risk assessment

## INTRODUCTION

The study of the optimal grid switching scheme during a blackout in Ukraine is an extremely important task in the current energy environment. Blackouts can lead to serious consequences for the economy, security, and public health, so it is important to actively work on developing and optimizing models aimed at minimizing their impact and ensuring reliable power supply to critical facilities. Given the growing threats from the war with Russia, effective strategies for managing the power grid in the face of unpredictability are becoming an urgent necessity. Research in this area will not only help to understand the risks and potential threats to the energy system, but will also contribute to the development of practical solutions for their effective management in times of uncertainty and emergency.

The relevance of the study is manifested in the consideration of the possibility and realism of scenarios where the energy system is subjected to constant shelling, especially in frontline areas. Even if an effective blackout prevention system is in place, these areas remain vulnerable to the constant threat of shelling, which can cause interruptions in power supply and negatively affect the safety and lives of the local population. In addition, the study focuses on the protection of critical infrastructure such as hospitals, water supply and transport hubs, which are vital for the functioning of society in times of crisis. The problem is the lack of effective measures to protect the power grid from such situations, which requires the development and implementation of power grid management strategies that consider the worst-case scenario of constant shelling. This research approach will help to identify opportunities and limitations in managing the power grid under continuous threat, which will allow developing effective measures to ensure the sustainability of energy supply and public safety in the context of military conflicts.

According to the study by S. Denisyuk *et al.* (2022), it is crucial to consider the impact of renewable energy sources on grid resilience and develop strategies to overcome the challenges associated with them. However, the study does not focus on optimizing the grid switching scheme in the context of war and crisis situations. In the study by D. Ostrenko & O. Kollarov (2022), the main emphasis is on the importance of using artificial intelligence to improve the efficiency of grid management. However, the paper does not study the various options for action in the event of a blackout, which is necessary for a thorough analysis. In conformity with the study by S. Kiyko *et al.* (2022), the implementation of energy efficiency strategies has the potential to improve competitiveness and sustainability in the industrial sector. However, the study does not cover additional aspects of grid security and reliability.

A study by S. Matyakh *et al.* (2021) highlights global trends in the use of solar energy and their impact on the energy sector. However, it does not analyse the optimal routes for energy transmission and the placement of backup power sources. Researchers A. Oleshko & K. Pavlyuk (2022) highlight the importance of using smart technologies to improve the security of energy supply in urban areas. However, the study does not investigate effective algorithms for managing the power grid in crisis situations. The paper by S. Onyshchenko *et al.* (2023) raises the important issue of developing effective models for managing the power grid in blackout conditions as a key task for ensuring the country's energy security. However, the study does not consider the possibility of reducing the blackout time and its impact on the economy and life of the population, provided that an optimal switching scheme is implemented.

The purpose of this study is to create an optimal model for switching the power grid in Volyn region during blackout to reduce the negative consequences and ensure priority power supply to critical facilities.

## MATERIALS AND METHODS

The mathematical modelling method helped to calculate the optimal parameters of the power grid, determine the system's capacity and reserves, and predict the impact of various blackout scenarios on the operation of the power grid. Modern mathematical methods, such as linear programming, dynamic programming, and optimization theory, made it possible to consider complex interactions between different components of the system and find optimal solutions for managing power supply. Mathematical modelling has also made it possible to assess risks and develop grid management strategies that will be most effective in blackout conditions.

The use of simulation methods made it possible to recreate various blackout scenarios and conduct a detailed analysis of their impact on the operation of the power grid. This method made it possible to simulate different scenarios and test different strategies for managing power supply in contingency situations. Simulation models can take into account various factors, such as weather conditions, technical condition of the power grid, electricity demand, and others, which allowed for comprehensive research of the situation and informed decisions on power grid management. Supervisory Control and Data Acquisition (SCADA) was used for modelling and simulation of power grids in the study. This software package provided a user-friendly interface for developing mathematical models and simulations.

The optimization method allowed us to find optimal solutions for managing the power grid in blackout conditions. This method was to identify the most effective parameters and strategies that ensure maximum reliability and efficiency of the power supply system. The use of optimization methods allowed us to find the optimal allocation of resources, determine the best time to activate backup power sources, and develop optimal strategies for restoring power supply after a blackout. This method helped reduce energy consumption, ensure system stability, and reduce the risk of emergencies. The application of the sensitivity analysis method made it possible to determine the impact of changes in the initial parameters on the results of modelling and controlling the power grid during blackout. This method helped to identify key factors that affect the effectiveness of management strategies and take them into account in the decision-making process. The sensitivity analysis helped identify the most critical system parameters and their interrelationships, which contributed to the development of more accurate and reliable grid management models. The sensitivity analysis helped identify the most critical system parameters and their interrelationships, which led to the development of more accurate and reliable grid management models.

Stochastic modelling methods were used to study random variables and uncertainty in the power supply system during blackouts. This method made it possible to take into account the probability of different scenarios and consider their impact on the operation of the power grid. The use of stochastic modelling methods helped to assess risks and develop management strategies that would be most effective under conditions of uncertainty. This method helped to consider various factors, such as changes in energy demand, weather conditions and the technical condition of equipment, and to consider their impact on the operation of the grid. The application of the system analysis method helped to study the power grid as a complex system with numerous interconnected components and processes. This method made it possible to consider the power supply system as an integral structure, considering the interaction between its various components. The application of system analysis helped to identify key links and dependencies between different elements of the system and understand their impact on the operation of the power grid in blackout conditions. This method allowed us to develop comprehensive management strategies that would be the most effective and optimal for ensuring the resilience and reliability of the power grid.

The Markov process method was a powerful tool for modelling and analysing stochastic processes. It was based on the Markov property, which implied that the future state of a system depended only on its current state, not on previous states. In this study, the Markov process method was used to model transient processes in the power grid and to analyse their dynamics during blackouts. Formula of the Markov process method (1):

$$P(X_{n+1}=x|X_n=x_n, X_{n-1}=x_{n-1}, \dots, X_0=x_0)=P(X_{n+1}=x|X_n=x_n), \quad (1)$$

where $P(X_{n+1}=x|X_n=x_n, X_{n-1}=x_{n-1}, \dots, X_0=x_0)=P(X_{n+1}=x|X_n=x_n)$ – the conditional probability of transition to state x at time n + 1, provided that the system is in state $x_n$ at time n, $x_{n-1}$ at time, N - 1, and so on up to $x_0$ at time 0; $X_n$ – the state of the system at time n, x is a specific state of the system; n is the time.

The Monte Carlo method was an effective tool for numerical modelling of complex systems or processes using random variables. By using random variables, this method allowed the evaluation of various model parameters and their impact on the results. In this study, the Monte Carlo method was used to study the sensitivity of the power grid to various parameter changes during blackouts. The formula for the Monte Carlo method to assess the sensitivity of the power grid to various parameter changes during blackout is presented as follows (2):

$$\widehat{I} = \frac{1}{N}\sum_{i=1}^{N} f(x_i), \quad (2)$$

where $\widehat{I}$ – an estimate of the expected value of the performance indicator or model result; N is the number of iterations used in the Monte Carlo method; $f(x_i)$ – the value of the function or performance indicator for each iteration i; $x_i$ – a random variable generated at the i-th iteration.

This formula allows estimating the expected value of a certain parameter or modelling result using random variables and the average value of N iterations.

## RESULTS

Modelling the optimal switching scheme for power grids during a blackout is a key aspect of ensuring the resilience and efficiency of power supply in emergency situations. This complex technical process requires an integrated approach and consideration of various factors affecting the power grid. The modelling needs to take into account the availability of resources such as generating capacity and network equipment, as well as the needs of consumers at different times (Venkatanagaraju & Biswal, 2022). In addition, it is important to consider possible risks and constraints, such as transmission line capacity constraints and potential equipment failures. Only by carefully analysing these factors can an optimal switching scheme be developed that will ensure a reliable and efficient power supply during a blackout. Block diagram of power grid management considering unforeseen situations (Fig. 1).

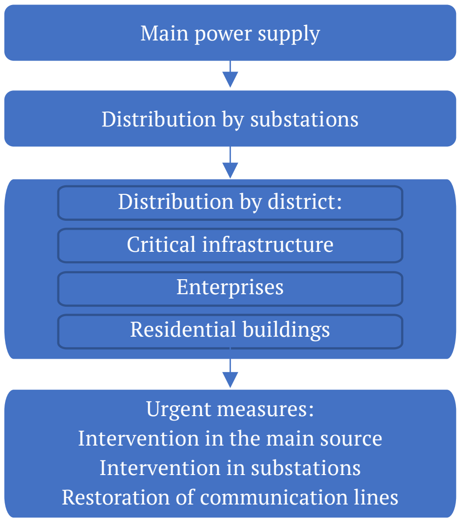


**Figure 1.** Optimal switching scheme for power grids during a blackout
**Source:** compiled by the authors

In this block diagram, the main power source is located at the top. From this source, power is supplied to substations, which in turn transmit electricity to different areas. The districts are divided into several categories, including critical infrastructure, businesses, and residential buildings. In the event of unforeseen situations that could lead to a crisis, urgent measures must be taken. These measures include intervening in the main power source to address the problem directly at the power source, intervening in substations to address problems at the level of power redistribution, and restoring communication lines and other critical facilities that may be disrupted by the crisis.

The scheduling of regional real consumption metering is an important component of effective grid management. This process determines the time and resources required to collect data on electricity consumption in different areas of the region. Taking into account geographical, weather and other factors, the metering schedule ensures that the data on the actual load on the grid is representative. This data is key for effective planning and management of the power system, helping to ensure the stability of electricity supply, optimize grid operation and maintain a balance between electricity generation and consumption. Considering the dynamics of electricity consumption and changes in grid operating conditions, the schedule for measuring real consumption in the regions allows us to respond effectively to changes and ensure reliable electricity supply for consumers. Electricity is generated in the Volyn region's power grid by a variety of sources, including: Rivne Nuclear Power Plant (NPP), which has a capacity of 4,400 MW and is the largest generating facility in the region; Dobrotvir Thermal Power Plant (TPP), which is coal-fired and has a capacity of 1,950 MW; and Lutsk Combined Heat and Power Plant (CHP), which generates 180 MW of electricity and heat for the city of Lutsk; Several small hydroelectric power plants (HPPs) are located in the region, with a total capacity of about 50 MW; The renewable energy sector includes solar and wind power plants, which are actively developing in the region. The capacity of such plants is constantly growing, which helps to reduce dependence on traditional energy sources.

Electricity from the generating facilities in Volyn Oblast is transported to distribution substations through a network of high-voltage power lines (HVL). The transmission line network includes lines of different voltages: 330 kV transmission lines stretch over 500 km and connect Rivne NPP, Dobrotvir TPP and other key energy facilities. 110 kV power lines stretch over 2,000 km and distribute power across the region. 35 kV power lines stretch over 5,000 km and supply cities and towns with electricity to meet their needs. Electricity supplied by distribution substations is transported to end consumers through a network of low-voltage power lines. The network of low-voltage power lines includes lines of different voltages, in particular: 10 kV power lines with a length of over 10,000 km. These lines supply electricity to homes, businesses, and other facilities, meeting their electricity needs (Guo *et al.*, 2023).

Electricity generated in the Volyn region's power grid is distributed among different categories of consumers. Industrial enterprises take the largest share – 40% of the total consumption. Residential consumers use 30% of electricity, in particular, for lighting, heating and household needs. Agriculture consumes approximately 10% of electricity, using it for irrigation, processing, and other needs. Other sectors such as transport, street lighting, utilities consume the remaining 20%. This distribution of consumption allows for optimized use of electricity and ensures the efficient functioning of the grid (Fig. 2). Negative scenarios that could occur in the Volyn region's power grid could lead to serious interruptions or even a complete system failure. Some of these include: accidents at power plants, such as generator failure, fire or explosion, which could lead to a suspension of electricity production and cause supply shortages; damage to transmission lines due to natural disasters or accidents, such as storms, ice, line breaks or cable theft, which could disrupt the transmission of electricity to consumers; increased consumption, which could cause peak loads or abnormally low temperatures that exceed the network's capacity. In addition, shelling could adversely affect the power grid, which could result in damage to power lines and infrastructure, as well as blackouts in certain areas.

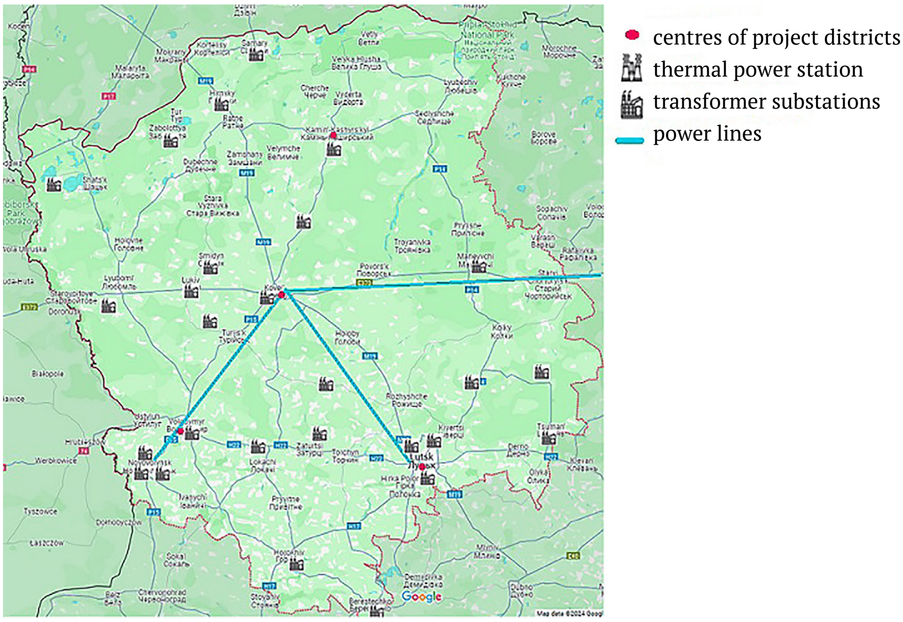


**Figure 2.** Power plants in the Volyn region

**Source:** created by the authors

Data collection involves the systematic and comprehensive collection of information about the structure, components, and characteristics of the power grid for the purpose of further analysis and identification of optimal solutions. The main objective of data collection is to obtain comprehensive information about all components of the power grid, including generating facilities, distribution lines, substations, transformers, consumers, and other important elements. Data on power, voltage, current, electricity consumption, and technical parameters of each component provide a complete picture of the grid's functioning (Panda & Das, 2021). Data collection can be done through a variety of sources, such as archival records, technical documentation, on-site measurements, specialized databases, and reports and statistics from energy companies and regulators. An important part of the data collection process is its systematization and analysis, which allows us to identify the main trends, problems, and opportunities in the development of the electricity grid. The accuracy and completeness of the data collected determines the quality of further research and the adoption of informed decisions on optimization and modernization of the power grid.

Grid load analysis involves estimating the expected load on the grid at different times of the day, considering various factors that may affect electricity consumption. It is necessary to take into account the peak load, which reflects the maximum amount of electricity consumption in a certain period of time (Rahman *et al.*, 2021). This usually refers to the peak hours when electricity demand reaches its maximum due to high consumption by households, industry, and other sectors of the economy. Peak loads can be predicted based on historical consumption data and other factors such as weather and economic activity. In addition, it is necessary to analyse the normal load, which reflects the average level of electricity consumption during the day or week. This allows for effective planning of electricity generation and distribution to ensure the most efficient use of resources. It is important to take into account the impact of weather conditions and seasonal variations on the load on the grid. For example, higher temperatures in the summer can lead to an increase in electricity consumption for air conditioning, and seasonal consumption can also affect electricity demand.

Blackout risk assessment is an important step in ensuring the reliability and efficiency of electricity supply in Volyn region. Investigating potential causes of blackouts allows us to identify factors that can cause a sudden loss of electricity supply (Carreras *et al.*, 2021). These may include technical failures, natural disasters, high network load, and equipment malfunctions. In addition, it is important to consider the possible consequences of blackouts for the grid and consumers. These consequences may include loss of productivity of enterprises, disruption of critical systems, as well as negative economic and social consequences for the population. In the current political environment, especially in the context of the war with Russia, the risk of blackout is growing significantly. Military actions may result in damage to the power grid due to shelling, attacks on energy facilities or interference with the operation of power supply systems. In addition, the possibility of a temporary interruption in the supply of gas or other resources required for power generation in the event of a military conflict could significantly complicate the situation with electricity supply. Thus, assessing blackout risks in the context of military conflict is extremely important for developing effective measures to protect and ensure the reliability of electricity supply not only in Volyn region, but also in Ukraine as a whole. A stochastic model takes into account randomness or uncertainty in a system, allowing for random changes or variations in input parameters or conditions. One of the widely used methods for building stochastic models is the Markov process method (1). Identification of these risks helps to develop strategies for prevention and effective management in emergency situations, which helps to ensure the reliability of electricity supply and protect the interests of consumers in Volyn region.

The development of a switching plan involves the development of a detailed action plan for the efficient disconnection and connection of power lines and substations in order to minimize interruptions in power supply and ensure maximum availability of electricity to consumers. In developing a switching plan, an important step is to determine the sequence of disconnection and connection of power lines and substations. This requires analysing the structure of the grid, the capacity of different lines and substations, and the needs of consumers at different times of the day and operating conditions. Specific criteria should be developed for switching lines and substations on and off. This may include assessing the capacity, condition, and load of each facility, as well as deciding on priorities for supplying critical facilities such as healthcare or emergency services (Bohra & Anvari-Moghaddam, 2022). Testing and improving the developed switching plan by simulating various blackout scenarios and implementing the necessary adjustments, taking into account the identified shortcomings and requirements for effective grid management in emergency situations.

Modelling of the power grid system was an important step in the process of developing and testing the effectiveness of the blackout switching plan. The use of specialized modelling software allowed for a detailed analysis of the developed plan and identification of its best parameters to ensure reliable power supply in unforeseen situations. Sensitivity analysis is used to determine the impact of changes in parameters on the model output. The main purpose of sensitivity analysis is to identify and quantify the impact of parameter variations on the model output. This can be done using a variety of methods, such as analytical or numerical approaches, or the use of appropriate software. One of the most common methods is the Monte Carlo method (2). This method is based on randomly selecting values of the input parameters of the model and repeating the model calculations for each random choice. Then the results of each calculation are averaged to obtain an estimate of the efficiency indicator or other model parameter. This approach allows evaluating the system's behaviour under a wide range of random conditions and considering their impact on the modelling results. The system modelling involved the creation of a virtual model of the power grid, which reflected all the main components of the system, such as power lines, substations, transformers, and their interconnections (Hoang & Nguyen, 2021). Based on this model, various blackout scenarios were simulated, and the switching plan was tested to see how it performs in real-world conditions. Next, different blackout scenarios were simulated and the impact on the grid was analysed. This included estimating the time to restore power supply, identifying possible overload points, and developing strategies to avoid them. After the simulation was completed, the efficiency and reliability of the developed switching plan was assessed. This allowed identifying its advantages and disadvantages, as well as making the necessary adjustments to ensure the optimal functioning of the power supply system in emergency situations.

By analysing the grid and its parameters, it is possible to improve the plan to minimize power losses and maximize energy availability to consumers (Mansouri *et al.*, 2021). This may include identifying suboptimal sequences of power line and substation disconnection and connection that lead to unnecessary power losses or limit energy availability to consumers. Next, strategies need to be developed to address the identified deficiencies and improve the switching plan. This may include optimizing the sequences of disconnection and connection, developing new criteria for making decisions on the operation of lines and substations in blackout mode, and using new technologies and methods of grid management. Validation and verification of the optimized switching plan using simulation methods and testing it on real data is an important step. This allows making sure of its effectiveness and reliability before implementing it in practice. To develop a model for urgent response to grid crises, such as blackouts, an algorithm can be used that will be able to respond quickly to problems and provide effective solutions to restore system operation. This algorithm can be implemented using software based on artificial intelligence, machine learning, and control systems such as SCADA systems. Continuous improvement and updating of the switching plan is a necessary component in ensuring efficient and reliable power supply in blackout conditions. The algorithm must constantly monitor the state of the grid and detect any signs of a crisis situation, such as overloads, circuit outages, consumption anomalies. Once a problem is detected, the algorithm should assess the severity of the situation, determine its priority and potential consequences. Based on the situation assessment, the algorithm should make a quick decision to activate the necessary measures to immediately restore the grid. The algorithm must ensure effective communication with all relevant parties, such as grid operators, rescue services, government agencies, and coordinate their actions to respond quickly and effectively to the crisis situation. The algorithm should automatically perform the necessary measures, such as disconnecting the load, switching on backup power sources, switching the power grid, to restore the system. After the system is restored, the algorithm should continue to monitor the state of the power grid and make necessary updates to prevent similar crisis situations in the future.

