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CONTENTS

O. Tarasiuk, M. Rutylo, V. Kravchenko, S. Voloshyn, V. Korolchuk
Autonomous power supply system for consumers 9

V. Loveikin, Yu. Romasevych, Yu. Loveikin, I. Kadykalo
Optimisation of tower crane rotation mechanism force acceleration mode at steady payload hoisting 21

O. Turchyn
Introduction of neural network technologies to optimise the control
of the operating modes of a sucker-rod pump installation 32

A. Rud
Analysis of deformation characteristics of spring elements of tillage tools under dynamic loads 43

E. Aliiev, K. Vedmedeva
Automated devices for quantitative phenotyping of sunflower seeds 54

V. Hruban, A. Panfilova, A. Galeeva, M. Khramov
Optimisation of structural parameters of rotary tillage units
to increase the stability of operation under the influence of variable loads 65

V. Nazarenko, B. Ostroushko
Comparative research of 3D printer main control parameters
and characteristics utilizing Klipper firmware 81

V. Duhanets, R. Semenyshena, P. Fedirko, V. Pukas, M. Volynkin
Application of automated welding processes in the restoration of pipelines of power facilities 91

T. Nechaieva, O. Teslenko, V. Trokhaniak, S. Makarevych
Modelling the energy balances community
under conditions increasing energy independence and reducing greenhouse gas emissions 104

I. Zakharova, S. Shchetynin, V. Shchetynina, A. Zusin, I. Volenko
Use of robotic and automated systems in welding and restoration of parts 117

I. Hrytsiuk, V. Volynets, Yu. Hrytsiuk, I. Bandura, N. Komenda
Prospects for the integration of distributed energy sources into the Ukrainian power grid 130

K. Aghayeva, G. Krauklit
Automated methane emission monitoring systems based on satellite data:
Radiation transfer model analysis 146

Yu. Malogulko, O. Sikorska, N. Ostra, V. Teptia
Ukrainian biogas and biomethane industry as the basis for national energy independence 157

O. Sadovoy, D. Koshkin, V. Martynenko, V. Sokolik
Electricity generation from biogas: Modern technologies
and prospects for Ukraine’s energy independence 173

ЗМІСТ

О. Тарасюк, М. Рутило, В. Кравченко, С. Волошин, В. Корольчук
Автономна система енергозабезпечення споживачів 9

В. Ловейкін, Ю. Ромасевич, Ю. Ловейкін, І. Кадикало
Оптимізація силового режиму пуску механізму повороту баштового крану
при усталеному підйомі вантажу 21

О. Турчин
Впровадження нейромережевих технологій для оптимізації
управління режимами роботи глибинно-насосної штангової установки 32

А. Рудь
Аналіз деформаційних характеристик пружинних елементів
ґрунтообробних знарядь під дією динамічних навантажень 43

Е. Алієв, К. Ведмедєва
Автоматизовані пристрої для кількісного фенотипування насіння соняшнику 54

В. Грубань, А. Панфілова, А. Галєєва, М. Храмов
Оптимізація конструкційних параметрів ротаційних ґрунтообробних агрегатів
для підвищення стійкості роботи під дією змінних навантажень 65

В. Назаренко, Б. Остроушко
Порівняльне дослідження основних параметрів і характеристик системи управління
параметрами 3D-принтера з використанням апаратного забезпечення типу Klipper 81

В. Дуганець, Р. Семенишена, П. Федірко, В. Пукас, М. Волинкін
Застосування автоматизованих зварювальних процесів
при відновленні трубопроводів енергетичних об'єктів 91

Т. Нечаєва, О. Тесленко, В. Троханяк, С. Макаревич
Моделювання енергетичних балансів громади
за умов збільшення енергонезалежності та скорочення викидів парникових газів 104

І. Захарова, С. Щетинін, В. Щетиніна, А. Зусін, І. Воленко
Використання роботизованих та автоматизованих систем
у процесах зварювання та відновлення деталей 117

І. Грицюк, В. Волинець, Ю. Грицюк, І. Бандура, Н. Коменда
Перспективи інтеграції розподілених джерел енергії в електромережу України 130