Improving the switching plan involves analysing the effectiveness of its operation in real conditions, identifying possible shortcomings, and identifying new opportunities to optimize grid management processes (Khismatullin & Bashirov, 2021). This may include revising the sequences of disconnection and connection, updating the technical parameters of equipment, and introducing new technologies and control methods. Updating the switching plan is also important to take into account changes in the structure of the grid, such as an increase or decrease in the number of substations, transmission lines and consumers. New technologies and the development of alternative energy sources may also affect the efficiency and reliability of power supply planning.

## DISCUSSION

Modelling the optimal blackout switching techniques for Volyn Oblast proved to be an important step in the region's readiness to manage energy crises. The analysis provided important data on the grid structure and load, as well as identified potential blackout risks. In particular, it identified critical points in the grid, such as overloaded lines and substations, which could cause accidents in the event of an emergency. On this basis, specific switching strategies were developed to reduce blackout risks and ensure a stable power supply for consumers. The use of specialized software tools made it possible to simulate various blackout scenarios and evaluate the effectiveness of the developed switching plan. The use of SCADA for modelling and simulation of power grids in the study provided a convenient interface for developing mathematical models and simulations. This helped to identify the advantages and disadvantages of the plan, as well as to improve it in order to increase reliability and efficiency. The results of the study confirmed the importance of modelling optimal switching strategies for power grids in solving energy security problems and ensuring stable power supply during emergencies. Given the ever-increasing challenges, such research is becoming an integral part of power grid management and ensuring the country's energy security.

According to the results of recent studies by F. Kebede *et al.* (2021), assessing the reliability of renewable energy systems by modelling power outages in distribution networks is a key step in ensuring the stability and continuity of electricity supply. This approach allows us to assess the efficiency and reliability of the system in unforeseen situations, such as accidents, emergencies, or blackouts. Power outage modelling helps identify weaknesses and potential problems in the grid, which helps develop strategies to improve reliability and restore supply in emergency situations. These data are consistent with the theses presented in the previous section. In particular, the modelling allows for the analysis of different power outage scenarios and their impact on the operation of the restoration system. This can include estimating the time to restore power supply, identifying possible overload points, and developing strategies to avoid them. Modelling also allows for an analysis of the effectiveness of measures to ensure reliable power supply in emergency situations, which helps to improve response plans and backup strategies.

Referring to the definition of D. Ivanov (2022), a power outage can trigger a chain reaction throughout the supply chain. This is due to the interstructural ripple effect, where power outages affect other sectors and industries. For example, a shutdown of power plants can lead to a halt in production at industrial enterprises, increased machine downtime and loss of productivity. An analysis of the impact of power outages on productivity shows that long interruptions in power supply can significantly reduce the efficiency of the production process. Uninterrupted power supply is key for many industries, such as manufacturing, healthcare, transport, and others. Losses in productivity can have serious economic consequences and lead to losses for businesses and society as a whole (Kuznetsov, 2024). It is worth noting that the resilience and viability of the electricity supply system become essential aspects in the face of interruptions. Developing and implementing measures to improve grid resilience, such as backup power supplies, emergency recovery plans and network system improvements, can help reduce the system's vulnerability to interruptions and increase its resilience in the face of unforeseen events (Ali *et al.*, 2022).

Researchers F. Mohamad *et al.* (2021) identified that the optimal planning of microgrids for sustainable distribution networks is a key challenge in modern energy infrastructure, especially in the context of growing challenges such as climate change and the increased use of renewable energy sources. Microgrids are small, self-sufficient systems that can function as standalone units or be integrated into the general power grid. Optimal planning of microgrids includes determining the optimal network size, location, and distribution of resources, including renewable energy, storage systems, control, and protection systems. This requires a coherent approach to the technical, economic, and environmental aspects of planning, taking into account the needs of consumers and the requirements for the sustainability and reliability of electricity supply. Optimal planning of microgrids contributes to the efficiency and resilience of distribution networks, reducing energy losses and increasing the use of renewable energy sources (Korduba, 2022). These results support the above study as they highlight the importance of optimal microgrid planning to ensure the resilience and efficiency of distribution networks. Taking into account technical, economic and environmental aspects allows determining the most optimal solutions for the size and location of microgrids, as well as the efficient use of resources, including renewable energy. This approach helps to reduce energy losses and improve the overall reliability of electricity supply, especially in the face of growing challenges associated with climate change and the expansion of renewable energy sources.

Researchers K. Liang *et al.* (2024) have shown in their work that the restoration of the power system with a high penetration of renewable energy sources is an important aspect of the development of modern energy, which is mostly a complex process. Today, the high penetration of renewable energy sources, such as solar and wind energy, creates new challenges and opportunities for the energy system (Stoliarov, 2024). The current state of play is the gradual introduction of renewable energy sources into the energy system, which contributes to reducing dependence on traditional sources such as coal and oil and reducing greenhouse gas emissions. Future trends in grid renewal include further increases in renewable energy generation, development, and improvement of energy storage technologies, improvement of infrastructure to support decentralized grids, and increased efficiency and reliability of the grid as a whole (Selvakumar *et al*., 2024). The authors of this study can agree with this opinion that the development of modern technologies and the increase in environmental awareness of society contribute to the activation of these trends and contribute to the formation of an energy system based on the use of renewable energy sources and demonstrating a high level of sustainability and resistance to external influences.

As noted by G. Fotis *et al.* (2022), the risks in the European electricity transmission system are becoming increasingly apparent in the face of growing complexity and instability driven by both external and internal factors. Large-scale power outages can occur for a variety of reasons, including technical problems, natural disasters, cyber-attacks, or manufacturing deficiencies. These outages can have serious consequences for the economy, security, and comfort of citizens. In this regard, the development of a new power system restoration strategy becomes extremely important to ensure the stability and reliability of electricity supply (Selvakumar *et al*., 2023). Analysing the results and conclusions, a new strategy for restoring the power system after a major power outage requires a comprehensive approach that considers various aspects of the energy infrastructure and the challenges it faces. It may include rapid identification and localization of problematic areas of the grid, effective management of reserve capacity, strategies for restoring power supply, and customer engagement to ensure maximum recovery efficiency. It is also important to use advanced technologies and analytical tools to predict and manage major outages, which allows for a prompt response to situations and minimizes their impact on the energy system and society as a whole.

Researchers S. Ghasemi *et al.* (2021) determined that the new predictive restoration of critical loads in distribution networks reflects modern requirements for energy management systems in emergency situations. Considering the load curve of critical consumers, this strategy is focused on ensuring priority restoration of power supply to the most important objects for society, such as medical facilities, emergency services, and infrastructure that ensures safety and vital services. This strategy is based on the analysis of data on electricity consumption by different categories of consumers at different times of the day and load conditions. It uses advanced forecasting and modelling algorithms to identify critical loads and their real-time power supply needs. This allows us to respond quickly to power outages and restore power to the most important places for society, ensuring the continuous operation of critical facilities and reducing the impact of unforeseen situations on public health and safety. In addition, the application of a new strategy for the predictive restoration of critical loads can contribute to the efficient use of resources in response to energy crises and emergencies. Through automated analysis and management, systems can respond quickly to power outages and mobilize the necessary resources to restore supply in critical areas.

## CONCLUSIONS

Modelling the optimal switching scheme of the Ukrainian electricity grid is an important step in ensuring stable electricity supply and avoiding possible power losses for consumers in the event of a blackout. Studies have shown that effective modelling can lead to the development of an optimal switching strategy that maximizes energy availability for consumers and minimizes supply interruptions. The schedule for measuring real electricity consumption has proved to be a key component for effective grid management. Analysis of the collected consumption data allowed us to understand the dynamics of electricity demand in different periods and conditions. This data was necessary to develop grid management strategies and plan its development. The efficient allocation of time for consumption measurement has led to a reduction in energy losses and an increase in the reliability of electricity supply. Constant updating and analysis of this data helped identify trends and problems in the operation of the grid, which in turn allowed for prompt response and improvement of the power supply management system.

The use of specialized software tools, including SCADA, made it possible to conduct a detailed analysis of the structure and capacity of the power grid, as well as to identify critical facilities that require the highest priority in ensuring power supply in the event of a blackout. This contributed to efficient resource management and quick response to unforeseen situations. Moreover, the modelling helped to improve management strategies and the optimal use of backup energy sources during crisis situations. This made it possible to identify weaknesses in the system and develop effective measures to address them. The use of real-world power grid switching models plays an important role in improving the reliability of power supply and ensuring the stability of the energy system during crisis situations. This approach helps to effectively address energy security issues and increases the level of protection of the population and the economy from the negative effects of blackouts, ensuring stable power supply even in the most difficult conditions.

Additional research could include analysing the effectiveness of the proposed switching plan in real-world conditions and improving the methods of managing power grids to take into account changes in the energy system and societal needs.

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## CONFLICT OF INTEREST

None.

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**Ірина Грицюк**
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0003-4472-306X

**Владислав Волинець**
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-9192-2785

**Наталія Коменда**
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-5944-8665

**Юрій Грицюк**
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-6463-3910

**Андрій Гадай**
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-4195-7218

# Моделювання оптимальної схеми перемикання електромереж України під час блекауту (Волинська область)

**Анотація.** Актуальність дослідження, зокрема у Волинській області, обумовлена необхідністю забезпечення надійності та ефективності енергетичної інфраструктури в умовах зростаючих викликів, пов'язаних з війною Росії та України, технологічним розвитком та забезпеченням енергетичної безпеки країни. Метою дослідження є розробка моделі оптимальної схеми перемикання електромереж Волинської області під час блекауту для мінімізації негативних наслідків та забезпечення пріоритетного електропостачання критично важливих об'єктів. Серед використаних методів слід виділити метод математичного моделювання, симуляційний метод, метод оптимізації, метод аналізу чутливості інші. У дослідженні було проведено оптимізацію схеми перемикання електромережі в умовах ризику війни та інших кризових ситуацій, зокрема, ретельний аналіз різних варіантів дій у випадку блекауту. Враховуючи додаткові аспекти безпеки та надійності електромережі, було визначено оптимальні маршрути передачі енергії, розміщення резервних джерел живлення та розроблено ефективні алгоритми керування електромережею. Завдяки оптимізації схеми перемикання електромережі можна мінімізувати шкоду від блекаутів та забезпечити швидке відновлення електропостачання. Результати підтвердили, що оптимальна схема перемикання може значно зменшити час блекауту та його вплив на економіку та життя населення. Розробка оптимальних схем перемикання електромереж є важливим кроком до підвищення стійкості електроенергетичної системи України до кризових ситуацій. Дослідження підкреслило важливість розробки таких моделей для забезпечення енергетичної безпеки та стійкості електромережі в умовах загрози блекауту, що відображається на практичних аспектах управління електропостачанням та забезпеченні економічного розвитку. Практичне значення дослідження полягає у вдосконаленні стратегій управління електромережею в умовах блекауту, сприяючи підвищенню стійкості енергетичних систем та економічного розвитку

**Ключові слова**: стабільність електропостачання; надзвичайні ситуації; графік вимірювання споживання; аналіз навантаження; оцінка ризиків знеструмлення

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**Maksat Sadykov***

PhD in Physical and Mathematical Sciences, Associate Professor
International University of Innovation Technologies
720048, 1/17 Ankara Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0001-6008-9551

**Nazgul Temirbaeva**

PhD in Technical Sciences, Associate Professor
Kyrgyz State Technical University named after I. Razzakov
720044, 66 Ch. Aitmatov Ave., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-9080-5368

**Maksat Narymbetov**

PhD in Technical Sciences, Associate Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Srt., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0001-8331-5689

**Bakyt Toktonaliev**

PhD in Technical Sciences, Associate Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Srt., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-2775-8474

**Zamirbek Nariev**

PhD in Technical Sciences, Associate Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Srt., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0001-9599-2839

# Comparative analysis of the efficiency of hydro, wind, and solar power plants in Kyrgyzstan

**Abstract.** Investigation of the efficiency of hydro, wind, and solar power plants in Kyrgyzstan is important in the context of developing sustainable energy sources to ensure energy security and reduce environmental impact. The purpose of this study was to identify the most promising sources of renewable energy capable of ensuring the sustainable development of the energy sector. This study is a comparative analysis of the three main renewable energy sources – hydro, wind, and solar power plants – in the context of their use in Kyrgyzstan. Various aspects of the efficiency of each type of plant are considered, including resource availability, economic and environmental efficiency, and technical reliability. The advantages and limitations of each energy source are discussed in the context of the Kyrgyz economy and climate conditions. In particular, the focus is on the rich potential of water, wind and solar resources in the country, which opens up prospects for developing renewable energy. The environmental impacts of each type of power plant are also investigated, including ecological consequences and possible risks to local fauna and flora. The findings highlight the need for the integrated use of different types of power plants to ensure energy security and sustainability in Kyrgyzstan, given their combined advantages

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*Corresponding author

and limitations. Ultimately, it was concluded that the optimal approach to ensuring energy security and sustainability in Kyrgyzstan may be the integrated use of all three types of power plants. The study results can be used to develop a strategy for the energy development of Kyrgyzstan based on the optimal combination of hydro, wind, and solar energy to ensure a sustainable and environmentally friendly energy complex in the country

**Keywords**: sustainable energy sources; environmental efficiency; renewable energy; energy security; technical reliability

## INTRODUCTION

The world is constantly moving towards the use of clean energy, and modern energy policy is increasingly focused on renewable energy sources, especially for countries with rich natural resources, such as Kyrgyzstan. In this regard, a comparative analysis of the efficiency of hydroelectric power plants (HPP), wind power plants (WPP) and solar power plants (SPP) in Kyrgyzstan is becoming an extremely important study. Global trends require switching to environmentally friendly energy sources to combat climate change and reduce greenhouse gas emissions. Renewable energy sources are inexhaustible resources, unlike fossil fuels, and can ensure the energy security of the country. Kyrgyzstan has significant potential for the use of hydropower, wind and solar energy due to its resource wealth.

The need for this study is driven not only by the desire for sustainable development of the energy sector, but also by the growing need to find alternative energy sources to mitigate the negative impact on the environment, reduce dependence on traditional energy sources, and ensure the energy security of the country. In the context of climate change and deepening environmental problems, energy policy is becoming a key element in ensuring sustainable development, and a variety of renewable energy sources can play an important role in achieving this goal.

The study of the efficiency of renewable energy sources has attracted the attention of many researchers. N. Naval & J. Yusta (2021) focused on analysing the economic efficiency of various types of power plants, identifying their impact on the country's energy market. A. Abu-Rayash & I. Dincer (2023) proposed an integrated approach to assessing the environmental sustainability of HPPs, WPPs, and SPPs, based on their impact on biodiversity and climate change. A. Levenda *et al.* (2021) considered the technical aspects of the implementation of renewable energy projects, assessing the technical readiness of infrastructure for the introduction of new energy systems. R. McKenna *et al.* (2022) analysed the potential of wind energy in various regions, identifying the most promising places for the construction of wind farms. S. Qadir *et al.* (2021) investigated the financing of renewable energy projects by analysing investment flows and sources of financing. L. Cui *et al.* (2022) conducted a comparative analysis of the structure of energy supply, considering the share of renewable energy sources in the total energy balance. A. Omri & F. Belaïd (2021) investigated the socio-economic aspects of renewable energy development, assessing the impact on employment and local economic development. J. Liu *et al.* (2021) focused on analysing the legal and institutional aspects of regulating the renewable energy market, identifying obstacles and possible ways to overcome them. A. Raihan *et al.* (2022) explored technological innovations in the field of solar energy, assessing their applicability and effectiveness.

Ultimately, W. Fang *et al.* (2022) analysed the strategic aspects of renewable energy development, assessing the benefits and risks to national energy security. A deeper analysis of the interrelationships between various aspects of the use of renewable energy sources is required, including the study of ways to optimise their integration into the country's energy system, considering the specifics of local conditions and needs.

The purpose of this study was to identify the most promising sources of renewable energy that can contribute to the stable development of the country's energy sector. Research tasks:

1. To consider the main advantages and limitations of each type of power plants: HPPs, WPPs, and SPPs in the context of their use in the energy system of Kyrgyzstan.

2. To identify the factors that have the greatest impact on the economic and environmental efficiency of HPPs, WPPs, and SPPs in Kyrgyzstan.

3. To explore what strategies and approaches can be developed for optimal integration of various types of power plants into the energy infrastructure of Kyrgyzstan to ensure sustainable development.

## MATERIALS AND METHODS

The study covered the period from April to June 2023, chosen to account for seasonal variations in energy production from SPPs and WPPs. This period was strategically determined, since the spring and summer months in Kyrgyzstan are characterised by a particularly high level of solar activity and variability in wind speed, which significantly affects the efficiency of the corresponding power plants. This time interval allowed covering different climatic conditions, leading to a more accurate assessment of the production potential of SPPs and WPPs at different times of the year.

The study was conducted on the territory of Kyrgyzstan, covering various regions of the country (Northern Kyrgyzstan, Chui Region, Issyk-Kul Region, Naryn Region, Osh Region, Jalal-Abad Region, Batken Region), to reflect the diversity of climatic and geographical conditions. The study considered the characteristics of various areas, such as mountainous, foothill, and valley areas, and their specific climate and topography. This approach allowed to get a better understanding of the potential of using hydroelectric power plants, wind power plants, and solar power plants in various parts of the country. Official statistical reports on electricity generation from HPPs, WPPs, and SPPs in Kyrgyzstan for 2019-2023 (Electricity generation by…, 2024) were used to collect data. This approach to data collection has provided access to extensive and up-to-date information on electricity generation from various renewable energy sources in the country.

After data collection, a comparative analysis of the efficiency of each type of power plant was carried out. The comparison method has been a key tool in evaluating the efficiency of various types of power plants. This method allowed comparing various characteristics of different types of power plants to identify their advantages and limitations. The use of the comparison method provided an objective idea of how each type of power plant corresponds to the requirements of the Kyrgyz energy system. By examining various aspects such as production capabilities, economic benefits, and environmental impacts, the most appropriate options for the energy system for the specific conditions of the country were identified. This method helped to identify the strengths and weaknesses of each type of power plant, which, in turn, contributed to making informed decisions in the field of energy sector development.

The study considered the availability of key resources needed to operate various types of power plants in Kyrgyzstan. It included an assessment of the availability of water resources for hydropower, the distribution of wind flows for wind energy, and the potential of solar radiation for solar energy in various regions of the country. The assessment identified the most promising and suitable locations for each type of power plant, considering the specifics of resources and energy needs in different regions. This helped to identify methods of using renewable energy sources and ensure the stability of the country's energy system. The assessment of the geographical distribution of resources was also an important basis for the development of a strategy for the development of renewable energy, identifying priority areas of investment and focusing on the most promising projects.

## RESULTS

In 2024, the energy sector faced a number of challenges due to the growing demands for a transition to more environmentally friendly energy sources (Kabeyi & Olanrewaju, 2022). This challenge arises in the context of efforts to reduce greenhouse gas emissions and mitigate climate impacts. The pursuit of a clean energy transition is becoming increasingly urgent in light of the threat of climate change and the need to ensure sustainable development. In such an environment, it is important to develop strategies that will make effective use of renewable energy sources, considering both environmental and economic aspects.

Kyrgyzstan, located in the centre of Central Asia, has significant water resources potential due to its mountainous terrain, rich rivers and lakes. This creates favourable conditions for the development of hydropower and makes it one of the most affordable energy sources in the country. HPPs play an important role in the energy system of Kyrgyzstan, providing a significant part of the electricity. The advantage of hydropower in Kyrgyzstan lies in the abundance of water resources, which provide a stable and continuous flow of energy. Mountain rivers and lakes in the country create the potential for the construction of powerful hydroelectric power plants capable of providing electricity to both the population and industrial enterprises. In addition, the use of hydropower helps to reduce greenhouse gas emissions and other pollutants into the atmosphere, which makes this energy source more environmentally friendly and sustainable. However, the operation of HPPs is not accompanied by such negative consequences as air or land pollution, which has made hydropower the preferred option for many countries (Kuriqi *et al.*, 2021). Hydropower is an important resource for ensuring energy security and sustainable development of Kyrgyzstan, using the country's natural resources for the benefit of its residents and economy.

Hydroelectric power plants are one of the most efficient sources of energy production, capable of providing stable electricity production for a long time. This high degree of efficiency makes hydroelectric power plants an attractive option to meet the energy needs of many countries, including Kyrgyzstan. The advantage of hydroelectric power plants lies in their ability to provide stable energy production. Dependence on changeable conditions, such as weather or seasons, is insignificant for hydroelectric power plants. This means that hydroelectric power plants can provide constant energy production throughout the year, which makes them a reliable source of electricity for the population and industry. In addition, the high degree of efficiency of the HPPs ensures a high energy return on investment. The costs of construction and operation of HPPs are recouped due to low operating costs and high productivity. This makes HPPs an economically attractive option for investments in the energy sector and contributes to the development of the country's energy infrastructure (Strielkowski *et al.*, 2021). HPPs are an efficient and sustainable energy source capable of providing stable electricity production for a long time. Their high degree of efficiency makes them an important component of the energy system of many countries, including Kyrgyzstan, and contributes to ensuring energy security and sustainable development.

The operation of HPPs is accompanied by environmental impacts, which is an important aspect when considering their effectiveness and sustainability. The environmental impact can be significant due to changes in the river regime and potential negative impacts on ecosystems. For example, the creation of reservoirs can lead to changes in the hydrological regime of rivers and reservoirs, which can have an impact on biological diversity and local communities of plants and animals. However, with an integrated approach and proper planning, negative environmental impacts can be mitigated or minimised. An important step is to carry out an environmental impact assessment at the design and construction stage of the HPP. Environmental impact assessment helps to identify potential threats to the environment and develop measures to reduce or compensate for them. In addition, the development and implementation of environmental protection and ecological restoration programmes can help reduce the negative impact of hydroelectric power plants on ecosystems (Wang *et al.*, 2021). These programmes may include measures to restore biodiversity, control water and air quality, and regular monitoring of the state of the natural environment. Thus, despite the potential environmental risks associated with the operation of hydroelectric power plants, through proper planning, environmental impact assessment and implementation of environmental programmes, it is possible to mitigate these consequences and ensure sustainable use of hydropower in the future.

Hydroelectric power plants are an important source of energy characterised by high technical reliability and long service life. However, despite their overall reliability, HPPs can be vulnerable to various natural and technical risks, including floods and geological hazards. Hydroelectric power plants have advantages in technical terms. They have a simple design and are usually equipped with reliable equipment, which ensures stable and long-term operation. Many HPPs have a long service life, which can be decades, which makes them an important and stable source of energy for providing electricity to the population and industry (Kumar & Saini, 2022). HPPs may be exposed to various risks that may threaten their technical reliability. For example, floods can damage the equipment and infrastructure of HPPs, which can cause downtime in energy production and potential threats to surrounding areas. In addition, geological hazards such as earthquakes or landslides may also pose a risk to the technical reliability of a hydroelectric power plant. In general, despite the potential risks associated with floods and geological hazards, HPPs remain one of the most reliable sources of energy. This is due to their robust construction and specialised safety measures designed to prevent possible emergencies. Nevertheless, to ensure the long-term technical reliability of HPPs, it is necessary to constantly update and modernise their equipment, and improve safety measures considering changing environmental conditions and risks.

Kyrgyzstan, located in a mountainous area, has significant wind energy potential, which makes this type of renewable resource an important component of the country's energy strategy. Wind conditions characterised by the presence of strong winds, especially in high-altitude and open areas, provide favourable conditions for the deployment of wind power plants. The significant potential of wind energy in Kyrgyzstan reflects the opportunities for diversification of the country's energy sector. At a time when the desire to reduce dependence on traditional energy sources and the transition to cleaner and more sustainable sources is becoming more urgent, the development of wind energy seems to be an attractive alternative. In addition, the use of wind energy in Kyrgyzstan contributes to reducing greenhouse gas emissions and reducing the negative impact on the environment. Wind turbines do not produce harmful emissions and do not pollute water or soil, which makes this energy source environmentally friendly and sustainable (Hamed & Alshare, 2022). Moreover, the development of wind energy in Kyrgyzstan can contribute to economic growth and create new jobs. Investments in this sector can attract new investments and technologies, and contribute to the development of local industry related to the production and maintenance of wind turbines. The availability of wind energy resources in Kyrgyzstan represents significant potential for the development of a sustainable and clean energy sector that contributes to reducing greenhouse gas emissions, diversifying the energy portfolio and stimulating economic growth.

The efficiency of wind farms is an important aspect when considering their role in the energy system. Wind energy is a clean and renewable energy source, however, its efficiency may be subject to fluctuations in wind speed, which is the main challenge in using this type of energy. The instability of energy production is a result of the variability of wind speed. WPPs can be effective only at a certain wind speed, their effectiveness is significantly reduced if the wind is too weak or too strong. This means that energy production can be unstable and unpredictable, making it difficult to integrate wind energy into the energy system. However, despite this instability, there are methods to improve the efficiency of WPPs (Azlan *et al.*, 2021). For example, wind speed forecasting and efficient energy production management can optimise the operation of wind turbines and reduce energy losses due to wind variability. Technological innovations, such as the use of more efficient blades and improved control systems, also contribute to increasing the efficiency of WPPs. Moreover, the diversification and combination of various energy sources, such as solar or hydropower, with wind energy can help smooth out the instability of energy production and provide a more reliable energy supply. Despite the challenges associated with the instability of energy production due to the variability of wind speed, modern technologies and management methods can improve the efficiency of wind farms and integrate them into the energy system as an important source of clean and sustainable energy.

In the context of sustainable development and environmental conservation, the environmental impacts of WPPs are an important aspect to consider. Unlike HPPs, WPPs have significantly less impact on the environment; however, they can also cause certain environmental problems. WPPs do not emit greenhouse gases and do not pollute water or soil, which makes them more environmentally friendly compared to traditional energy sources. This is especially important given the growing concern about climate change and the need to reduce carbon emissions into the atmosphere. However, despite this, WPPs may have a certain negative impact on the local ecosystem (Pekkan *et al.*, 2021). In particular, collisions with rotating blades of wind turbines can cause damage to local birds and bats, which can lead to loss of biodiversity and disruption of the ecological balance in the region. In addition, the construction and operation of WPPs can also lead to a change in the landscape and the destruction of natural ecosystems. The installation of tall towers and blades can change the visual appearance of the region and attract attention, which can affect the scenic area and lead to a reduction in the tourist potential of the region. However, these negative effects can be mitigated with proper planning and environmental impact assessment. Given the threat of climate change and the need to switch to cleaner and more sustainable energy sources, the development of wind energy remains an important component of the strategy to reduce greenhouse gas emissions and ensure energy security. Therefore, despite some environmental challenges, WPPs remain one of the key tools in the transition to clean and sustainable energy.

The technical reliability of WPPs is an important aspect in assessing their role in the energy system. Wind energy, as a renewable energy source, has the potential to become an important element of the energy mix, however, the technical aspects of the operation of wind farms may pose challenges. WPPs require regular maintenance and technical support to ensure their reliable operation (Kou *et al.*, 2022). This includes monitoring the condition of blades, cooling systems, electronics, and other components that may be subject to wear or damage during operation. Inadequate maintenance or unforeseen breakdowns can lead to plant failures and reduced energy production. In addition, the variability of wind speed poses additional challenges to the technical reliability of power plants. Wind energy depends on the speed and direction of the wind, and significant fluctuations in these parameters can affect the efficiency of the stations. The instability of energy production due to wind speed variability may lead to the need to develop more sophisticated and reliable control and prediction systems to ensure a stable energy supply. Nevertheless, modern technologies and engineering solutions help to cope with these challenges. The development of highly efficient blades, improvement of monitoring and diagnostic systems, and the use of data-based control algorithms allow increasing the technical reliability of WPPs and ensure their more stable and efficient operation. Despite the challenges associated with technical reliability, WPPs continue to develop as an important source of clean and sustainable energy, and modern engineering solutions and technologies are aimed at improving their operation and integration into the energy system.

Solar energy is an important source of renewable energy that can play a key role in ensuring energy security and sustainable development. In the context of Kyrgyzstan, a country with vast natural resources, solar energy has significant potential, which makes it an important object of study. Kyrgyzstan's significant solar potential is conditioned by its geographical location and climatic features. Most of the country is located in a zone of high solar insolation, which contributes to more intensive use of solar energy. This opens up wide opportunities for the deployment of SPPs and the exploitation of solar energy in various regions of the country. In addition, solar energy is an affordable resource that can be used almost everywhere. Unlike hydropower, which requires rivers or lakes, or wind power, which depends on wind conditions, solar energy can be captured using solar panels almost anywhere with sufficient access to sunlight (Sharma *et al.*, 2022). This makes solar energy more flexible and versatile compared to other renewable energy sources. However, despite all its advantages, solar energy also has its challenges and limitations. In particular, the issues of energy storage and use during periods of lack of sunlight remain relevant. Efficient energy storage systems and network infrastructures for the transmission and distribution of solar energy may require additional investments and technological solutions. Nevertheless, solar energy remains a key element of the transition to sustainable and clean energy in Kyrgyzstan and around the world. With the development of technology and the reduction in the cost of solar panels, solar energy is becoming more affordable and competitive, which creates favourable conditions for its further development and distribution.

The efficiency of solar energy is a key aspect when considering its potential as a source of renewable energy. In the context of Kyrgyzstan, where climatic conditions change significantly in different seasons, the efficient use of solar energy has its own characteristics and challenges. Solar energy is highly efficient, especially in the summer months when the amount of sunlight reaches its maximum. At this time, solar panels can provide a high level of energy production, which makes solar energy an attractive source of energy for many regions. However, in winter, when daylight hours are shortened and cloudy weather is often observed, solar energy production may be limited (Tanu *et al.*, 2021). This is due to a decrease in the amount of sunlight that reaches the solar panels, which leads to a decrease in the efficiency of the SPPs. In such conditions, it becomes important to develop methods and technologies for energy storage or alternative energy sources to ensure continuity of energy supply in winter. Nevertheless, even with these limitations, solar energy continues to be an important source of energy, especially in regions with high insolation. The use of innovative technologies such as high-efficiency solar panels and energy storage systems can significantly improve the use of solar energy and make it a more reliable and stable source of energy throughout the year. Thus, despite seasonal changes in efficiency, solar energy remains an important component of the energy system, which can reduce dependence on traditional energy sources and promote sustainable development.

The environmental aspects of solar energy play an important role when considering it as an alternative energy source. In the context of modern environmental problems and the search for more sustainable and cleaner forms of energy, solar energy is an attractive alternative with minimal environmental consequences (Abdibattayeva *et al.*, 2021). SPPs have a significant advantage in terms of their impact on the environment. Unlike traditional energy sources such as coal-fired or nuclear power plants, the operation of SPPs does not lead to greenhouse gas emissions, water pollution, or radioactive contamination (Iqbal *et al.*, 2021). This significantly reduces the negative impact on the atmosphere, water and land resources, and human health. Moreover, SPPs can be deployed on relatively small plots of land, which minimises the need for massive deforestation or ecosystem disruption. Instead, solar panels can be installed on the roofs of buildings, undeveloped areas, or use already polluted or undeveloped land, which allows the most efficient use of available territories without serious impact on natural ecosystems. However, other aspects of the environmental sustainability of solar energy should not be ignored. For example, the production of solar panels may require resource consumption and the use of certain chemicals, which may lead to some contamination during the manufacturing process (Rabaia *et al.*, 2021). However, with proper waste management and recycling, these problems can be minimised. Solar energy is not only an efficient source of energy, but also environmentally sustainable. Minimal environmental impact and the possibility of using undeveloped areas make solar energy an important component of the transition to a cleaner and more sustainable energy system.

The technical reliability of solar panels plays an important role in ensuring the stability and continuity of energy production from solar sources. Despite their relative ease of operation, solar panels can be exposed to various atmospheric conditions and technical failures that can affect their performance and energy production. Solar panels require minimal maintenance compared to traditional power plants. They have no moving parts and usually do not require regular replacement or maintenance. This makes them an attractive option for long-term investment, as their operation requires minimal operating costs. However, solar panels can also be vulnerable to various atmospheric conditions and technical failures. For example, intense precipitation, snowfall, or hail can temporarily reduce the efficiency of solar panels by covering their surface or leading to the formation of ice. In such cases, it is necessary to ensure regular maintenance and cleaning of the panels to maintain their performance (Orosz *et al.*, 2024). Technical failures can also affect the operation of solar panels. For example, defects in electrical wiring, problems with inverters, or loss of contact between panels and the energy collection system can lead to a decrease in energy production or even to a complete shutdown of the system. In such cases, prompt detection and troubleshooting is required to minimise downtime and losses in energy production. The technical reliability of solar panels is a key aspect of their use as an energy source. Minimal maintenance and low operating costs are combined with potential vulnerabilities to atmospheric conditions and technical failures, which underlines the importance of regular maintenance and monitoring to ensure stable operation of SPPs. Table 1 presents a comparative analysis of the three main types of power plants: HPP, WPP, and SPP, using the comparison method.

**Table 1.** Comparative analysis of the efficiency of hydroelectric, wind, and solar power plants in the context of the energy sector of Kyrgyzstan

| Aspect | HPP | WPP | SPP |
|---|---|---|---|
| Production capabilities | High:<br>1. Capacity: 100-1,000 MW<br>(example: Toktogul HPP – 1,200 MW).<br>2. Annual production: 5-10 TWh<br>(example: Toktogul HPP – 17.2 TWh).<br>3. ICUF: 0.5-0.9<br>(example: Toktogul HPP – 0.75). | Average:<br>1. Capacity: 0.5-5 MW<br>(example: Issyk-Kul WPP – 2.1 MW).<br>2. Annual production: 0.5-2 TWh<br>(example: Issyk-Kul WPP – 0.7 TWh).<br>3. ICUF: 0.2-0.4<br>(example: Issyk-Kul WPP – 0.35). | Low:<br>1. Capacity: 0.05-0.5 MW<br>(example: Bishkek-2 SPP – 0.2 MW).<br>2. Annual production: 0.1-0.5 TWh<br>(example: Bishkek-2 SPP – 0.3 TWh).<br>3. ICUF: 0.15-0.25<br>(example: Bishkek-2 SPP – 0.2). |
| Economic benefit | Average:<br>1.Construction:USD1,000-2,000million/GW<br>(example: Toktogul HPP – USD 2 billion).<br>2. Operation: USD 0.05-0.10/kWh<br>(example: Toktogul HPP – USD 0.07/kWh).<br>3. Service life: 50-100 years<br>(example: Toktogul HPP – 50 years). | Low:<br>1. Construction: USD 100-200 million/MW<br>(example: Issyk-Kul WPP – USD 150 million).<br>2. Operation: USD 0.03-0.05/kWh<br>(example: Issyk-Kul WPP – USD 0.04/kWh).<br>3. Service life: 20-30 years<br>(example: Issyk-Kul WPP – 25 years). | High:<br>1. Construction: USD 300-500 million/MW<br>(example: Bishkek-2 SPP – USD 400 million).<br>2. Operation: USD 0.02-0.04/kWh<br>(example: Bishkek-2 SPP – USD 0.03/kWh).<br>3. Service life: 25-30 years<br>(example: Bishkek-2 SPP – 30 years). |
| Environmental impact | Significant:<br>1. Land flooding: 10-100 km²<br>(example: Toktogul reservoir – 927 km²).<br>2.Greenhousegasemissions:0-50gCO2/kWh<br>(example: Toktogul HPP – 10 g CO2/kWh).<br>3. Impact on aquatic ecosystems: high<br>(example: change in the regime of the Naryn River).<br>4. Climate change. | Minimum:<br>1. Noise: 40-50 dB (approximate noise level of a wind turbine at a distance of 100 meters).<br>2. Occupied area: 0.1-0.2 km²<br>(example: Issyk-Kul WPP – 0.15 km²).<br>3. Impact on the landscape: low<br>(example: change in the landscape within a radius of 500 metres from the WPP).<br>4. Mortality of birds. | Minimum:<br>1. Noise: 0 dB.<br>2. Occupied area: 0.01-0.02 km²<br>(example: Bishkek-2 SPP – 0.018 km²).<br>3. Impact on the landscape: low<br>(example: change in the landscape within a radius of 100 metres from the SPP).<br>4. Recycling of solar panels. |
| Strengths | Stable production, high capacity | Low operating costs, flexible location | Minimal environmental impact, availability of resources. |
| Weaknesses | High construction costs, impact on ecosystems | Dependence on weather conditions, instability of production | High installation costs, seasonal production |

**Note:** ICUF – installed capacity utilisation factor
**Source:** compiled by the authors based on data from the Green Economy programme (n.d.)

This comparative analysis allows assessing the advantages and limitations of each type of power plant, which helps in making informed decisions in the field of energy sector development. Table 2 presents data on the availability of water resources, wind flows and solar radiation in various regions of Kyrgyzstan.

**Table 2.** Comparative analysis of the efficiency of hydroelectric, wind, and solar power plants in the context of the energy sector of Kyrgyzstan

| Region | Water resources ($m^3/s$) | Wind flows (m/s) | Solar radiation ($kWh/m^2/day$) |
|---|---|---|---|
| Northern Kyrgyzstan | >100 (Chu, Aksu rivers) | 5-7 (Chui Valley) | 5.5-6 |
| Chui Region | 50-100 (Chu, Ala-Archa rivers) | 4-5 (Chui Valley) | 5-5.5 |
| Issyk-Kul Region | >100 (Aksu, Issyk-Kul rivers) | 5-7 (Issyk-Kul basin) | 5.5-6 |
| Naryn region | >100 (Naryn river, Son-Kul lake) | 5-7 (Naryn Valley) | 5.5-6 |
| Osh Region | 50-100 (Ak-Buura, Kara-Darya rivers) | 4-5 (Osh Valley) | 5-5.5 |
| Jalal-Abad Region | 50-100 (Kyogart river, Kara-Suu lake) | 4-5 (Chatkal Valley) | 5-5.5 |
| Batken Region | 50-100 (Isfara, Leilek rivers) | 4-5 (Batken Valley) | 5-5.5 |

**Source:** compiled by the authors based on data from the Renewable Energy Readiness Assessment: Kyrgyz Republic (2022)

Based on these data, it can be concluded that hydropower is the most promising type of power plant for the Northern, Issyk-Kul, and Naryn regions. Wind energy can be effective in the Chui and Jalal-Abad regions. Solar energy has potential in all regions of the country.

## DISCUSSION

In general, the choice between different types of power plants in Kyrgyzstan depends on a variety of factors, including climatic conditions, resource availability, economic benefits, and environmental impacts. Each of these types – hydroelectric, wind and solar – have their own unique advantages and limitations, which makes a combined approach the most desirable to ensure stable and environmentally sustainable energy production in the country. According to the results of recent studies by X. Jin *et al.* (2022), assessing the impact of climate change on the hydro-wind-solar energy supply system is a key aspect in developing a sustainable energy strategy. Climate change has a significant impact on the availability and reliability of renewable energy sources. For example, impacts on hydropower can manifest themselves through changes in precipitation patterns and water resource allocation, which affects reservoir volumes and energy production potential. In addition, changes in the wind regime may affect the efficiency of the wind farm, which will affect the overall energy balance in the system. In addition, the variability of solar activity and the distribution of solar radiation can have an impact on the production of solar energy and its availability in different regions. These data are consistent with the theses given in the previous section. Understanding these impacts allows developing adaptive strategies for managing the hydro-wind-solar energy supply system, including measures to increase the sustainability and resilience of infrastructure, developing mechanisms for predicting climate change and its impact on the energy system, and diversifying energy sources to reduce risks. There is also a need for active cooperation at the international level to share knowledge and experience in adapting energy systems to a changing climate, which contributes to the achievement of global sustainable development goals and reducing negative environmental impacts.

HPPs, due to their long-term efficiency and high production capacity, can become a fundamental part of Kyrgyzstan's energy infrastructure. Their use is especially valuable in conditions of abundance of mountain rivers and lakes, which provides a sustainable source of water for energy generation. Referring to the definition of P. Anakhov *et al.* (2022), improvement of the functionality of hydroelectric power plants is an important aspect of the energy sector development strategy. It includes several aspects, ranging from improving the technical parameters of the equipment to optimising management and operation. One of the key areas of improvement is to increase the efficiency of water resources use, which can be achieved with the help of modern technologies such as hydraulic storage, controlled distribution of water flow, and optimisation of operating modes. This allows increasing electricity generation while reducing the negative impact on the environment and natural ecosystems. Notably, the introduction of modern automation and remote control systems enables a more effective management of the operation of power plants, promptly respond to changes in the operating mode and prevent possible emergencies (Ali *et al.*, 2022). In addition, the implementation of monitoring systems allows monitoring production indicators in real time, ensuring prompt decision-making and optimisation of HPP operation. Such measures to improve the functionality of hydroelectric power plants contribute to increasing their reliability, efficiency and economic efficiency, which is an important step towards the sustainable development of energy infrastructure (Selvakumar *et al.*, 2023).