К. Агаєва, Г. Краукліт
Автоматизовані системи для моніторингу викидів метану
за допомогою супутникових даних: аналіз із використанням моделі радіаційного переносу 146

Ю. Малогулко, О. Сікорська, Н. Остра, В. Тептя
Біогазова та біометанова промисловість України як основа енергетичної незалежності країни 157

О. Садовий, Д. Кошкін, В. Мартиненко, В. Соколік
Виробництво електроенергії з біогазу: сучасні технології
та перспективи для енергетичної незалежності України 173

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Autonomous power supply system for consumers

Abstract. The study aimed to develop the structure of an imitation model of an autonomous power supply system for consumers, which includes subsystems of wind turbine and alternator models, and to describe the characteristics of its components. The procedure for functioning the elements of the autonomous power supply system for consumers and the peculiarities of their interaction were considered. The imitation model of the autonomous power supply system for consumers was created in the Simulink (Matlab) software environment using standard and specialised blocks of the Simulink library, which will allow the most visual and detailed display of the mechanisms of interaction of objects in the automated power supply system for consumers and analysis of the results obtained. A simulation model of an autonomous consumer power supply system, wind turbine, and alternator subsystems has been developed. The resulting simulation model and its main components were described in detail. To ensure maximum efficiency of converting wind energy into electricity, a model of a universal step-up and step-down voltage converter AC-DC_MPPT_Wind with the function of maintaining the

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maximum power point, which served as a wind turbine load and a charger, and whose output is connected to a battery, was created. The features of the DC-AC_inverter subsystem model were the ability to adjust the output voltage and current frequency and select the output current modelling mode – AC or DC, depending on the nature of the research tasks. An experiment conducted using this model was also described and analysed. The results showed that the simulation model of the autonomous power supply system for consumers worked correctly and performed all the specified functions. The results can be used in industrial enterprises to ensure energy independence and reduce electricity costs

Keywords: simulation model; energy independence; wind energy sources; electricity; wind turbine

INTRODUCTION

Wind energy's potential by 2030 depends to a large extent on climate and energy policies determined at the EU level. The potential for wind power development until 2030 largely depends on climate and energy policies defined at the EU level. In particular, the governance of the Energy Union, the Renewable Energy Directive for the period after 2020, the Emissions Trading System (ETS), and the European Electricity Market Framework will have a significant impact not only on the pace of wind energy development but also on other renewable energy sources at the national level. (Wind Europe, wind energy in Europe, scenarios for 2030, 2017). The technologies used in renewable energy and improving energy systems must compete with climate change and consider greenhouse gas emission reduction targets, according to A. Tantau *et al.* (2021), the spread of renewable energy sources (e.g., wind or photovoltaic installations) must be balanced by new technologies and tools for new energy systems characterised by intermittent and uncertain energy generated and new measures to ensure the stability and reliability of the energy system. Y. Charabi *et al.* (2019) noted that from solar panels to wind turbine generators, a wide range of devices can convert ambient energy into a more useful form, like electricity.

Iu. Zachepa *et al.* (2022) presented a mathematical model of the operation of a local autonomous power supply using a diesel generator as the main power source. The primary source of mechanical energy was a diesel internal combustion engine equipped with an automatic speed regulator. The engine was based on the classical principle developed by Polzunov and Watt. Continuous power generation through wind power was mainly the most crucial way to use wind energy. G. Zining (2021) claimed that this power generation method has been highly valued by various countries, mainly using a natural energy source for power generation. This technology had many advantages in the actual application process and had a relatively important role in energy-saving renewable energy and crucial ecological protection.

Transport infrastructure facilities are located in an open area, providing sufficient space for placement and simplifying the orientation of photovoltaic solar panels in the sun (Kozyrsky *et al.*, 2020). The research presented by A. Skrypnyk *et al.* (2023) indicated the prospects for developing solar power sources in Ukraine. The authors presented an optimisation model of electricity generation that corresponded to the state of the energy market in 2019, which made it possible to assess the contribution of reverse externalities of each electricity sector and estimate external tariffs for each electricity generation sector.