WPPs, in turn, can be effectively used in well-ventilated areas, which is typical for mountainous areas of Kyrgyzstan. Their flexibility and relative ease of operation make it possible to compensate for the variability of wind speed and supplement energy production during periods of shortage of water or solar resources. J. Li *et al.* (2021) determined that the improvement of wind farms plays a key role in the modern strategy for the development of renewable energy. One of the areas of improvement is to increase the efficiency of the design of wind turbines. This includes developing more efficient blades, improving generators and transmission systems, and optimising turbine design and installation. Due to modern technologies and engineering developments, new wind turbines are becoming more productive and reliable, which leads to increased electricity generation with lower operating and maintenance costs. These results confirm the above study, as they reflect a steady trend in the development of wind energy not only at the global but also at the regional level. The continued growth of installed capacity and electricity generation at the WPP indicates the significant potential of this type of renewable energy. Moreover, reducing the cost of installing and operating wind farms makes them more attractive from an economic standpoint, which can stimulate further development of this industry. It should also be noted that wind farms have flexible placement capabilities, which allows them to be used both in large urban centres and in remote areas where there is no access to central power systems (Sirko *et al.*, 2023). These factors make WPPs an important element of modern energy and an appropriate option for diversifying the energy mix in the region.

SPPs, in turn, represent an attractive option for diversifying energy production. Their installation can be carried out on various plots of land, which makes them accessible even in remote areas. It is important to note that in Kyrgyzstan, where on average there are more than 300 sunny days per year, SPPs have significant potential to increase the share of renewable energy in the country's energy balance. L. Ali *et al.* (2021) argued that SPPs play an important role in diversifying energy sources and mitigating negative environmental impacts. In recent years, there has been an increase in interest in solar energy, especially due to technological improvements and a decrease in the cost of solar panels. One of the key areas of solar power development is to increase its efficiency. This is achieved through the use of new materials and technologies, such as more efficient solar panels, increased throughput and durability of components. It can be agreed that an important aspect of the development of SPPs is the optimisation of their integration into the energy system. This includes the development of energy storage systems to compensate for the lack of solar activity at night or in cloudy conditions (Smyk & Arkhypova, 2023). These measures allow improving the performance of SPPs and make them more competitive compared to traditional energy sources.

However, to ensure the stability and continuity of energy production, it is important to consider the limitations of each type of power plant. That is why a combined approach, including hydroelectric, wind, and solar power plants, seems to be the most reasonable solution. This approach will not only reduce dependence on a single energy source, but also ensure the stability of the energy system in various climatic conditions. According to P. Moriarty & D. Honnery (2022), renewable energy has many advantages, but also comes with certain limitations. One of the main limitations is the instability and volatility of renewable energy sources such as solar and wind. For example, the production of electricity from solar panels depends on the availability of sunlight, which can vary depending on the time of day, time of year, and weather conditions. Similarly, the wind speed required to operate wind turbines may vary and be insufficient to maintain stable energy production. Analysing the results and conclusions obtained, renewable energy sources can also affect ecosystems and surrounding areas. For example, the construction of a HPP may lead to a change in the river regime and affect the flora and fauna in the region (Rumiantseva *et al.*, 2022). Such impacts require serious analysis and assessment in the planning and construction of renewable energy installations.

Thus, for Kyrgyzstan, the optimal solution would be to use an integrated approach to energy production, including hydroelectric, wind, and solar power plants. This will allow the country to ensure stable and environmentally sustainable energy production that meets its needs and conditions. L. Pham *et al.* (2022) determined that optimal energy flow management in integrated wind-solar-hydrothermal power systems is a complex task requiring balancing different energy sources depending on their availability and variability. These systems combine a variety of technologies, such as wind turbines, solar panels, hydroelectric power plants and geothermal installations, to ensure a stable and reliable energy supply. In addition, to achieve optimal energy flow, many factors must be considered, such as weather forecast, resource availability, technical limitations of equipment, and current energy demand.

A comparison of the efficiency of HPPs, WPPs, and SPPs in Kyrgyzstan revealed that each type has its advantages and disadvantages. HPPs have high capacity and stable production, but require significant investments and can affect ecosystems. WPPs are characterised by low operating costs and flexible placement, but depend on weather conditions. SPPs have minimal environmental impact and available resources, but require high installation costs and are subject to seasonal changes. This diversity can be the key to a stable and sustainable energy sector, provided that it is managed competently and integrated into the overall system.

## CONCLUSIONS

A comparative analysis of the efficiency of the use of hydroelectric, wind, and solar power plants in Kyrgyzstan has revealed a number of important conclusions that can have a significant impact on the development of the country's energy sector. Hydropower demonstrates significant potential in the country due to its numerous rivers and lakes, ensuring stable energy production. However, there is a risk of negative impacts on ecosystems due to changes in the river regime.

Wind energy is a promising source of renewable energy, especially in mountainous and well-ventilated areas. Despite this, wind speed variability can create instability in energy production. Solar energy has high potential in Kyrgyzstan, especially in areas with high insolation. However, energy production may be limited in winter due to cloud cover. In addition, it is necessary to consider environmental aspects when deploying energy projects to minimise the negative impact on the environment and preserve the biodiversity of the region. To improve the efficiency of renewable energy sources, it is also important to improve energy storage technologies and develop flexible network management mechanisms. Ultimately, cooperation with international partners and attracting investments in the development of renewable energy can help accelerate the introduction of new technologies and reduce energy production costs.

To optimise the use of renewable energy sources in Kyrgyzstan, it is necessary to develop an integrated approach, including the integration of various types of power plants, the creation of energy storage systems, and the improvement of energy infrastructure. This approach will improve the stability of energy supply and reduce dependence on conventional energy sources, which ultimately contributes to achieving energy security and sustainable development of the country. Additional research is required to assess the potential of an integrated system for the use of hydroelectric, wind, and solar power plants, considering climate change, and to develop optimal energy system management strategies to ensure stable and sustainable energy supply in Kyrgyzstan. The limitation of the study is the lack of data accuracy or standardisation of methodologies for collecting information on energy production from various types of power plants, which may affect the reliability of the results of the study.

The development of the energy sector in Kyrgyzstan is of strategic importance for ensuring the sustainable development of the country. Based on the findings, a number of recommendations were developed aimed at optimising the use of HPPs, WPPs, and SPPs, and improving infrastructure and increasing the energy sustainability of the country. It is recommended to actively develop and improve hydropower. Given the wealth of water resources in the country, reforms should be carried out in the hydropower sector to increase the production capacity and efficiency of existing hydropower plants. It is also worth exploring the possibilities of building new hydroelectric power plants based on modern technologies. Given the country's potential in the field of wind energy, it is necessary to create incentives for investors and developers of wind farms. This may include the provision of benefits and subsidies, and simplification of procedures for obtaining permits for the construction and operation of wind turbines.

For the development of solar energy, it is necessary to promote the introduction of SPPs based on both large and small systems. The provision of tax incentives and government subsidies, and the creation of incentives for private investors, will help accelerate the deployment of solar power plants. In addition, it is recommended to improve the country's energy infrastructure, including the grid system and energy storage systems. This would facilitate a more effective use of energy produced and ensure stable energy supply throughout the country. In general, the successful implementation of these recommendations contributes to the development of the Kyrgyz energy sector, ensuring its sustainability and contributing to economic growth.

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## CONFLICT OF INTEREST

None.

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**Максат Садиков**

Кандидат фізико-математичних наук, доцент
Міжнародний університет інноваційних технологій
720048, вул. Анкари, 1/17, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0001-6008-9551

**Назгуль Темірбаєва**

Кандидат технічних наук, доцент
Киргизький державний технічний університет ім. І. Раззакова
720044, просп. Ч. Айтматова, 66, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-9080-5368

**Максат Наримбетов**

Кандидат технічних наук, доцент
Киргизький національний аграрний університет ім. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0001-8331-5689

**Бакит Токтоналієв**

Кандидат технічних наук, доцент
Киргизький національний аграрний університет ім. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-2775-8474

**Замірбек Нарієв**

Кандидат технічних наук, доцент
Киргизький національний аграрний університет ім. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0001-9599-2839

# Порівняльний аналіз ефективності використання гідро-, вітряних і сонячних електростанцій у Киргизстані

**Анотація.** Проведення дослідження ефективності використання гідро-, вітряних і сонячних електростанцій у Киргизстані є важливим у контексті розвитку стійких джерел енергії для забезпечення енергетичної безпеки та зниження впливу на навколишнє середовище. Це дослідження спрямоване на виявлення найбільш перспективних джерел відновлюваної енергії, здатних забезпечити сталий розвиток енергетичного сектора. Дослідження являє собою порівняльний аналіз трьох основних джерел відновлюваної енергії – гідро-, вітряних і сонячних електростанцій – у контексті їх використання в Киргизстані. У рамках дослідження розглядаються різні аспекти ефективності кожного типу станцій, включно з доступністю ресурсів, економічною та екологічною ефективністю, а також технічною надійністю. Обговорюються переваги та обмеження кожного джерела енергії в контексті киргизької економіки та кліматичних умов. Зокрема, акцент робиться на багатому потенціалі водних, вітрових і сонячних ресурсів у країні, що відкриває перспективи для розвитку відновлюваної енергетики. Також досліджуються питання впливу кожного типу енергостанцій на навколишнє середовище, включно з екологічними наслідками та можливими ризиками для місцевої фауни і флори. Результати дослідження підкреслюють необхідність комплексного використання різних типів електростанцій для забезпечення енергетичної безпеки та стійкості в Киргизстані, з огляду на їхні сукупні переваги та обмеження. Насамкінець, робиться висновок про те, що оптимальним підходом до забезпечення енергетичної безпеки та стійкості в Киргизстані може стати комплексне використання всіх трьох типів електростанцій, з огляду на їхні сукупні переваги та обмеження. Результати дослідження можуть бути використані під час розроблення стратегії енергетичного розвитку Киргизстану з урахуванням оптимального поєднання гідро-, вітро- та сонячної енергії для забезпечення сталого та екологічно безпечного енергетичного комплексу країни

**Ключові слова**: стійкі джерела енергії; екологічна ефективність; відновлювальна енергія; енергетична безпека; технічна надійність; стійкі джерела енергії; відновлювальна енергія

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**Oleh Semenenko***

Doctor of Military Sciences, Professor
Central Research Institute of the Armed Forces of Ukraine
03049, 28B Air Force Ave., Kyiv, Ukraine
https://orcid.org/0000-0001-6477-3414

**Serhii Kirsanov**

Doctor of Technical Sciences, Senior Researcher
Central Research Institute of the Armed Forces of Ukraine
03049, 28B Air Force Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-9696-0369

**Artur Movchan**

PhD in Technical Sciences
Central Research Institute of the Armed Forces of Ukraine
03049, 28B Air Force Ave., Kyiv, Ukraine
https://orcid.org/0009-0006-0559-4962

**Mykola Ihnatiev**

PhD in Technical Sciences
Central Research Institute of the Armed Forces of Ukraine
03049, 28B Air Force Ave., Kyiv, Ukraine
https://orcid.org/0009-0007-8797-3364

**Uzef Dobrovolskyi**

PhD in Technical Sciences, Associate Professor
National Aviation University
03058, 1 Liubomyr Huzar Ave., Kyiv, Ukraine
https://orcid.org/0000-0002-1077-1402

# Impact of computer-integrated technologies on cybersecurity in the defence sector

**Abstract.** The research relevance is determined by the ever-increasing threat of cyberattacks and the need to protect defence systems from these threats through the introduction of integrated computer technologies. The study aims to develop strategies for ensuring digital security in the defence sector, addressing the impact of information technology. The study analyses the impact of integrated computer technologies on information security in the military sphere, develops cybersecurity strategies and analyses examples of their application in the defence sector. The study determined that integrated computer technologies are substantial in improving cybersecurity in the defence sector. The analysis showed that they can effectively detect, analyse and respond to cyber threats, ensuring reliable protection of critical information resources. In addition, the digital security strategies developed addressed the specifics of the defence sector, helping to improve protection against cyberattacks and ensuring immediate action in the event of a threat. The resulting strategies for

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*Corresponding author

improving the digital security of the defence sector consider the specifics of the industry, contributing to increased resilience against cyber threats and ensuring prompt action in the event of potential attacks. The most significant examples of the introduction of these technologies, namely data mining, big data, distributed blockchain technology, analytical methods of cyber-analysis and cyber-physical systems, have demonstrated their effectiveness in real-world conditions, contributing to the security and resilience of defence systems. The results show the importance of information technology in improving cybersecurity in the defence sector. This confirms the need for systematic implementation of such technologies to ensure effective protection against modern cyber threats

**Keywords**: information systems; digital defence; military complex; use of innovations; electronic threats

## INTRODUCTION

Identification and elimination of digital security problems is an urgent task, as military information systems are subject to constant cyber threats. There is a gap in the development of digital security strategies in the defence sector, as well as in the understanding of the challenges associated with this area. The lack of proper digital security can have serious consequences for military systems and national security in general. To understand the study, it is important to get acquainted with the general theoretical aspects of digital security in the context of the defence sector. This includes an understanding of the basic principles of cyber security, covering a wide range of measures to prevent unauthorised access, destruction or modification of data, and to ensure the confidentiality and integrity of information. Analysing typical threats and vulnerabilities of information systems is key to identifying potential risks and developing effective protection measures. In addition, the study of modern approaches to the cybersecurity of military facilities allows to identify the most effective and innovative methods and technologies that can be used to ensure security in this area.

For a more detailed analysis of the current state of cybersecurity in the context of the defence sector, it is necessary to consider other studies in this area. For instance, the study of I.L. Humeniuk (2023) showed the positive impact of information technology on the Ukrainian economy, in particular, the growth of labour productivity, optimisation of business processes and improvement of the quality of services, and identified potential challenges related to employment, competitiveness of industries and cybersecurity. M. Rakushev *et al*. (2022) identified the main capabilities and shortcomings of the Terminal information and telecommunication system for the intelligence needs of the Kyiv Defence Forces and proposed recommendations for its further improvement. In turn, A. Munko (2023) determined the place of cybersecurity in the financial security policy of Ukraine, addressing the importance of a strategic approach and the development of a sectoral cybersecurity strategy, and proposed measures to counter cyber threats in this context.

S. Toliupa & L. Slipachuk (2023) revealed the composition and structure of measures and tools that are part of the system of protection of industrial integrated information management systems in the cybersecurity sector, as well as providing a detailed description of the various resources and tools included in this system. In addition, a study by J.H. Eom *et al*. (2023) determine that the key to creating an intelligent intelligence unit, which is being developed by advanced military countries, is to strengthen the security of the information system and real-time network using the latest technologies, such as artificial intelligence (AI) and big data (BD). Study results by F. Ahmed *et al*. (2023) highlight the interaction between cybersecurity and cyber defence with a focus on the development of the concept of cyber resilience.

D. Galinec (2023) demonstrated how cybersecurity and cyber defence contribute to cyber resilience using a new model developed by the author. Moreover, C.O. Qader & D.Z. Ablahd (2023) reflected on the current state of cybersecurity of computer systems, including the main threats and measures aimed at reducing these risks. According to S. Mishra (2023), the AI-based cybersecurity method improves the performance of cybersecurity systems by enhancing their defence capabilities, which is manifested in improved data protection, scalability, risk mitigation, information security and attack avoidance. Similarly, W.K. Too & M. Mutuku (2023) gained a deeper understanding of the state of cybersecurity implementation and identified problems and strategies to improve this process. The findings of the study can influence policy and decision-making, guiding future investments in cybersecurity and related technologies.

It is worth noting that the scientific contributions of these studies can help to form a more complete understanding of the current state of cybersecurity, especially in the context of the defence sector and other areas of life. The authors covered various aspects of cybersecurity, but some aspects remain insufficiently covered. For instance, these studies focus on describing information system security measures but do not consider their impact on military facilities. It is also worth analysing the possibilities of applying cybersecurity principles in the defence sector to ensure information security and protection against cyber threats. In general, this study focuses on the identification of optimal strategies for ensuring information security in the defence sector, including the impact of modern information technologies. The study aims to examine the current state of digital technologies in the military sphere, as well as to identify the main challenges and threats arising from digital security in the defence sector.

## MATERIALS AND METHODS

To achieve the objective of the study, an overview of the impact of integrated computing technologies on defence cybersecurity was conducted, focusing on their role and potential for strengthening digital security in the sector. The next phase of the study was to develop strategies to ensure digital security in the industry. Given the specifics of this area, the strategies developed were aimed at protecting against cyberattacks, ensuring data confidentiality and implementing other measures of great importance to the security of the state. In addition, a review of best practice examples in this area was conducted, which meant analysing successful initiatives and programmes that have already been implemented in the defence sector in different countries. As such, effective methods that could be used to develop new strategies to ensure digital security were identified.

The study analysed how these strategies can be applied, including their effectiveness and suitability for addressing specific challenges and threats in the defence context. Various technologies used in the defence sector to improve cybersecurity were studied. These technologies include intelligent threat monitoring and detection systems, data encryption systems, innovative approaches to protecting critical infrastructures from cyberattacks, as well as cyber-analytical and cyber-physical systems, blockchain technologies, BD and AI. This stage of the study included an analysis of the use of AI and machine learning in the defence sector cybersecurity. These advanced technologies are used to detect new threats, review large amounts of data and respond to cyberattacks in real-time. The effectiveness of blockchain technologies in the field of cybersecurity, which can be used to create reliable and unbreakable data storage systems was determined, which may be especially important for the defence sector, where confidential and critical information is stored.

Thus, the consideration of the introduction of technologies in the cybersecurity of the defence sector covered a wide range of innovative solutions aimed at improving digital security and protecting important information resources. Additionally, diagrams of complex data protection systems and cybersecurity strategies that reflected the structure and functionality of the various components of these systems were developed. Each scheme has been designed to meet the specific requirements and challenges faced by the defence sector. To develop the schemes, modelling methods were used that involved abstracting the essential aspects of data protection systems and using various cybersecurity components. The functions of each component, their interaction and their impact on the overall effectiveness of the system were addressed to better assess the level of protection and identify weaknesses.

The key problems and challenges faced by modern security systems were also identified, which allowed to identify priority areas for further research in this area. The results obtained were systematised and summarised, which were used to formulate the main conclusions based on the data obtained and provide the necessary recommendations.

## RESULTS

In the digital environment, where information technology plays a crucial role in defence, digital security is becoming an extremely important task for ensuring national security and defence capability. Information technology, including computerised systems, communication networks, software and electronic databases, enables the exchange of information, the management of military operations and the storage of sensitive data. However, this environment also poses new challenges and threats to cybersecurity, including cyberattacks, espionage, sabotage and terrorist activities. Therefore, the development of effective strategies to ensure cybersecurity in the defence sector, considering the impact of information technology, is an extremely urgent and important task.

The first strategy is to develop and implement robust data protection systems (Fig. 1). This strategy envisages the creation of modern data protection systems in the defence sector. It includes the development of software that provides data encryption, network monitoring, intrusion detection and protection against cyberattacks. Implementing robust data protection systems protects confidential information from unauthorised access, preserves data integrity and ensures that information is available to the appropriate users. In addition, this strategy also provides for regular updates and audits of data protection systems to identify and eliminate vulnerabilities.

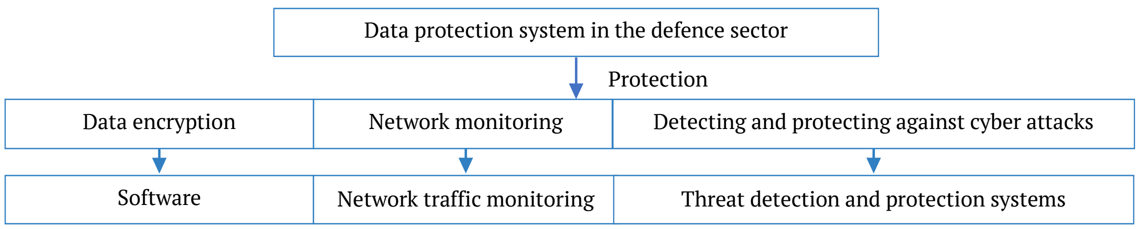


**Figure 1.** Developing and implementing robust data protection systems
**Source:** compiled by the authors

This diagram shows that the defence data protection system includes various components, such as data encryption, network monitoring, and detection and protection against cyberattacks. Each of these components performs its function to ensure the security and integrity of important information. Moreover, it is worth giving an example of how to apply the strategy. For example, a government defence organisation may develop and deploy specialised software to encrypt sensitive information, control access to systems, and detect anomalous activity on the network. Such systems can prevent unauthorised access to sensitive military data and ensure the security and integrity of information.

The second strategy is to ensure cyber hygiene (Fig. 2). It involves the implementation and support of initiatives aimed at enhancing the cybersecurity culture among defence personnel and users. This strategy is aimed at training staff in the correct practices of using computer systems, implementing data security policies and raising awareness of potential cyber threats. It is possible to note that cyber hygiene includes not only technical security measures but also the awareness and responsibility of each user for the security of information. Enhanced cyber hygiene can avoid many threats, such as phishing, social engineering and other forms of attacks that use social engineering techniques to gain access to a system.