The development and benefits of renewable energy technologies mean that their applications are constantly expanding. The development of roads, transport systems, and electric mobility also increases the demand for electricity. According to D. Kurz *et al.* (2024), roads occupy a specific area that can be used for the installation of wind turbines or photovoltaic systems, which can be used to power, among other things, electric vehicle charging stations and road technical infrastructure (road maintenance areas, tunnel lighting, road signs).

The introduction of autonomous energy supply systems for consumers is driven by the need to improve the reliability of electricity supply, reduce electricity losses, and modernise power grids. A centralised power supply system with significant technological losses and a vast distribution network can compromise the quality and reliability of power supply to remote locations. Using autonomous systems based on renewable energy sources can solve this problem. However, the practicality of using a particular energy source requires the development of simulation models of these systems to optimise the determination of their design parameters. To solve this problem, this study develops a simulation model of an autonomous energy supply system for consumers, subsystems of wind turbines, and alternator models.

MATERIALS AND METHODS

The study was conducted at the National University of Life and Environmental Sciences of Ukraine and Ternopil Volodymyr Hnatiuk National Pedagogical University in 2023-2024. An imitation model of an autonomous power supply system for a consumer and subsystems of wind turbine and alternator models was developed as part of the study. The simulation model was developed using Simulink software (Matlab) and standard and specialised blocks of the Simulink Library – Simscape, SimElectronics, and SimPowerSystem sections.

The structure of the simulation model of an autonomous power supply system for consumers based on the use of a renewable wind energy source to generate electricity using a transmissionless wind turbine with a vertical rotor is shown in Figure 1.

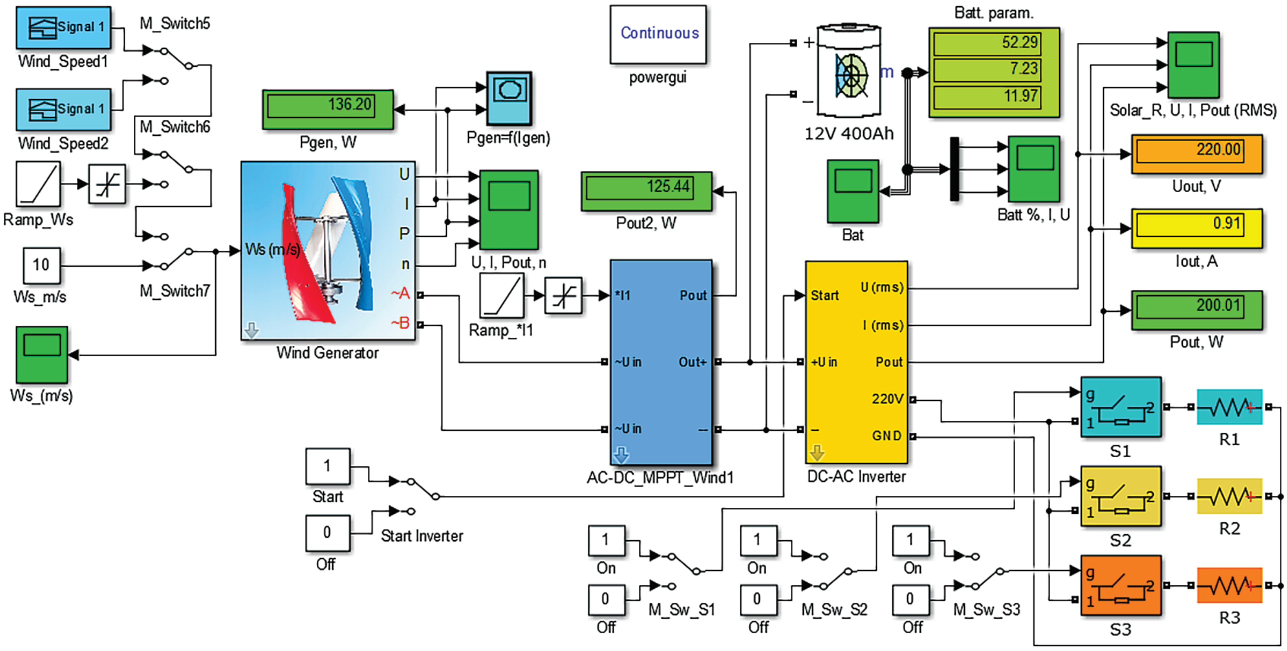


Figure 1. Structure of the simulation model
Source: compiled by the authors of this study

The structure of the model (according to Fig. 1) included the following main elements:

- wind turbine;
- universal step-up DC-DC_MPPT_Wind1 DC-DC_MPPT_Wind1 DC-DC_MPPT_Wind1 universal step-down converter with the function of maintaining the maximum power point (Maximum Power Point Tracking – MPPT), which was the load of the wind turbine and was intended to charge the battery;
- a battery with a nominal voltage of 12V and a capacity of 400 Ah was selected from the Simulink Library of blocks.

The subsystems of the DC-DC_MPPT_Wind1 converter and the DC-AC_inverter were designed as simplified "behavioral" models that reproduce the basics of converter operation without the need to simulate individual switching events associated with pulse width modulation (PWM) processes. They were based on energy conservation and conversion laws, considering input and output power balances and energy losses during conversion. The simplified simulation model structure facilitated a more concise mathematical description, reducing the computational operations required per unit of time. This optimisation led to significant reductions in both simulation time and computer resource utilisation. As a result, the simulation of 24 hours of system operation was completed within a few minutes, an essential factor in the study of long-term processes, the entire cycle of which can be measured in hours or even days.

The wind generator (WG) was represented by the block of the Wind_Generator subsystem, which also included the Wind_Turbine and Generator subsystems (Fig. 2).

The presented wind turbine model contained the basic mathematical and logical operations used to model a wind turbine's performance (Fig. 3).

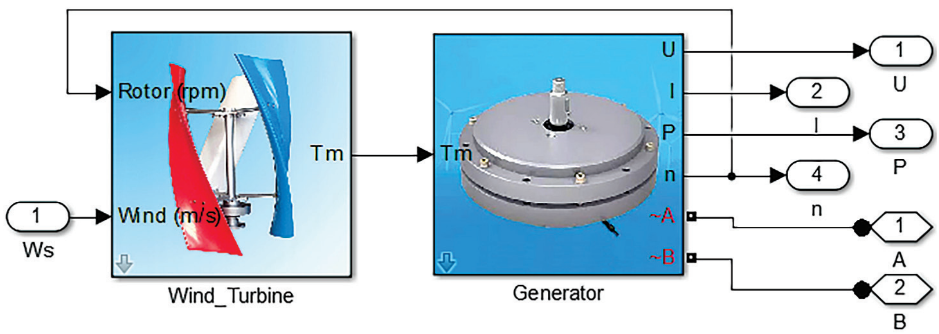


Figure 2. Structure of the Wind_Generator subsystem
Note: Ws – wind speed, m/s; Tm – transmission; U – voltage, V; I – current, A; P – power, W; n – rotor speed; A, B – alternating voltage, V
Source: compiled by the authors of this study

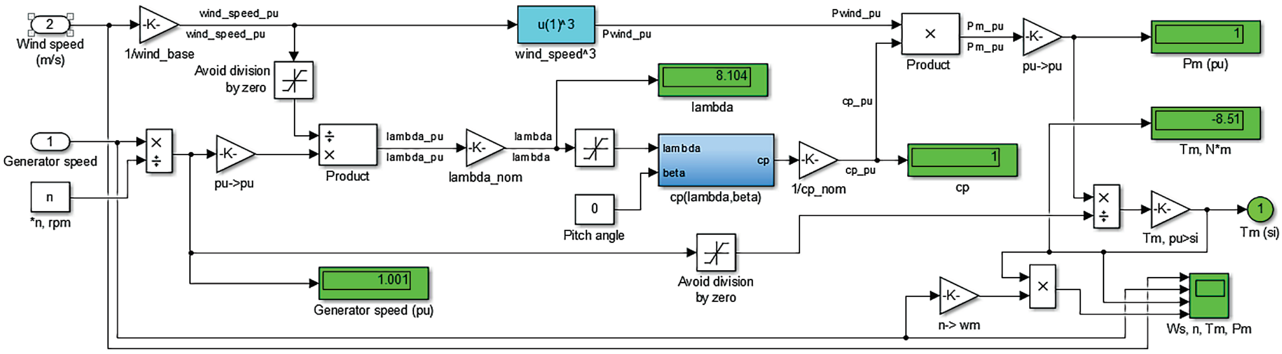


Figure 3. Structure of subsystems of wind turbine models
Source: compiled by the authors of this study

The main elements of the wind turbine model were:

1. Input parameters: wind speed (wind speed, m/s) – a parameter that determines the wind speed in meters per second; generator speed (generator speed, rpm) – a parameter that determines the generator speed in revolutions per minute (rpm).