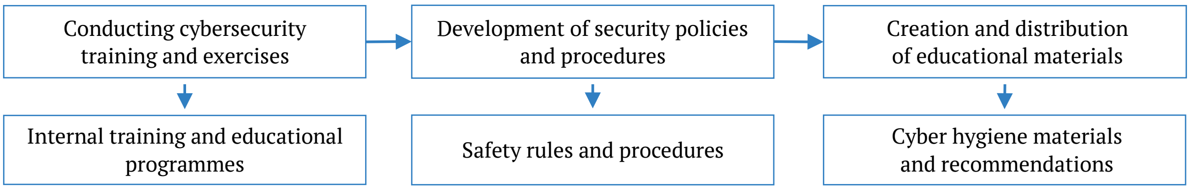


**Figure 2.** Ensuring cyber hygiene
**Source:** compiled by the authors

This flowchart presents the main steps of this strategy, including conducting cybersecurity training and exercises, developing security policies and procedures, and creating and distributing educational materials. For instance, a governmental organisation can provide regular cybersecurity training for its staff, make cyber hygiene materials and resources available, and implement policies and procedures to protect sensitive information. Such measures can help staff avoid situations where their actions could be vulnerable to cyberattacks.

Another strategy is the development and implementation of cyber security strategies and policies, which involves the development and implementation of comprehensive defence sector practices and policies to ensure digital security (Fig. 3). This strategy aims to establish principles governing cybersecurity in the defence sector and identify specific measures for their implementation. The analysis of this strategy indicates that the creation of digital security methods and policies is a key element of effective cybersecurity management in the military sphere. They define strategic goals and priorities and are developed with the unique needs and challenges of the defence sector in mind. In addition, they unify approaches to cybersecurity, create standards and procedures, and promote coordination between different governance structures and agencies.

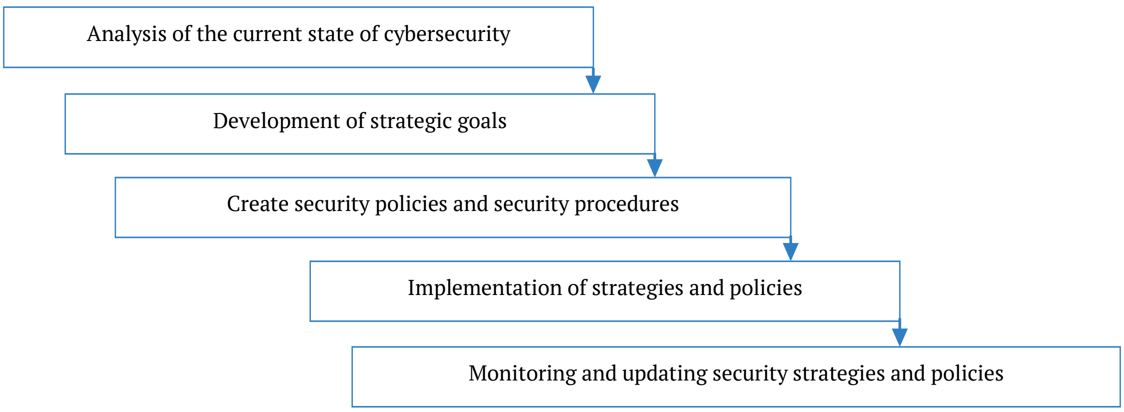


**Figure 3.** Developing and implementing cyber strategies and security policies
**Source:** compiled by the authors

The resulting scheme reflects the sequential process of implementing this strategy in the defence sector. An example of the application of this strategy could include the development of a national cyber strategy for the defence sector, which defines strategic goals and priorities in the field of cyber security and establishes a framework and standards for its implementation. Additionally, this strategy may include the creation of internal security policies and procedures to protect confidential information, critical systems and infrastructure from cyber threats. In addition, it should include a strategy to improve the ability to detect and respond to cyberattacks (Fig. 4). It aims to improve the ability of defence institutions to detect and respond effectively to cyberattacks. This strategy envisages a comprehensive approach to cybersecurity management, including analysis of existing detection and response systems, their enhancement, testing and continuous improvement. The main steps in the implementation of this strategy are to analyse the current systems for detecting and responding to cyberattacks in the defence sector, improve existing systems and introduce new technologies to more effectively detect and respond to threats.

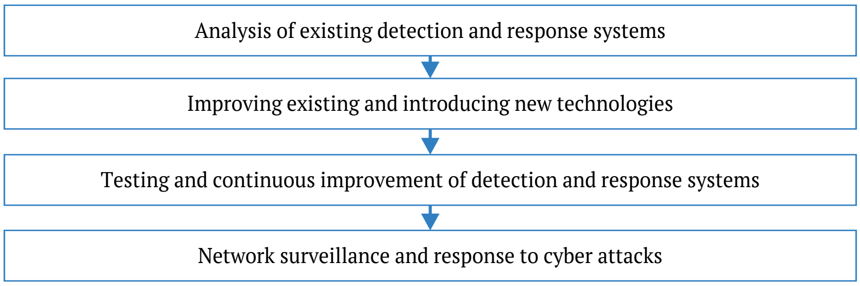


**Figure 4.** Improving the ability to detect and respond to cyber attacks
**Source:** compiled by the authors

This flowchart illustrates the sequence of actions that are included in a strategy to improve the ability to detect and respond to cyberattacks. In terms of the practical application of this strategy, a government defence organisation could develop and implement a new cyberattack detection system based on AI and BD analysis. This system automatically detects anomalous activity on the network and quickly alerts potential threats. When a cyberattack is detected, the system will automatically launch procedures to isolate and neutralise the threat, allowing the organisation to respond quickly and effectively to cyberattacks, ensuring the security and integrity of information.

Attention should also be devoted to the strategy of creating cyber defence teams and competence centres (Fig. 5). It envisages the creation of specialised groups and expert centres dealing with cyber defence. This strategy aims to increase the effectiveness of the response to cyber threats by analysing, identifying and eliminating potential threats to information security in depth. Establishing cyber defence teams and competence centres involves several steps. Firstly, it is necessary to identify the needs and staffing requirements for cyber defence. Then, specialised cybersecurity personnel are recruited and trained. After that, teams and centres are formed to ensure continuous monitoring and protection of defence information systems.

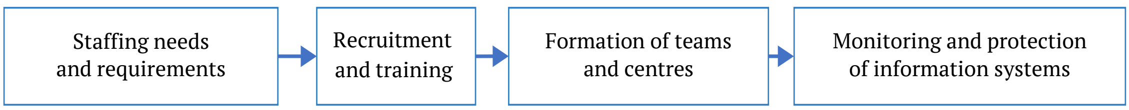


**Figure 5.** Establishment of cyber defence teams and competence centres
**Source:** compiled by the authors

This flowchart shows the sequence of steps to implement this defence strategy. It starts with identifying needs and staffing requirements, then includes recruiting and training specialised staff, forming teams and centres, and ends with monitoring and protecting information systems. An example of this strategy could include the creation of cyber defence centres that specialise in detecting and responding to cyberattacks in the military sphere. These centres may be responsible for network monitoring, analysing security incidents and developing data protection strategies. For instance, a government defence organisation may establish a cyber defence centre to protect critical military information resources and infrastructure from cyber threats.

Equally important is the strategy of conducting regular security audits and penetration testing, which is an important component of the defence cyber defence system (Fig. 6). This strategy involves periodic assessments of vulnerabilities in information systems and infrastructure to identify potential risks and security gaps. A security audit is a systematic review, testing and analysis of information systems and processes to identify weaknesses and potential security threats. This process includes reviewing security policies, applying access control measures, assessing network security, analysing system configurations and identifying potential vulnerabilities. Penetration testing is a method of systematically testing the security of information systems by attempting to penetrate or intrude into them. This process simulates the actions of a potential attacker and identifies weaknesses in security systems that can be used for unauthorised access or attack.

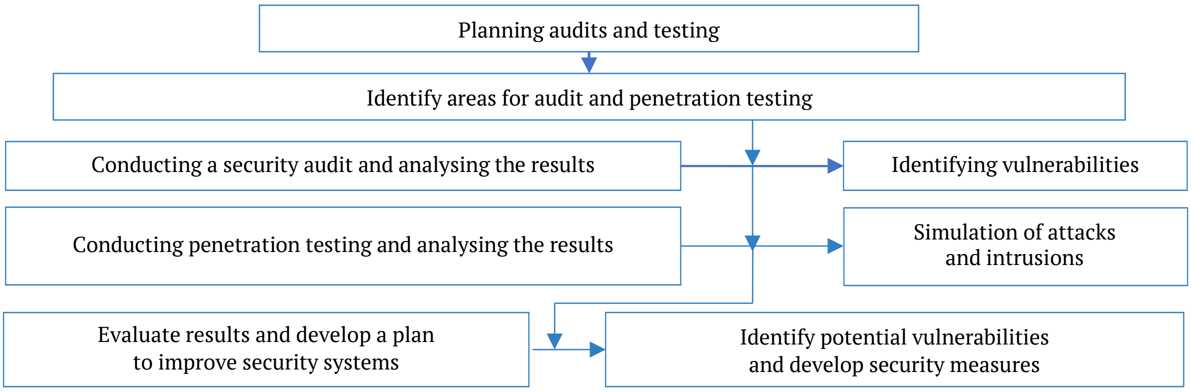


**Figure 6.** Conducting regular security audits and penetration testing
**Source:** compiled by the authors

This diagram shows the sequence of steps involved in conducting regular security audits and penetration testing. Each block represents a separate stage of the process, from planning to evaluating the results and developing protective measures. Thus, this strategy can be implemented, for example, in a government defence organisation that can regularly conduct security audits of its information systems and networks, as well as penetration testing using expert teams or external partners. This identifies potential security threats, risks, and takes timely measures to prevent or eliminate them.

The strategy of introducing strict access rules and restrictions at the user level involves the establishment of integrated access control systems and the development of security policies that regulate user access to information resources in the defence sector (Fig. 7). This strategy is aimed at reducing the risk of confidential information leakage and ensuring compliance with regulatory and legal requirements in the field of cybersecurity. Strict access rules imply that users' access rights to confidential information and critical infrastructure resources are limited to the minimum necessary, depending on their role and functional responsibilities. This may include restricting access rights through roles and privileges, two-factor authentication, access control lists, and system access auditing mechanisms.

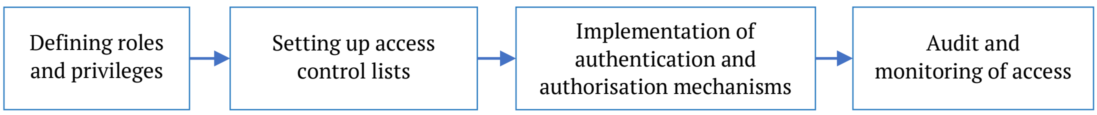


**Figure 7.** Introduce strict access rules and restrictions at the user level
**Source:** compiled by the authors

This flowchart shows the sequence of actions when implementing strict access rules and restrictions at the user level. As an example of the use of the strategy, a government defence organisation can implement this strategy by establishing a system of roles and privileges for users depending on their position and functional responsibilities. For example, high-level employees may be granted enhanced access rights to confidential information, while low-level employees may be granted limited access rights. This strategy reduces the possibility of internal threats and provides greater control over access to important information. Moreover, the strategy of cooperation with the private sector and international partners should be noted (Fig. 8). It involves partnerships with companies, organisations and other countries to share information, technologies and best practices in the field of cybersecurity. This strategy aims to increase the level of cyber defence capability by combining the efforts and resources of various actors. Cooperation with the private sector may include partnerships with information technology companies to create and implement new data protection systems, develop software to detect cyber threats, and other initiatives. It is also possible to jointly conduct training and training programmes to improve the skills of cybersecurity specialists.

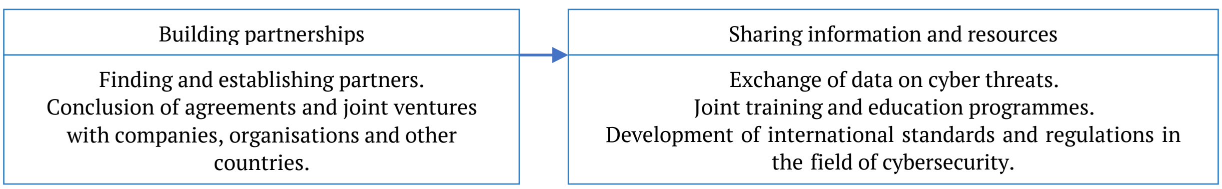


**Figure 8.** Cooperation with the private sector and international partners
**Source:** compiled by the authors

This diagram illustrates the main steps included in the strategy for cooperation with the private sector and international partners in the field of cybersecurity. Internationally, the strategy envisages information exchange and cooperation with other countries in the field of cybersecurity. This could include sharing data on cyber threats, joint exercises and training programmes, and the development of international standards and regulations in this area. For example, the government can cooperate with leading technology companies to create innovative data protection systems. In addition, cooperation agreements can be concluded with other countries to share information on cyber threats and respond to them jointly through joint operations centres. It is worth noting that these strategies complement each other and form a comprehensive approach to cyber defence. These include developing technological defences, promoting a culture of cybersecurity among staff, collaborating with the private sector and international partners, and conducting security audits and penetration testing (Piera *et al*., 2016). These strategies are aimed at preventing cyberattacks, identifying potential threats and responding effectively to them, thus ensuring the security and integrity of information in the defence sector. Implementation of strategies requires constant updating and adaptation to the rapidly changing cyber threat environment, but at the same time, it opens new opportunities to improve cybersecurity and protect critical information resources (Metelskyi & Kravchuk, 2023).

In general, integrated computer technologies are a complex combination of different information systems that interact with each other to achieve a common goal. In the defence sector, these technologies play a key role in ensuring the efficiency, reliability and security of military operations. Their role is to improve the armed forces, provide communications infrastructure, increase the accuracy and speed of response to threats, as well as to enhance defence capabilities and reduce the risk of cyberattacks. With the advent of the latest integrated computer technologies in the defence sector, new challenges for cybersecurity have emerged. Technological developments, such as the Internet of Things, cloud services and AI, provide the military with new opportunities but also increase their vulnerability to cyberattacks (Savytska *et al*., 2024). Analysing technological trends allows to understand which specific aspects of cybersecurity require the most attention and protection measures. A variety of innovative solutions are widely used to implement computer-integrated technologies in defence cybersecurity. For example, the use of AI to analyse data sets detects anomalous activity and potential cyber threats. Systems that use machine learning to analyse network traffic can detect and respond to malicious activity promptly (Pidpalyi, 2024). The large amounts of data generated in the defence sector can be used to identify patterns and predict cyber threats. BD analytics systems identify unusual connections and unusual events that may indicate cyberattacks. In addition, the use of blockchain in cybersecurity can help ensure that data is not available for unauthorised access and ensure the integrity of information. For example, using blockchain technology to create a distributed system for logging network activity can provide a reliable history of events, making it easier to detect attacks (Smutchak *et al*., 2023).

It is also important to use analytical methods and technologies to identify and analyse cyber threats. Various algorithms and software tools identify and classify threats based on their characteristics and properties. And the integration of computer systems with physical processes to detect and respond to cyber threats in real-time. For example, cyber-physical security systems can monitor the operation of physical facilities, such as power plants or heavy machinery, and automatically respond to attacks. These technologies can be successfully used in the defence sector to ensure cybersecurity and protect critical information resources. However, it is important to consider their advantages and disadvantages when choosing and implementing them (Table 1).

**Table 1.** Comparison of technologies in defence cyber security

| Technology | Advantages | Limitations |
|---|---|---|
| Artificial Intellect | High speed of response to threats | Requires large amounts of data |
| BD | Ability to detect complex patterns | High demands on computing resources |
| Blockchain technologies | High reliability and data integrity | Limited scalability |
| Cyber analytics | Effective threat detection and classification | Requires constant updating of models |
| Cyber-physical systems | Real-time response to threats | Requires integration with physical systems |

**Source:** compiled by the authors

A general analysis of the table shows that each technology has its unique advantages and disadvantages. AI and BD analysis enable fast and efficient detection of cyber threats but require significant computing resources. Blockchain technologies and cyber-physical systems provide reliability and real-time response but may be limited in scalability and integration. Cyber analytics provides an effective way of classifying threats but needs to be constantly updated. When choosing technologies to be implemented in the defence sector, their characteristics and the needs of a particular application should be addressed.

In the context of cybersecurity in the defence sector, there is a need to introduce computer-integrated technologies to protect critical information resources and effectively counter cyber threats. A variety of innovative solutions can be used to improve the level of protection and response to potential threats. Recommendations for ensuring digital security in the defence sector, considering the impact of information technology, are based on a comprehensive approach to cybersecurity. First, a detailed analysis of the impact of integrated computer technologies on defence cybersecurity should be conducted. This will identify potential threats and determine the most effective ways to protect yourself. After that, it is necessary to develop strategies for digital security that meet the requirements and characteristics of the defence sector and address the impact of information technology. These strategies can include regular security audits, penetration testing, strict access rules and user-level restrictions, and collaboration with the private sector and international partners.

It is also important to consider the introduction of computer-integrated technologies in the cybersecurity of the defence sector. Technologies such as AI, BD, blockchain, cyber analytics and cyber-physical systems can be successfully used to ensure cybersecurity and protect critical information resources in the defence sector. For instance, the introduction of machine learning and AI systems to detect anomalous activity in networks helps to quickly identify and respond to potential threats. The use of blockchain technologies to create decentralised and non-destructive data storage systems can provide a high level of protection against cyberattacks and malicious interference. These examples demonstrate how information technology can be effectively used to strengthen cybersecurity in the defence sector.

## DISCUSSION

This study analysed the impact of computer technology on cybersecurity, by examining integrated monitoring systems, data encryption systems and innovative approaches. The findings confirmed the importance of a comprehensive approach to cyberspace protection and the need to develop cyber analytics systems for effective network defence. These findings are also noted by J.M. Couretas (2022). Moreover, the results of the study pointed to the growth of security problems due to the introduction of new technologies and the need for new defence measures, which also coincides with the findings of Y. Zheng *et al*. (2021). The results of the study of R.M. Rajendran & B. Vyas (2023) emphasised the complexity of cyber threats and stressed the need to further improve security systems to effectively counter cybercriminals. Thus, this study has revealed that integrated monitoring systems and data encryption systems play a key role in improving cybersecurity in the defence sector. The results confirmed that the development of innovative approaches is necessary for the effective protection of the network and information resources.

Additionally, this paper confirmed the importance of using AI in cybersecurity and noted that it contributes to the effectiveness of computer system protection, as noted by B.S. Guru Prasad *et al*. (2023). What makes this study different is the detailed analysis of various strategies and technologies, including both passive and active defences, that can be used to ensure cybersecurity. This work focused on developing strategies and considering technologies for defence in the digital environment, in the context of the defence sector, rather than reviewing aspects of cyber-physical systems, as was done by T. Liu *et al*. (2019). Compared to the above study, this work has identified additional advantages in the use of AI in ensuring high resistance to complex cyberattacks and reducing vulnerability to smart threats. Thus, this paper has highlighted the importance of using AI in cybersecurity, confirming that it contributes to the efficiency of computer system protection.

This study has expanded the understanding of comprehensive cybersecurity in the defence sector, focusing on the implementation of robust data protection systems. It is possible to state that this study complemented the results of S.B. Rahayu *et al*. (2023), which emphasised the importance of comprehensive cybersecurity education among employees in the defence and security sectors, as it discussed in detail strategies for ensuring cybersecurity. This work focused on general cybersecurity technologies, not limited to aspects related to quantum computing or cyber-physical protection methods developed by M. Barbeau & J. Garcia-Alfaro (2022). Compared to the aforementioned study, this paper focuses on the development and implementation of general cybersecurity strategies, including improving methods of detecting and responding to cyberattacks, protecting against real-time threats, and ensuring data integrity. Additionally, this study complemented the work of M. Kaur (2022), which focused on the importance of cybersecurity and data protection in the information environment, as both works focused on improving security measures in the digital space. Moreover, the results obtained highlighted the importance of using comprehensive strategies in ensuring the information security of systems, as also noted in the study by U.K. Singh *et al*. (2022). However, this work has expanded this understanding by presenting concrete ways to protect computer systems and networks from cyber threats. This study identified common approaches to cybersecurity, including both passive and active defence strategies, which was also done by B. Latha *et al*. (2024), where an intrusion detection system was developed. In other words, the results of this study pointed to the importance of improving intrusion detection systems for computer systems and networks. To this end, effective methods have been developed to integrate these systems into existing infrastructures, which helps to increase the level of security and protection against cyber threats.