2. Input value converters. Wind and generator speed input values were converted to conventional units for further calculations.

3. Blocks for calculating model parameters: Lambda (λ) was the ratio of the wind turbine blade tip speed to the wind speed; Cp (power factor) was a function of λ, and the blade angle (beta); Pm (mechanical power, pu) was calculated based on Cp and wind power.

4. Unit for converting mechanical power to torque (Torque, Tm).

5. The model outputs include wind speed, generator speed, torque, and power, which could be shown in conventional units (pu) or system units (SI).

The model of an alternator made it possible to illustrate the detailed structure and functioning of an electric generator's control and monitoring system. It presented how various parameters were calculated and monitored in real-time to ensure efficient generator operation (Fig. 4).

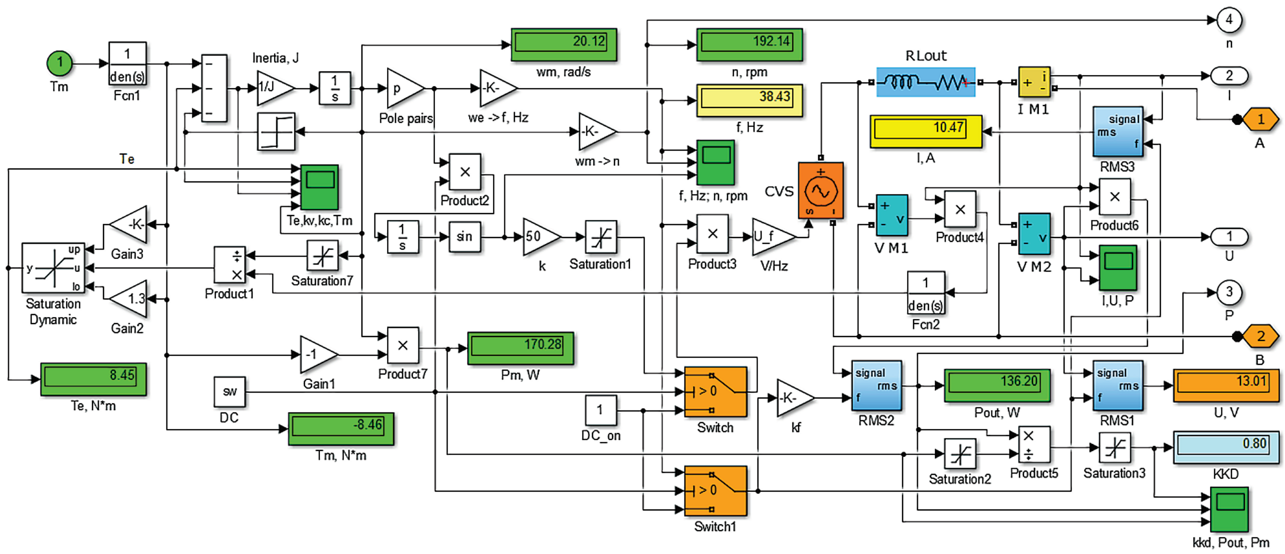


Figure 4. Structure of alternator subsystems
Source: compiled by the authors of this study

The main components of the alternator model were Inertia – a block that takes into account the moment of inertia of the rotor; Pole pairs – blocks for calculating the number of generator poles; Frequency conversion – blocks for converting the rotational speed to different units (radians per second, revolutions per minute, hertz); Saturation – blocks that limited the output values to prevent excessive amplification; Gain – blocks for increasing or decreasing the signal amplitude; Root et al. (RMS) – blocks for calculating the root mean square value of an alternating current; Switches – blocks for switching between different input signals; Multiplication blocks – blocks for multiplying signals and calculating power; Various output parameter blocks: Output torque, Nm; Angular velocity, rad/s; Rotational speed, rpm; AC frequency, Hz; Current, A; Voltage, V; Power, W.

The simulation model of the generator (Fig. 4) was based on the use of a controlled ideal voltage source (CVS) with a series-connected active-inductive element RLout, which is equivalent to the internal resistance and inductance of the stator winding, which, in particular, allowed us to determine the electrical losses in the stator (and the associated efficiency) and its reactive power component. It also included VM1, VM2, IM1, RMS1 – RMS3 voltage and current meters with corresponding digital indicators and oscilloscopes. The input value of the source controlled by CVS can be either DC or AC emf (depending on the selected modelling mode in the subsystem settings window). In the case of the selected "AC" modelling mode, the input of the CVS source was supplied with the EMF value, the amplitude Em and frequency f of which were determined by the mechanical characteristics of the rotor rotational motion ωm, its induction (magnetic flux value) Fm, and the number of pairs of stator poles p.

RESULTS AND DISCUSSION

The input value for the developed wind turbine was the wind speed (m/s), which could be set in several ways: as a constant – Ws_m/s, monotonically increasing or decreasing – Ramp_Ws, or arbitrarily changed according to statistical data during a specified period (day) using Wind_Speed1, Wind_Speed2 (Fig. 5a). The signal source was selected by changing the states of the M_Switch5 – M_Switch7 switches. The oscilloscope Ws_(m/s) allowed us to display the set wind speed parameters graphically. The output parameters of the wind turbine (voltage, current and its frequency, power, rotor speed, and torque) were determined from the overall balance of mechanical and electrical power, taking into account mechanical losses associated with static and dynamic rotor friction, its moment of inertia, and electrical losses in the stator winding. Most of them were reproduced by the oscilloscope U, I, Pout, n, and the digital display Pgen, W. The dialogue window for setting the generator parameters is shown in Figure 5b.

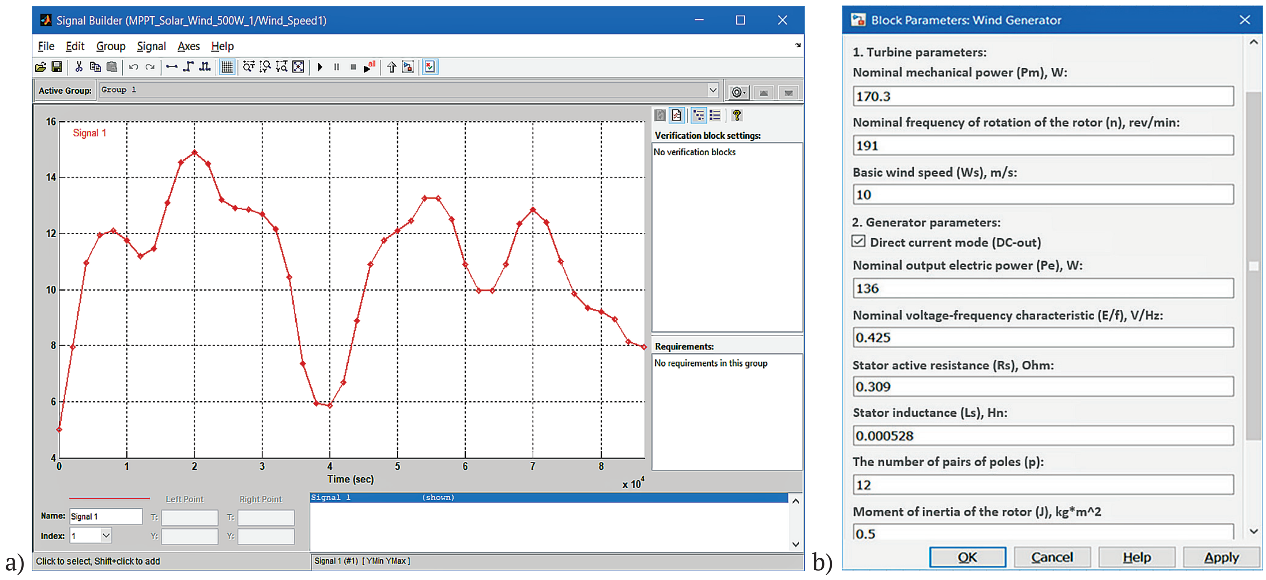


Figure 5. Analysis of wind speed and turbine settings
Note: a – formation of a daily wind speed graph, b – wind turbine parameter settings window
Source: compiled by the authors of this stud