While this study pointed to the importance of a comprehensive approach to cybersecurity in the defence sector, J. Kallberg (2022) highlighted the strategic inefficiency of redistributing military capabilities to combat civilian cyber threats. Additionally, the study questioned the effectiveness of the integrated intelligence approach in the defence sector and suggested alternative strategies, while the study by K. Veni *et al*. (2024) emphasised the use of this approach to improve intrusion detection and classification capabilities for digital-double industrial cyber-physical systems. Finally, this study examined the specific challenges and opportunities associated with the impact of computer-integrated technologies on cybersecurity in the defence sector, which is an important aspect of global security and defence, and H. Singh *et al*. (2023) focused on the relevance of cybersecurity in the data technology industry. Thus, they demonstrated that a comprehensive approach to cybersecurity in defence is extremely important, especially given the risks associated with civilian cyber threats.

The study determined that the introduction of computer-integrated technologies in the cybersecurity of the defence sector involves not only the use of the latest methods but also requires active improvement of existing protection systems. The development of cyber defence requires not only technological solutions but also consideration of the human factor and organisational aspects (Smailov *et al*., 2023). This study highlighted cybersecurity issues and the need to improve critical infrastructure protection measures, as in the study by I. Cesarec (2020). However, the aforementioned paper focused on analysing the general state of cybersecurity and identifying threats in general, while this paper addresses the protection of critical infrastructure, which plays an important role in the defence and security sector. The use of machine learning to ensure the security of computers and information in the digital environment was also emphasised, as noted by B.B. Gupta & Q.Z. Sheng (2018). Overall, the study found that computer-integrated technologies have a significant impact on cybersecurity in the defence sector. However, in comparison to the above-mentioned studies, this work focused on the impact of technology on cybersecurity in the military structure and considered a wider range of cybersecurity aspects.

It is worth noting that the study provided some defence-specific protection strategies, while C.F. Azubuike (2023) demonstrated the results of the motivation of state cyberattacks and the need to develop international norms and standards for cybersecurity. This study did not identify the role of cyberspace in special operations, unlike D. Trifunovic & Z. Bjelica (2018), as this study concluded on the technical aspects of cyber defence and the impact of technology on the defence sector. The study also provided a broad overview of cybersecurity technologies specific to the sector under consideration, and the study by S. Lee & S. Kim (2021) demonstrated the introduction of blockchain technologies into national cybersecurity systems. Thus, the study results included the use of specific protection measures aimed at ensuring cybersecurity in the defence sector. Emphasising the importance of a comprehensive approach, specific recommendations were made on the use of technologies and strategies for the effective protection of information resources.

Finally, this study has identified certain challenges in creating and implementing modern cyber defence strategies. While O.A. Guidetti *et al*. (2023) identified general cyber defence strategies, this study focused on adapting these strategies to the specific needs of the defence sector, considering its unique challenges and requirements. In addition, as the study by C. Shi *et al*. (2024), this paper presents strategies and technologies for active and passive network protection. However, the technologies and strategies themselves differ across studies. This paper added important details to the understanding of current cyber defence strategies, focusing on specific challenges and recommendations for the defence sector. Certain aspects of digital defence have been identified that can be used to develop effective network defence methods in the context of military structures.

Based on a comparative analysis with other studies in the field of cybersecurity in the defence sector, several conclusions can be drawn. The study analysed the impact of computer-integrated technologies on cybersecurity in the defence sector, focusing on specific aspects of technology application in this area. Addressing the results of other studies, it is possible to emphasise the importance of a comprehensive approach to cybersecurity, covering current challenges and opportunities of technology. This confirms the need to develop new strategies and technologies to protect against cyber threats in the military sector.

## CONCLUSIONS

The study analysed the impact of integrated computer technologies on information security in the military sphere, created cybersecurity strategies and analysed examples of the use of these strategies in the defence sector. The study determined that integrated computer technologies are substantial in improving cybersecurity in the defence sector. The analysis showed that they can effectively detect, analyse and respond to cyber threats, ensuring reliable protection of critical information resources. In addition, the digital security strategies developed addressed the specifics of the defence sector, helping to improve protection against cyberattacks and ensuring immediate action in the event of a threat. The resulting strategies for improving the digital security of the defence sector consider the specifics of the industry, contributing to increased resilience against cyber threats and ensuring prompt action in the event of potential attacks.

The most significant examples of the introduction of these technologies, namely data mining, BD, distributed blockchain technology, cyber analytics and cyber-physical systems, have demonstrated their effectiveness in improving the security and resilience of defence systems. The results show the importance of information technology in improving cybersecurity in the defence sector. This confirms the need for systematic implementation of such technologies to ensure effective protection against modern cyber threats. It should be noted that the study was limited by the availability of certain data and resources, which may affect the completeness of the analysis. The rapid pace of technology development in the cybersecurity industry may make some results outdated within a short time after the study is completed. In addition, disadvantages may include the limited scope of the models or algorithms used, which may affect the accuracy of the results obtained.

Given the results of the study, it is worth recommending further improvement of integrated computer technologies in the field of cybersecurity in the defence sector. To do this, it is necessary to actively introduce new methods of data analysis, and the use of AI and machine learning technologies to detect and counter cyber threats. One area for further research could be the development of other cybersecurity methods specifically tailored to the needs of the defence sector. In addition, it is recommended to improve cooperation between the military and civilian sectors in the field of cybersecurity. To this end, joint research centres should be established where specialists from both sectors can work together to solve problems and develop innovative methods of protecting against cyber threats. It is also necessary to establish mechanisms for information exchange between military and civilian scientists so that they can interact and learn from each other's best practices and experiences. The development of joint research projects and funding programmes can help bring these sectors closer together and jointly address cybersecurity issues. Thus, further research in this area can help improve cybersecurity in the defence sector and ensure effective protection against modern cyber threats.

## ACKNOWLEDGEMENTS

None.

## CONFLICT OF INTEREST

None.

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**Олег Семененко**
Доктор військових наук, професор
Центральний науково-дослідний інститут Збройних Сил України
03049, просп. Повітряних Сил, 28Б, м. Київ, Україна
https://orcid.org/0000-0001-6477-3414

**Сергій Кірсанов**
Доктор технічних наук, старший науковий співробітник
Центральний науково-дослідний інститут Збройних Сил України
03049, просп. Повітряних Сил, 28Б, м. Київ, Україна
https://orcid.org/0000-0002-9696-0369

**Артур Мовчан**
Кандидат технічних наук
Центральний науково-дослідний інститут Збройних Сил України
03049, просп. Повітряних Сил, 28Б, м. Київ, Україна
https://orcid.org/0009-0006-0559-4962

**Микола Ігнатьєв**
Кандидат технічних наук
Центральний науково-дослідний інститут Збройних Сил України
03049, просп. Повітряних Сил, 28Б, м. Київ, Україна
https://orcid.org/0009-0007-8797-3364

**Юзеф Добровольський**
Кандидат технічних наук, доцент
Національний авіаційний університет
03058, просп. Любомира Гузара, 1, м. Київ, Україна
https://orcid.org/0000-0002-1077-1402

# Вплив комп'ютерно-інтегрованих технологій на кібербезпеку в оборонному секторі

**Анотація.** Актуальність дослідження визначається постійно зростаючою загрозою кібератак та необхідністю захисту оборонних систем від цих загроз шляхом впровадження інтегрованих комп'ютерних технологій. Метою дослідження є розробка стратегій забезпечення цифрової безпеки в оборонному секторі з урахуванням впливу інформаційних технологій. У дослідженні проаналізовано вплив інтегрованих комп'ютерних технологій на інформаційну безпеку у військовій сфері, розроблено стратегії кібербезпеки та проаналізовано приклади їх застосування в оборонному секторі. Дослідження визначило, що інтегровані комп'ютерні технології відіграють важливу роль у покращенні кібербезпеки в оборонному секторі. Аналіз показав, що вони можуть ефективно виявляти, аналізувати та реагувати на кіберзагрози, забезпечуючи надійний захист критично важливих інформаційних ресурсів. Крім того, розроблені стратегії цифрової безпеки враховують специфіку оборонного сектору, допомагаючи покращити захист від кібератак та забезпечуючи негайні дії у разі виникнення загрози. Розроблені стратегії підвищення цифрової безпеки оборонного сектору враховують специфіку галузі, сприяючи підвищенню стійкості до кіберзагроз і забезпечуючи негайні дії у разі потенційних атак. Найбільш значущі приклади впровадження цих технологій, а саме: інтелектуальний аналіз даних, великі дані, розподілена технологія блокчейн, аналітичні методи кібер-аналізу та кібер-фізичні системи, продемонстрували свою ефективність в реальних умовах, сприяючи підвищенню безпеки та стійкості оборонних систем. Результати показують важливість інформаційних технологій для покращення кібербезпеки в оборонному секторі. Це підтверджує необхідність системного впровадження таких технологій для забезпечення ефективного захисту від сучасних кіберзагроз

**Ключові слова**: інформаційні системи; цифровий захист; оборонний комплекс; використання інновацій; електронні загрози

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**Vladyslav Sokolovskyi***
Postgraduate Student, Assistant
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
03056, 37 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0000-0003-2381-3373

**Eduard Zharikov**
Doctor of Technical Sciences, Professor
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
03056, 37 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0000-0003-1811-9336

**Sergii Telenyk**
Doctor of Technical Sciences, Professor
Cracow University of Technology
31-155, 24 Warszawska Str., Cracow, Poland
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
03056, 37 Beresteiskyi Ave., Kyiv, Ukraine
https://orcid.org/0000-0001-9202-9406

# Software and algorithmic support as part of regional systems for monitoring the state of objects for calculation of filtration through earthen hydraulic structures

**Abstract.** The basis for ensuring the safe operation of hydraulic structures is facility monitoring systems. The introduction of software tools for diagnostic modelling of filtration flows into the software of such systems is an objective step caused by recent real-life events. The aim of this study is to improve the accuracy of existing methods for numerical modelling of two-dimensional stationary filtration flows using the mesh method in the software of the facility monitoring system. The methods used in the study included the mesh method, the finite difference method, as well as approximation methods and numerical algorithms. As a result of the study, it was found that the proposed method of organizing the iterative computing process was effective and useful. Its application can significantly reduce the complexity of software development, as it is based on the formalization and standardization of operations, which simplifies the programming process. In addition, the use of conventional loop statements makes the process of writing programmes more understandable and accessible to developers. The additional array used in the algorithm allows easily changing the configuration of the grid boundaries and the order of operations for each node, which makes the method flexible and suitable for various challenges. A special advantage of the algorithm is its logical simplicity, which contributes to successful adaptation in the case of using multiprocessor systems. Thus, the results of the study confirm the high efficiency and potential of the proposed method for use in practical computing tasks. The

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*Corresponding author

proposed method of iterative computation is of considerable practical importance in the field of software development for numerical modelling, since its use simplifies the programming process and provides flexibility in working with different problem conditions, which makes it an important tool for a wide range of research and practical applications in hydraulic engineering and related fields

**Keywords**: object state monitoring systems; grid method; Darcy's law; porous medium; finite difference principle; iterative computing algorithm

## INTRODUCTION

Ukraine faces a variety of challenges, including man-made accidents, natural disasters, and other socio-economic crises that require ensuring public safety and societal stability in emergency situations. Such situations can lead to significant human losses, economic damage and negative impact on infrastructure. Early warning of such situations and competent management during the aftermath of the consequences require comprehensive analysis, consideration of various factors and accurate forecasting.

The relevance of this issue is underlined by the growing number of emergencies in the context of military operations and global challenges, which require new strategies and tools to effectively manage risks and minimize possible consequences. In particular, hydraulic structures, which include reservoirs, dams and canals, can become potential sources of danger in emergency situations such as accidents or floods. It is therefore important to develop mathematical models to predict risk and manage such situations. Such mathematical models can allow analysing different scenarios, calculating the probability of negative consequences and developing optimal response strategies (Kupin *et al.*, 2018).

It is important to bear in mind that failure to consider such important aspects can lead to serious consequences. Insufficient forecasting and management of emergencies related to hydraulic structures can lead to human casualties, material damage and environmental disaster. Lack of proper planning and effective response measures can exacerbate the situation and increase the threat to human life and health. Thus, research on the development and improvement of mathematical models for predicting emergencies related to hydraulic structures is an urgent and critical task. Understanding and studying these aspects will ensure an effective system of public protection and minimize risks to life and economy in the event of emergencies.

According to research by V. Pryshlyak & V. Dubchak (2020), in order to predict the possibility of emergencies at hydraulic structures, one of the crucial areas is the use of mathematical modelling methods, such as methods for numerical solution of the Navier-Stokes equations. It is noted that such equations are used to model the movement of fluid in various hydraulic systems, including rivers, reservoirs, and canals. These methods allow analysing and predicting the movement of water, pressure distribution at different points of the system, which helps in managing and preventing possible negative consequences, such as the destruction of hydraulic structures.

The study by Y. Ivanchuk *et al*. (2019) also noted that the method of hydrodynamic modelling using the Navier-Stokes equations can be used to simulate hydrodynamic phenomena in rivers and reservoirs. Importantly, this method can be highly effective in reproducing complex hydrodynamic processes, such as turbulent flows, current interactions, and the formation of hydrological regimes. This makes hydrodynamic modelling an important tool for predicting hydrodynamic processes and developing effective water management strategies.

In the study by O. Brazaluk *et al.* (2023), boundary element methods based on the idea of solving the equations of fluid motion at the boundary of a domain were used to model the movement of water in rivers and reservoirs. These methods include approximation of internal values by finding exact or approximate solutions only at the boundary of the domain. It is emphasized that such methods avoid the complexity of solving equations in the entire domain, reducing the amount of computation and improving the efficiency of numerical modelling of hydrodynamic processes.

In the work of O. Zakharchuk (2022), the author notes that the finite difference method can be used to build numerical models of water movement in reservoirs, taking into account various hydrodynamic phenomena. These models can accurately reproduce the movement of fluid under various conditions, including the impact of hydraulic structures and thermodynamic processes. Importantly, the finite difference method can also be used to solve heat transfer equations, which allows analysing the temperature fields of water in hydraulic systems.

According to O. Vorontsov *et al.* (2022), the finite difference method has several significant advantages. As a result of the work, it is noted that one of the main advantages is its high versatility and flexibility, which allows it to be used for modelling. In addition, this method can provide stable and reliable solutions in a wide range of conditions, including complex geometries and different physical properties of the medium. Its use allows for fast and efficient results, especially when the computational parameters are properly selected (Miroshnyk *et al*., 2023). Since the above-mentioned studies did not pay sufficient attention to the numerical modelling of two-dimensional stationary filtration flows by the grid method, the aim of this work is to improve these known methods. This work is based on an in-depth study of the principles and algorithms of numerical modelling of filtration flows, which allows increasing the accuracy and efficiency of prediction of hydrodynamic phenomena.

## MATERIALS AND METHODS

In the course of this study, such methods as the grid method for solving two-dimensional stationary filtration flows, the finite difference method, as well as approximation methods and numerical algorithms for calculating the values of the potential function under physical conditions were used. The numerical modelling of two-dimensional steady-state filtration flows in hydraulic systems was carried out using the grid method. Firstly, the region in which the solution was to be sought was considered and approximated by a grid with a boundary. After that, the grid spacing was selected, which allowed the differential equations to be replaced by difference analogues. A five-point template was used to replace the second-order derivatives.

For each internal grid node, the value of the potential function was calculated as the arithmetic mean of the function values in neighbouring nodes located at a distance of step h. This iterative process was organized in such a way that for each internal and external grid node, an additional grid node was matched. Each node of this grid had a specific value that determined the actions and arithmetic operations for each node of the main grid. This approach reduced the complexity of software development by simplifying the process of writing code through the use of common loop statements and formalization of operations. The use of an additional array made it easy to change the configuration of the grid boundaries and the order of operations for each node. The logical simplicity of the algorithm contributes to its successful adaptation for use in multiprocessor systems.

The method of finite differences was used to numerically approximate the differential equations describing physical processes in hydraulic engineering systems. This method is based on the approximation of derivatives by difference expressions and their subsequent use to calculate the values of functions on a grid of points. By dividing the domain into a grid and replacing the derivatives with difference analogues, the problem of the differential equation was transformed into a system of algebraic equations that could be solved and numerical results obtained. The finite difference method made it possible to study the distribution of potentials, pressures and other parameters in space and time, which is important for the correct understanding and modelling of hydrodynamic phenomena in hydraulic structures.

The least-squares method and the method of successive approximations were also used to optimize the parameters of the mathematical models used in hydraulic engineering studies. They allowed selecting parameter values that best fit the required data, ensuring the accuracy and reliability of the modelling results. The least-squares method was used to build regression models and solve linear approximation problems, while the method of successive approximations was used to iteratively solve nonlinear problems and converge to the optimal solution. The use of these methods helped to improve the accuracy and reliability of the research results, and made the models more adaptable to different conditions and input data.

In addition, various approximation methods and numerical algorithms were also used to achieve the goal (Hulianytskyi & Riasna, 2017). They were used to approximate continuous functions, such as domain boundaries or boundary conditions. This approach made it possible to obtain a discrete representation of the continuous quantities required to solve the equations on the grid.

Finally, the study used various numerical methods for solving Laplace's equations and other differential equations. These methods were used to approximate the derivatives and numerically solve the equations at the internal points of the grid. The use of a combination of different methods allowed obtaining more accurate and efficient results in modelling steady-state filtration flows in hydraulic systems. Each of these methods contributed to the solution of the problem and improved the quality and accuracy of the calculations.

## RESULTS

Hydraulic structures in Ukraine are an important element of the engineering and technical infrastructure aimed at solving a number of key tasks related to the management of the country's water resources. They were built to prevent floods, which have historically caused huge material damage to the national economy and resulted in human casualties. Floods that regularly occur in Ukraine are often catastrophic, so the creation of hydraulic structures has become a necessity to ensure the safety of the population and the country's economic development (Nikitenko, 2020).

Another important function of hydraulic structures is to regulate the flow of rivers, such as the Dnipro, Dniester, Southern Bug, Siverskyi Donets and others. River flow requires attention and control, as uncontrolled water levels can lead to flooding, bank erosion and other negative consequences. Hydraulic structures provide the ability to regulate water flows, which helps prevent excessive flooding or drying up of rivers, maintaining ecological balance and ensuring the rational use of water resources. It should also be borne in mind that hydraulic structures perform an important function in providing water to certain regions of the country. Rural and urban settlements, industrial facilities, as well as agricultural land, require stable access to water for drinking water supply, production needs and irrigation. Hydraulic structures, such as reservoirs and canals, provide the ability to regulate the distribution of water resources, which is important for the sustainable development of various sectors of the economy and the livelihoods of the population.

The efficient operation of industrial enterprises is extremely important for the economic development of a country. However, even with full compliance with regulations, a completely safe environment at industrial facilities is not possible. For this reason, the Civil Protection Code of Ukraine (2013), Law of Ukraine No. 2245-III "On High Risk Facilities" (2001) and Order of the Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine No. 29 "On Approval of DBN B.2.5-76:2014

'Automated Systems for Early Detection of Emergency Threats and Public Warning'“ (2014) stipulate the need to implement automated systems for early detection of potential threats and rapid notification of the public about possible emergencies. These measures are aimed at minimizing risks and improving safety at industrial facilities, which is an important step in ensuring stability and protecting the public.

Hydraulic structures are a complex system of engineering structures aimed at optimizing the use of water resources and reducing the negative impact of the water element. They include a variety of structures such as dams, weirs, canals, locks, tunnels, and others that are used for a variety of purposes, from power generation to improving navigation and ensuring water supply (Table 1).

**Table 1.** Emergencies at Ukrainian hydraulic structures

| Waterworks | Date of the emergency | Reasons | Consequences |
|---|---|---|---|
| Dnipro HPP | September 1948 | Technical fault, deficiencies in operation | Large human losses and serious material damage |
| Kaniv HPP | 1979 | Equipment malfunction, technical failure | Human casualties and material damage |
| Kremenchuk HPP | 2009 | Technical failure, improper maintenance | Large flooding on the territory of the power plant |
| Dnipro HPP | 2014 | Poor coordination, weather conditions | Damage to infrastructure, flooding |
| Horodok HPP | 2017 | Poor technical structure, natural factors | Flooding of territories, damage to infrastructure |
| Dnipro HPP | 2019 | Insufficient planning work, natural factors | Flooding of the surrounding areas, evacuation of residents |
| Kaniv HPP | 2021 | Insufficient planning work, natural factors | Flooding of the surrounding areas, damage to infrastructure |

**Note:** HPP – hydroelectric power plant
**Source:** V. Sheremet & M. Kravtsov (2019)

Tailings ponds, as one of the hydraulic structures, play an important role in the storage and treatment of various types of waste, including radioactive, toxic and other wastes, as well as mineral processing. However, their importance is accompanied by potential hazards, as accidents can have serious consequences. Hydrodynamic accidents that can occur at hydraulic structures lead to the formation of artificial floods and breakthrough waves. These phenomena can lead to the destruction of buildings and structures, as well as the loss of life and animals, and cause significant environmental damage. If radiation and chemical hazardous facilities are present in the area of the breakthrough wave, chemical and radioactive contamination zones may be formed. This could lead to serious consequences for human health and the environment. In addition, the destruction of hydraulic structures can cause fires and explosions due to short circuits in electrical networks and damage to fire and explosion hazardous facilities. Therefore, hydraulic structures, playing an important role in the use of water resources and combating the harmful effects of water, require a systematic approach to safety and risk management to prevent potential emergencies and minimize their consequences.

Ukraine's hydropower facilities typically use earthen dams made of sand, sandy loam, loam, clay, gravel, pebble, and their mixtures, as well as rubble stone, which play an important role in controlling water levels and managing water flows. Filtration is a process characterized by the slow movement of liquids or other substances through a porous medium under the influence of various factors. In hydraulic structures, earthen dams in particular act as filtration barriers that allow water to pass through them (Maggay *et al.*, 2021).

Taking into account the above factors, it should be noted that the development of new mathematical models of the filtration process and the improvement of mathematical modelling algorithms play a critical role in ensuring the efficiency and safety of hydraulic structures in Ukraine. However, the understanding and forecasting of these processes needs to be constantly improved and enhanced. New mathematical models and algorithms allow better understanding the dynamics of seepage flows, predict their development and effectively intervene in the event of emergencies such as floods. Such new models and algorithms can form the basis for developing more accurate and efficient monitoring and control systems for hydraulic structures. They will help to ensure a prompt response to changes in filtration processes and make informed decisions in a wide variety of situations that may arise during the operation of hydraulic structures. When analysing filtration flows in hydraulic structures, it is important to use effective numerical analysis methods that allow obtaining accurate solutions to complex mathematical problems. One of these methods, the method of the theory of functions of a complex variable, can be applied in some cases, but it has its limitations.

The most versatile methods are numerical methods, including the mesh method, the finite element method, the method of major domains, the method of summation representations, the method of dummy domains, and others. For example, the mesh method is used to approximate differential equations in different parts of space, which allows obtaining a numerical solution to the problem. The finite element method is used to divide a region into a finite number of elements, where a differential equation is solved on each element. At the same time, each of these methods has its advantages and disadvantages that must be taken into account when using them (Long *et al.*, 2021). Thus, the development of new and improvement of existing methods for numerical analysis of filtration flows is an important scientific task. This will improve the accuracy and speed of solving complex problems, as well as ensure more efficient management and decision-making in the field of hydraulic structures.

Mathematical models of filtration flows are usually based on Darcy's law. This law was discovered and empirically established by the French engineer Henri Darcy in the mid-19th century. He established the relationship between the filtration rate and the hydrodynamic pressure gradient in a porous medium. Darcy's law allows describing the process of filtration through a porous medium and understand its characteristics, such as the rate of seepage of a liquid or gas (Suárez-Grau, 2022). This law is fundamental in hydrodynamics and hydrogeology, and it is an important tool for solving various engineering problems related to water flow and filtration, as shown in (1):

$$v = kJ = -\mathrm{k}\frac{dH}{ds}, \tag{1}$$

where: $k$ is the filtration coefficient; $J$ is the piezometric pressure gradient along the path $S$.

In this case, (2, 3):

$$J = -\frac{dH}{ds}, \tag{2}$$

$$H = \frac{P}{\rho g} + z(\rho g = \gamma), \tag{3}$$

where $p$ – hydrostatic pressure acting on the liquid; $\rho$ – density; $\gamma$ – specific gravity; $g$ – gravitational acceleration; $z$ – height relative to the initial plane.

Thus, according to Darcy's law (1), the head loss during filtration through a porous medium is proportional to the velocity of the liquid or gas through the medium. This means that the higher the filtration rate, the greater the head loss. It is also important to note that the filtration coefficient $k$ is a parameter that determines the rate of seepage of a liquid or gas through a porous medium. It depends on various factors, including the properties of the porous medium, as well as the fluid that is filtered through it (4):

$$k = \frac{k_f \rho g}{\mu}, \tag{4}$$

where $k_f$ – is the filtration permeability of the medium; $\rho$ is the mass density of the liquid; μ is the dynamic viscosity parameter; $g$ is the gravitational acceleration.

The diversity of porous media and the liquids that seep through them results in different filtration coefficients. The filtration coefficient of water, for example, can vary depending on soil properties, depth of liquid penetration, pressure and other factors. For this reason, typical values of this coefficient are often used for ease and accuracy of design and calculation (Table 2).

**Table 2.** Typical values of the filtration coefficient for different soils

| No. | Type of soil | Filtration coefficient | Unit of measurement |
|---|---|---|---|
| 1 | Gravel | $10^{-2}$-$10^{-1}$ | cm/s |
| 2 | Coarse sand | $10^{-2}$-$10^{-1}$ | cm/s |
| 3 | Fine sand | $10^{-3}$-$10^{-2}$ | cm/s |
| 4 | Sandy loam | $10^{-5}$-$10^{-4}$ | cm/s |
| 5 | Loam | $10^{-7}$-$10^{-6}$ | cm/s |

**Source:** A. Arifjanov *et al.* (2023)

When it comes to filtration in an anisotropic medium, where the properties of the porous structure can vary depending on the direction, certain peculiarities arise that should be taken into account. For example, the linear relationship between the filtration rate and the pressure gradient remains valid. That is, as the pressure gradient increases, the filtration rate also increases, and vice versa. However, it is worth noting that in the case of an anisotropic medium, the vectors corresponding to the direction of the pressure gradient and the filtration rate may not remain collinear. Thus, the direction in which the liquid or gas moves may differ from the direction in which the pressure in the medium changes. Such differences need to be taken into account when analysing and modelling filtration processes in anisotropic media for more accurate results and predictions. A key role in creating the foundation for mathematical modelling of hydromechanical filtration processes was played by a system of equations to describe various aspects of fluid movement in porous media (Khujaev *et al.*, 2019). This system of equations allows modelling filtration processes with high accuracy and allows taking into account various conditions and properties of the medium (5-9):

$$\frac{1}{g}\frac{\partial v_x}{\partial t} + \frac{\partial H}{\partial x} + \frac{1}{k}\,v_x = 0, \tag{5}$$

$$\frac{1}{g}\frac{\partial v_y}{\partial t} + \frac{\partial H}{\partial y} + \frac{1}{k}\,v_y = 0, \tag{6}$$

$$\frac{1}{g}\frac{\partial v_z}{\partial t} + \frac{\partial H}{\partial z} + \frac{1}{k}\,v_z = 0, \tag{7}$$

$$\mathrm{n}\,\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) + \frac{\partial}{\partial z}(\rho v_z) = 0, \tag{8}$$

$$f(\rho, H, T) = 0. \tag{9}$$

These models were proposed in the form of a system of closed equations that allows describing non-stationary processes of fluid filtration in undeformed soil. However, it is important to note that these equations are applicable only in the case of Darcy's law. Particular attention should be paid to the continuity equation and the equation of state. Thus, the continuity equation (8) takes into account the soil porosity (n), which is an important characteristic for determining the volume fraction of pores during filtration. In addition, the equation of state (9) establishes the relationship between the fluid density (ρ), isothermal head (H) and absolute temperature (T). This allows for a detailed description of the fluid state and the relationship between the various parameters, which is important for proper modelling and understanding of filtration processes.

Integration of the system of equations (5-9), taking into account specific boundary and initial conditions, within the area where the filtration process takes place, allows obtaining the values of projections of the filtration rate, piezometric head and liquid density. The projection of the filtration rate indicates the rate of movement of the liquid through the pores and channels of the soil. The piezometric head reflects the pressure generated by the difference in liquid levels at different points in the porous medium. Fluid density allows determining the mass of fluid present in a given volume of porous media, which is important for understanding and modelling filtration processes. This approach helps to understand the physical processes that occur in a porous medium during filtration and to establish relationships between various parameters of these processes. In the case of incompressible homogeneous liquids, the equation of state is given by (10):

$$\rho = const. \tag{10}$$

In this case, the continuity equation will look like (11):

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0. \tag{11}$$

In the case where all parameters remain constant, i.e., with stationary filtration, using equations (5-7), (12-14) will be obtained:

$$v_x = -k\,\frac{\partial H}{\partial x}, \tag{12}$$

$$v_y = -k\,\frac{\partial H}{\partial y}, \tag{13}$$

$$v_z = -k\,\frac{\partial H}{\partial z}. \tag{14}$$

If substituting equation (12) into equation (11), the result is (15):

$$-\frac{\partial}{\partial x}\left(k\frac{\partial H}{\partial x}\right) - \frac{\partial}{\partial y}\left(k\frac{\partial H}{\partial y}\right) - \frac{\partial}{\partial z}\left(k\frac{\partial H}{\partial z}\right) = 0. \tag{15}$$

Thus, when considering the filtration of a liquid in a porous medium, the head $H$ can be described by a homogeneous elliptic equation. This is possible provided that the filtration coefficient $k$ remains constant, indicating that the soil is isotropic and homogeneous. In this case, the equation describing the head distribution takes the form of the Laplace equation (16):

$$\Delta H = \frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} = 0. \tag{16}$$

Also, if defining the function φ as follows (17):

$$\varphi = -kH. \tag{17}$$

Then, at a constant value of $k$ ($k = const$), using equations (15) and (16), we have (18):

$$\Delta\varphi = \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0. \tag{18}$$

That is, it should be noted that this function $\varphi$ is harmonic within the filtering region. Given this information, it is important to understand that the points where the function $\varphi$ has a constant value, form equipotential surfaces. In the context of equation (17), these equipotential surfaces are essentially surfaces of equal head. Thus, each point on such a surface will have the same head. At the same time, taking into account equation (17), it can be understood that the filtration velocity vector at any point within the filtration area will be directed perpendicular to the surface of equal head. This means that the direction of the water flow at these points will be directed along the potential lines corresponding to the gradient vector of the function $\varphi$.

When considering the system of equations (5-9) in the case of two-dimensional liquid filtration, the specific conditions of this process in a limited area of space are taken into account. In the context of in-plane filtration, when the process takes place in a plane parallel to the $XOY$ coordinate plane, the system of equations takes the following form (19-21):

$$v_x = -\mathrm{k}\,\frac{\partial H}{\partial x}, \tag{19}$$

$$v_y = -\mathrm{k}\,\frac{\partial H}{\partial y}, \tag{20}$$

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0. \tag{21}$$

In this case, equation (18) will take the form (22):

$$\Delta\varphi = \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = 0. \tag{22}$$

Thus, when considering plane filtration flows, it will be useful to use the flow function ψ equal to (23, 24):

$$V_y = \frac{\partial \psi}{\partial y}, \tag{23}$$

$$V_x = \frac{\partial \psi}{\partial x}. \tag{24}$$

In the case of such a description of ψ, the continuity equation (21) actually becomes an identity, and equations (12-14) yield (25, 26):

$$\frac{\partial H}{\partial x} = -\frac{1}{k}\,\frac{\partial \psi}{\partial y}, \tag{25}$$

$$\frac{\partial H}{\partial y} = \frac{1}{k}\,\frac{\partial \psi}{\partial x}. \tag{26}$$

Also, given that $k = const$ and the function $\varphi$ (17), it turns out that $\varphi$ is related to ψ as follows (27, 28):

$$\frac{\partial \varphi}{\partial x} = \frac{\partial \psi}{\partial y}, \tag{27}$$

$$\frac{\partial \varphi}{\partial y} = -\frac{\partial \psi}{\partial x}. \tag{28}$$

After differentiating from equations (25) and (26), and then subtracting equation (26) from (25), the following expression (29) is obtained:

$$-\frac{\partial}{\partial x}\left(\frac{1}{k}\frac{\partial \psi}{\partial x}\right) - \frac{\partial}{\partial y}\left(\frac{1}{k}\frac{\partial \psi}{\partial y}\right) = 0. \tag{29}$$

So, it turns out that this equation describes the flow function $\psi$ in the filtering region. It is also important that the flow lines, where the value of the flow function is constant ($\psi$=*const*), are the key to analysing this motion. These lines allow tracking the direction of fluid flow at each point in the filtration area: the filtration velocity vector is always tangential to the flow line that passes through that point. At the boundaries of the filtration area, where the fluid does not penetrate, the normal component of the velocity should be zero, reflecting the impermeability of these surfaces (30):

$$V_n = 0. \tag{30}$$

In practical applications of modelling filtration processes, the mesh method is often used (Zhu *et al.*, 2021). This method is known for its effectiveness in transforming systems of partial differential equations into systems of linear algebraic equations, which greatly simplifies their solution. In most cases, the solution using this method is carried out in 3 stages:

1. The first step in using the mesh method is to replace the domain of continuously varying arguments with a finite, discrete set of points. For the two-dimensional case, this set forms a difference grid containing both internal nodes and nodes on the boundaries. The equations are usually solved for the internal nodes, and the values of the functions at the boundary nodes are set according to the boundary conditions of the problem.

2. Next, the differential equations are replaced by their difference analogues, which leads to a system of algebraic equations. The number of these equations is proportional to the number of internal nodes of the difference grid.

3. The resulting system of algebraic equations is usually of large order. The solution of such a system can be achieved by various methods, but in practice, an iterative approach is often used to find a solution.

To illustrate the method of meshes for solving systems of equations, we should consider the Dirichlet problem for a classical elliptic equation, namely the Laplace equation. This problem involves setting boundary conditions to determine the solution within a given domain:

$$\varphi(x, y)|_G = \varphi_0(x, y), \tag{31}$$

where *iG* – is the boundary of the domain in which the solution is to be found, and $(x, y)$ satisfies equation (22) and boundary condition (31) (Fig. 1). To compute the solution on this domain, it is approximated using a mesh. The domain *G* is replaced by an approximate domain, $G_h$ which consists of the internal nodes of the mesh and the boundary $G'_h$.

At the first stage of mesh formation, the domain *G* of the continuously varying argument is replaced by a mesh $G_h$ where each internal node corresponds to a specific solution value. Given the boundary conditions, the boundary $G'_h$ which corresponds to the boundary of *G*. The grid spacing can be different in different directions, but most often it is the same in the *x* and *y* axes. This simplifies the calculations and makes them more efficient. Also, keep in mind that if the grid spacing is too large, it may lead to insufficient accuracy of the solution.

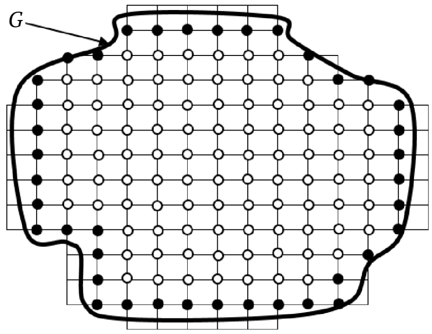


**Figure 1.** The domain G and its boundary, in which it is planned to search for a solution to the system of equations
**Source:** developed by the authors

In the context of the mesh method, nodes are the intersection points of lines with fixed *x* and *y* values. These nodes divide the area *G* into parts, which simplifies the calculation of values at these points. In general, there are internal and external (or boundary) nodes. The inner nodes are located inside the domain *G* and have four neighbouring nodes that also belong to this domain. In Figure 1, they are denoted as circles. The outer nodes, in turn, lie on the edge or boundary of the region *G*. They have only a limited number of neighbours, since one or more sides of these nodes may be outside the region *G*. On the grid, these nodes are marked with black circles to distinguish them from the interior nodes.

When proceeding to the numerical solution of the Laplace equation, the Laplace operator is usually replaced by a difference operator for computing on a grid. To replace the second-order derivatives included in the Laplace operator, we used a five-point calculation template based on the function values at neighbouring grid nodes (Fig. 2). This template allows approximating the second derivatives with sufficient accuracy. In this case, it is usually assumed that the grid spacing along the *x* and *y* axes is the same and equal to *h*. This simplifies the calculations and ensures uniformity in the numerical method, which makes it easier to solve the equation on a computer (Catino *et al.*, 2023; Nguyen & Phuc, 2023).

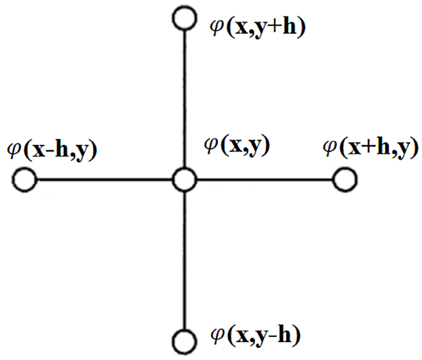


**Figure 2.** Five-point calculation pattern based on five points
**Source:** developed by the authors

Expanding the function into a Taylor series around $(x, y)$ yields (32, 33):

$$\varphi(x \pm h, y) = \varphi(x, y) \pm h\frac{\partial \varphi}{\partial x} + \frac{h^2}{2!}\frac{\partial^2 \varphi}{\partial x^2} + \\ + \frac{h^3}{3!}\frac{\partial^3 \varphi}{\partial x^3} + O(h^4), \quad (32)$$

$$\varphi(x, y \pm h) = \varphi(x, y) \pm h\frac{\partial \varphi}{\partial y} + \\ + \frac{h^2}{2!}\frac{\partial^2 \varphi}{\partial y^2} + \frac{h^3}{3!}\frac{\partial^3 \varphi}{\partial y^3} + O(h^4). \quad (33)$$

Then, from equations (32) and (33), (34, 35) are obtained:

$$\frac{\partial^2 \varphi}{\partial x^2} = \frac{\varphi(x+h,y) - 2\varphi(x,y) + \varphi(x-h,y)}{h^2} + O(h^2), \quad (34)$$

$$\frac{\partial^2 \varphi}{\partial y^2} = \frac{\varphi(x,y+h) - 2\varphi(x,y) + \varphi(x,y-h)}{h^2} + O(h^2). \quad (35)$$

Also, when using a five-point pattern, the Laplace operator will look like (36):

$$\varphi(x+h, y) + \varphi(x+h, y) + \varphi(x+h, y) + \varphi(x+h, y) - 4\varphi(x, y) = 0. \quad (36)$$

Then, equation (36) is written in the form (37):

$$\varphi(x, y) = \frac{1}{4}(\varphi(x+h, y) + \varphi(x+h, y) + \varphi(x+h, y) + \varphi(x+h, y)). \quad (37)$$

When implementing the iterative process to solve the equation on the grid, for each internal node, the value of the potential function $\varphi$ $(x, y)$ is calculated as the arithmetic mean of the values $\varphi$ in the nodes located at a distance $h$ from the central node. The proposed algorithm of iterative calculations for determining the values of the potential function for internal nodes at given values for external (boundary) nodes involves the use of an additional grid that has the same shape and dimension as the main difference domain $G$. Each node of this additional grid has a certain value, which is set before the start of the calculation and is used as a control sign. For each inner and outer node of the main grid $G$, it is proposed to establish a correspondence with a node of the additional grid. This auxiliary grid node determines what actions and arithmetic operations should be performed for each node of the main grid $G$. Thus, the use of an auxiliary grid allows effectively managing the computation process and provides flexibility in choosing operations for each node of the main grid depending on its location and task properties.

The proposed algorithm can be implemented in different programming languages. The algorithm shown in Figure 3 implements a fragment of the Python program from Figure 4. To verify the performance of the proposed algorithm, the depression line of an earthen dam on an impermeable foundation was calculated.

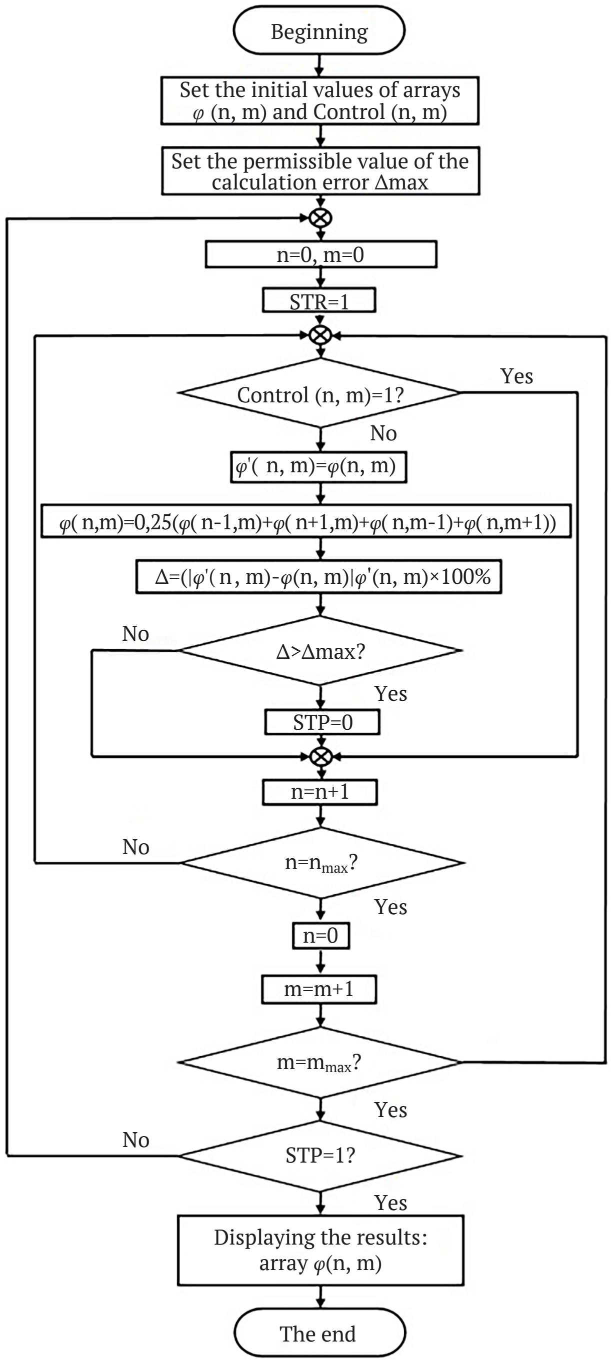


**Figure 3.** Algorithm of the iterative computing process
**Source:** developed by the authors

```python
errors = {"cycle":[0],"value":[100]}
k = 0
error = 100
accuracy = 0.005
dataMatrix = input
while error > accuracy:
    error = 0
    k = k + 1
    newDataMatrix = np.zeros((rows,columns))
    for i in range(rows):
        for j in range(columns):
            if control[i,j] == 0:
                # print("i:",i,"j:",j)
                if(i==1 and j == 16):
                    # print("Cycle:",k,"OLD",dataMatrix[i,j],"NEW",newDataMatrix[i,j])
                newDataMatrix[i,j] = (dataMatrix[i+1,j]+dataMatrix[i-1,j]+dataMatrix[i,j+1]+dataMatrix[i,j-1])/4
                if abs(newDataMatrix[i,j]) == 0:
                    error = 100
                else:
                    tempError = (abs(newDataMatrix[i,j] - dataMatrix[i,j])/abs(newDataMatrix[i,j]))* 100
                    if tempError > error:
                        error = tempError
                    if tempError > 100:
                        #       print("Cycle:",k,"OLD",dataMatrix[i,j],"NEW",newDataMatrix[i,j],"Error", (abs(newDataMatrix[i,j] - dataMatrix[i,j])/abs(newDataMatrix[i,j]))* 100 )
            else:
                newDataMatrix[i,j] = dataMatrix[i,j]
    dataMatrix = newDataMatrix
    errors["cycle"].append(k)
    errors["value"].append(error)
    # print("Finish cycle ",k," with error: ",error)
```

**Figure 4.** A fragment of a Python program
**Source:** developed by the authors

Two matrices were defined for the calculations: a control matrix and a data matrix. The values of the elements of the control matrix (earthen dam on an impermeable base) are shown on Figure 5. The initial values of the elements of the data matrix (earthen dam on an impermeable base) are shown on Figure 6.

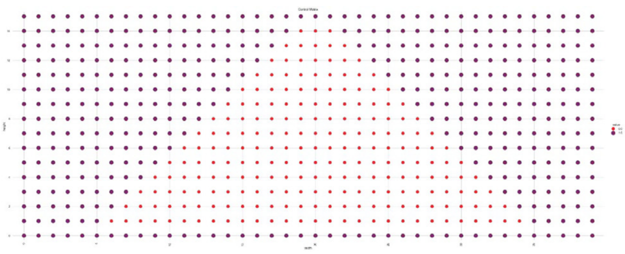

**Figure 5.** Values of the elements of the control matrix (earthen dam on an impermeable base)
**Source:** developed by the authors

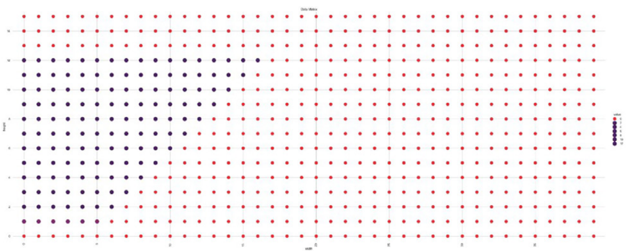

**Figure 6.** Values of data matrix elements (earthen dam on impermeable base)
**Source:** developed by the authors

For clarity, Figure 7 shows the convergence graph of the iterative process. The analysis of the graph allows concluding that after the 200$^{th}$ cycle, the values of the data matrix elements obtained as a result of iterative calculations hardly change, and the convergence process is short-lived.

The graph of the depression line for the earth dam on an impermeable base, which was obtained from the calculations, is shown on Figure 8. The analysis of the results suggests that the depression line does not extend to the downstream slope of the dam, and therefore no filtration deformation will occur.

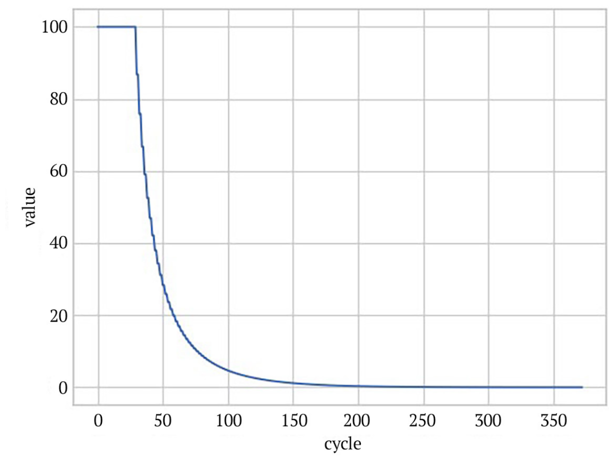


**Figure 7.** Convergence graph of the iterative process (earthen dam on an impermeable base)
**Source:** developed by the authors

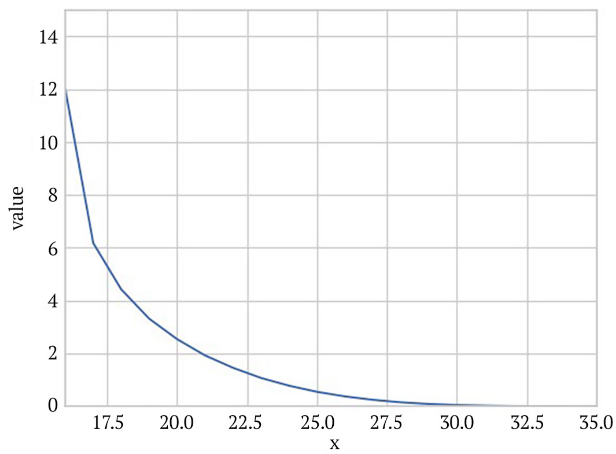


**Figure 8.** Depression line graph (earthen dam on impermeable foundation)
**Source:** developed by the authors

The proposed method of organizing the iterative computing process has several advantages that make it attractive for use:

1. Formalization and standardization of operations can simplify the process of developing software for hydraulic structures. Developers can concentrate on improving algorithms and models instead of spending time on implementation details, which increases the efficiency and speed of development.

2. The use of common loop statements makes the logic of the iteration process clear and easy to reproduce. This simplifies code debugging and allows developers to quickly implement and test new ideas.

3. The use of an additional array to determine the order of operations for each node provides flexibility in working with mesh configurations. This allows easily changing the grid boundaries and adjusting the calculation process to meet the specific requirements of the task.

4. The logical simplicity of the algorithm contributes to its successful adaptation for use in multiprocessor systems, which is important in the context of modern computing environments. This makes it possible to optimally use the power of multiprocessor systems and accelerate calculations, reducing the time for solving complex hydraulic engineering problems.

Thus, the proposed method of iterative calculations for finding the values of the potential function is not only effective but also quite versatile in its application to the design and modelling of hydraulic structures. It allows making the process of software development for hydraulic engineering facilities simpler and more structured, provides flexibility in working with mesh configurations and ensures easy adaptation for use in different computing environments, which is critical in hydraulic modelling. This method opens up wide possibilities for solving complex computational problems and studying various physical phenomena arising in hydraulic engineering.

## DISCUSSION

In today's world, the role of hydraulic structures in providing water resources and controlling water flows is becoming increasingly important. Earthen structures such as dams, canals, and reservoirs play a crucial role in providing water for industry, agriculture and urban consumption, as well as regulating water flows to prevent floods and meet energy needs. However, earthworks also face numerous challenges, including seepage through their structures. Water infiltration through hydraulic structures can cause destruction and damage, threatening the quality and safe operation of these structures. In this context, the development of software for calculating seepage through earthen hydraulic structures is of great importance. Properly designed and calculated systems can effectively minimize seepage risks and ensure the safety and reliability of hydraulic structures. Such software will enable engineers and researchers to perform accurate and reliable seepage analyses of hydraulic structures, opening up new opportunities for improving their design, construction, and operation. Thus, mathematical modelling methods are an integral part of achieving accuracy and efficiency in predicting hydrodynamic phenomena (Sachaniuk-Kavets'ka *et al.*, 2022). They can be used to create analytical and numerical models that allow predicting the movement of water through hydraulic structures, taking into account various hydrodynamic processes occurring in the environment of earth structures. In addition, mathematical modelling methods allow for various sensitivity and statistical analyses to help understand the impact of various factors on the operation of hydraulic structures, as well as to predict and manage potential risks and emergencies (Afgan *et al.*, 2023). This approach is key to ensuring the safety and efficiency of hydraulic structures in different conditions and circumstances.

The work of X. Gao *et al.* (2023) used the finite element method to predict emergencies in hydraulic structures. By solving the filtration, the finite element method showed the ability to take into account the various physical processes occurring in the system. Also, a particular advantage of the finite element method was its ability to adapt to different conditions. It is noted that it can be used to model different types of hydraulic structures and in different geographical conditions. Such an approach can ensure not only the safety and stability of hydraulic structures, but also allow optimizing their efficiency while minimizing risks and costs. Comparing the results of this study with those of the researchers, it should be noted that both studies reflect significant progress in the use of mathematical modelling for forecasting emergencies at hydraulic structures, but apply different approaches and methods. In contrast to the work of the researchers using different mathematical models, including Laplace's equation and Darcy's law, this study developed and proposed an effective method that allows for versatility in applying it to different hydraulic structures and processes. In general, both approaches can be complemented and applied depending on specific needs and circumstances, providing a comprehensive and reliable modelling of hydraulic structures and their operation.

The work of S. Sun *et al.* (2020) also used the finite element method, which allowed for detailed modelling of hydraulic structures and their environment. This method allows for the consideration of complex geometric configurations of structures, material properties, and hydrodynamic conditions that affect the movement of fluid through the system. The use of the finite element method in the work of the researchers made it possible to study various aspects of filtration and pressure distribution in hydraulic structures, which allowed for accurate predictions and the development of effective measures to prevent possible emergencies. It allowed us to consider in detail the inhomogeneities and asymmetries in the geometry of hydraulic structures, as well as to take into account various hydrodynamic phenomena such as turbulence and heat transfer. It should be noted that in this study, similar to the work of the researchers also used the finite element method to model hydraulic structures and their environment. In the work of the researchers, the finite element method allowed for a detailed study of various aspects of filtration and pressure distribution in hydraulic structures, taking into account complex geometric configurations of structures, material properties, and hydrodynamic conditions. This has helped to develop effective measures to prevent possible emergencies and enabled accurate forecasts to be made. In this study, the use of the iterative computing method for modelling hydraulic engineering problems also yielded significant results. This method allowed for the efficient modelling of filtration flows and the consideration of various physical conditions such as turbulence and viscosity (Moldabayeva *et al*., 2021). Although the proposed method is not as detailed in taking into account the geometric details of structures as the finite element method, it allows focusing on a wide range of hydraulic engineering problems and quickly developing effective solutions for them.

In the study by E. Mahiques *et al.* (2023), authors used the finite element method to perform mathematical modelling of filtration processes with great accuracy. This method, which is based on numerical calculations, made it possible to take into account complex geometric configurations, soil properties, and hydrodynamic conditions of fluid movement in the system. The use of the finite element method in the study by the researchers made it possible to conduct a detailed analysis of the impact of various factors on the filtration process. In particular, it was possible to investigate the influence of geometric parameters of hydraulic structures, such as shape and size, on pressure distribution and liquid penetration. Also, the influence of hydrodynamic conditions, such as the speed and direction of fluid movement, on the efficiency of filtration processes was taken into account. Analysing the results of the researchers, it should be noted that a particular advantage of the finite element method was the ability to conduct a detailed analysis of the impact of various factors on the filtration process, including the geometric parameters of hydraulic structures and hydrodynamic conditions. In turn, this study used the method of iterative calculations to find the values of the potential function in hydraulic engineering problems. Although this method is not as detailed in taking into account the geometric details of structures as the bounded element method, it is more versatile and adaptable to a wide range of hydraulic engineering problems. Taking into account the peculiarities of both approaches, it can be noted that the finite element method is detailed and effective for detailed analysis, while the iterative computation method is more general and can be applied to a wide range of hydraulic engineering problems (Cherniha *et al*., 2016). The choice of method depends on the specific needs of the study and time and resource constraints.

In the work by M. Cremonesi *et al.* (2020), it was noted that the bounded element method has significant advantages over other approaches, as it allows for accurate consideration of the complex geometry and inhomogeneities in hydraulic structures that may occur in real conditions. In addition, it was found that the bounded element method provides high accuracy of the modelling results and allows analysing the impact of various factors on the filtration process. In particular, it made it possible to take into account variable hydraulic conditions, including different fluid flow rates and directions, as well as different boundary conditions at the boundaries of hydraulic structures. One of the key features of the finite element method, as noted by the researchers is its ability to accurately account for complex geometries and inhomogeneities in hydraulic structures. This makes it particularly useful for modelling real hydraulic structures where a variety of geometric features may occur. However, it is worth noting that the finite element method can be computationally intensive and time-consuming to perform calculations, especially in the case of large and complex hydraulic systems (Dyvak *et al*., 2022). This may be a limitation for the use of this method in some cases where computational speed is of the essence. In addition, the successful application of the finite element method requires detailed data on the geometry and material properties of hydraulic structures, which can be a challenge in some situations.

In the work by M. Wu *et al.* (2020), the finite element method was used to model two-dimensional stationary filtration flows through earthen hydraulic structures. It is emphasized that the use of the finite element method made it possible to optimize the calculations and reduce the computational complexity of the model. This allowed for faster and more efficient results, which is important for practical applications in the field of hydraulic engineering. The results of the study showed that the finite element model allows for accurate reproduction of filtration processes in hydraulic structures of various configurations and sizes. Compared to the work of the researchers this study is aimed at developing a method of iterative calculations to find the values of the potential function in hydraulic engineering problems. Comparing these studies, it can be noted that both have their advantages. However, it is important to note that the present study is more focused on the iterative computation method, which is aimed at improving the known methods of numerical modelling, in particular for two-dimensional stationary filtration flows through hydraulic structures. This approach allows achieving accurate results with minimal computational complexity and contributes to more efficient use of computing resources. Thus, both approaches have their advantages and can be useful in different scenarios and for solving different problems in the field of hydraulic engineering.

In general, the research conducted within the framework of the analysis of software for calculating filtration through earthen hydraulic structures is an important contribution to the field of hydraulic engineering and hydrology. The results of these studies demonstrate a high level of efficiency and accuracy of numerical modelling, which allows for forecasting and developing measures to prevent possible emergencies at hydraulic structures. The use of different mathematical modelling methods underlines the importance of a multidisciplinary approach to solving problems in this area. Such studies provide valuable guidance for the development and improvement of software tools used to analyse and model hydraulic systems, ensuring the safety and stability of hydraulic structures and contributing to the optimization of their design and performance.

## CONCLUSIONS

As a result of this study, software based on the method of iterative calculations was developed to find the values of the potential function in hydraulic engineering problems. This method proved to be effective and quite versatile in its application to various hydraulic structures and processes. The implementation of the proposed method can significantly simplify the process of developing software for the analysis and modelling of hydraulic systems. The proposed method makes it possible to implement software for diagnostic modelling of filtration flows in the body of earthen hydraulic structures. The main goal of the work was achieved through the use of various mathematical models, including the Laplace equation. The study also used such a law as Darcy's law, which describes the movement of fluid in porous media. Darcy's law was used to describe filtration processes in porous media and to determine the filtration coefficient, which characterizes the permeability of a liquid through a porous medium. This law is one of the main tools in hydrodynamics and hydraulic engineering for calculating fluid flows through soil, including problems related to water supply, drainage, and other hydraulic structures.

In general, the combination of Darcy's law, Laplace's equations, and other physical laws together with numerical approximation methods has allowed the development of efficient and accurate mathematical models for the analysis and modelling of various hydraulic systems and processes. Thus, formalization of operations and standardization of approaches can allow developers to focus on the algorithmic aspects of the problem, which speeds up the development process and increases productivity. The use of common loop statements makes the method understandable and accessible to developers. The logic of the iterative process becomes easy to understand, which contributes to the rapid development and maintenance of software. The use of an additional array to determine the order of operations for each node allows changing mesh configurations and adapting the method to various hydraulic engineering problems. This provides flexibility in dealing with different types of problems and allows for efficient solution of complex hydraulic engineering challenges. In general, the method of iterative calculations for finding the values of the potential function in hydraulic engineering problems opens up wide opportunities for solving complex computational problems and studying various physical phenomena in hydraulic engineering. It should also be noted that due to the implementation of the proposed iterative method, the accuracy of calculations sufficient for practical use was achieved.

Directions for further research in this area may include further refinement of the iterative computation method, extension of the application to a variety of hydraulic systems and conditions, and the possibility of combining this method with other technologies, opening up new perspectives in solving complex hydraulic problems.

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## CONFLICT OF INTEREST

None.

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**Владислав Соколовський**
Аспірант, асистент
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
https://orcid.org/0000-0003-2381-3373

**Едуард Жаріков**
Доктор технічних наук, професор
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
https://orcid.org/0000-0003-1811-9336

**Сергій Телеником**
Доктор технічних наук, професор
Краківська політехніка імені Тадеуша Костюшко
31-155, вул. Варшавська, 24, м. Краків, Польща
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
https://orcid.org/0000-0001-9202-9406

# Програмно-алгоритмічне забезпечення у складі регіональних систем моніторингу стану об'єктів для розрахунку фільтрації крізь земляні гідроспоруди

**Анотація.** Основою забезпечення безпечної експлуатації гідроспоруд є системи моніторингу стану об'єктів. Впровадження в склад програмного забезпечення таких систем програмних засобів для діагностичного моделювання фільтраційних течій – це об'єктивний крок, викликаний реальними подіями останнього часу. Метою даного дослідження є покращення точності вже існуючих методів для чисельного моделювання двовимірних стаціонарних фільтраційних течій за допомогою методу сіток у складі програмного забезпечення системи моніторингу стану об'єкту. Методи, що використовувалися в ході дослідження, включали в себе метод сіток, метод скінчених різниць, а також методи апроксимації та чисельні алгоритми. В результаті дослідження було встановлено, що запропонований спосіб організації ітераційного обчислювального процесу виявився ефективним та корисним. Його застосування дозволяє значно зменшити складність розробки програмного забезпечення, оскільки він базується на формалізації та стандартизації операцій, що спрощує процес програмування. Крім того, використання звичайних операторів циклу робить процес написання програм більш зрозумілим та доступним для розробників. Додатковий масив, який використовується в алгоритмі, дозволяє з легкістю змінювати конфігурацію границь сіткової області та порядок виконання операцій для кожного вузла, що робить метод гнучким та придатним для різноманітних викликів. Особливою перевагою алгоритму є його логічна простота, що сприяє успішній адаптації у випадку використання багатопроцесорних систем. Таким чином, результати дослідження підтверджують високу ефективність та потенціал запропонованого методу для використання у практичних обчислювальних завданнях. Запропонований метод ітераційних обчислень має значне практичне значення в галузі розробки програмного забезпечення для чисельного моделювання, адже його використання спрощує процес програмування та забезпечує гнучкість у роботі з різними умовами задач, що робить його важливим інструментом для широкого кола досліджень та практичних застосувань в гідротехніці та суміжних галузях

**Ключові слова**: системи моніторингу стану об'єкту; метод сіток; закон Дарсі; пористе середовище; принцип скінчених різниць; алгоритм ітераційних обчислень

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**Editors Office Address**:
National University of Life and Environmental Sciences of Ukraine
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Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
Тел.: +38(044)-258-42-63
E-mail: info@technicalscience.com.ua
https://technicalscience.com.ua/uk