The mechanical component of the rotational motion of the rotor ω_m (angular velocity, rad/s) was defined as the integral of dividing the difference of the components: torque T_m, electromagnetic torque T_e, static moments T_{kc}, and dynamic (viscous) friction T_{kv} by the moment of rotor inertia J:

$$\omega_m=\int\frac{T_m-T_e-(T_{kc}+T_{kv})}{J}\,dt\,\cdot \tag{1}$$

The electric frequency of the generator is defined as the product of the rotor angular velocity and the number of stator pole pairs divided by 2π:

$$f = two\frac{p\omega_m}{2\pi}; \tag{2}$$

$$E_r = 24 * 20 * \frac{0.00022}{0.0065} = 16.246\ (V). \tag{3}$$

The coefficient k_{ef} of the voltage-frequency characteristic, based on the known nominal values of the electromotive force E and the period $T = 1/f$, is:

$$k_{ef} = \frac{E}{f} = \mathrm{E} * \mathrm{T} = 16.246 * 0.026 = 0.4224\ \mathrm{V/Hz}. \tag{4}$$

During the generator's operation simulation, by integrating the product $p\omega_m$ and calculating the sine from the result, harmonic oscillations were obtained with the corresponding frequency related to ω_m by the above dependence and amplitude values from -1 to +1. Since the amplitude value of the generator's emf is directly proportional to the rate of change of the magnetic field induction (electric frequency). The shape of the output voltage curve is theoretically close to rectangular (due to the design features of the stator and rotor magnetic poles). To reproduce these parameters in the model, it was necessary to increase the amplitude of the obtained sinusoidal oscillations by 50-100 times (using a multiplier) and limit it to the same unit value with the limit function. In this way, a signal whose shape was close to rectangular was generated with an amplitude that did not depend on frequency. To obtain a monotonically increasing dependence of the output EMF on the rotor speed (electric frequency), it was necessary to first determine the amplitude value of the EMF at the rated frequency, as well as the associated coefficient k_{ef} f of the voltage-frequency response (*E/f*). It was obtained a monotonically increasing generator EMF with frequency by multiplying this coefficient by the signal frequency at the current time and the nominal EMF amplitude.

Based on the calculated data of the physical model of the generator (for the rated rotor speed), namely the resultant rotor magnetic flux $F_m = 0.00022$ Vb, the time interval of magnetic flux change $dt = 0.0065$ s (equal to $\pi/2$, the entire period $T = 0.026$ s, respectively), the total number of coils on both sides of the disc rotor – 24, the number of turns of one coil winding – 20, according to the formula $E_m = -dF_m/dt$ (for one turn), obtained the total amplitude value of the generator's EMF.

DC out mode, the CVS source receives the calculated EMF value, which is proportional to the rotor speed by the k_{ef} coefficient and equivalent to its actual AC value. This mode significantly reduced the model execution time, essential for modelling long-term processes with a daily or seasonal cyclic nature. At the same time, the main electromechanical characteristics of the generator and the overall power balance during the conversion of mechanical energy into electrical energy were preserved.

The electromagnetic torque of the generator T_e was determined from its total electrical power, taking into account losses in the windings, equal to the product of the output EMF and the load current divided by the current rotor angular velocity ω_m.

The parameters of the wind turbine determined the input mechanical power of the generator and were equal to the product of the nominal rotor speed (rad/s) and torque (N·m); its nominal value, according to the calculations, is 170.28 W. Considering the efficiency of 80%, the generator's electric power is 136.2 W.

Based on the results of modelling the operation of a transmissionless wind turbine generator with a vertical rotor, it was obtained oscillograms of the output voltage and current when it reaches the rated operating mode (Fig. 6a) and graphical dependences of power on load current for different wind speeds (Fig. 6b). As can be seen from the graphical materials presented, the generator's output power is cubically dependent on the wind speed. For its efficient operation, it is necessary to apply an appropriate algorithm with the MPPT function based on the obtained modelling results.

To ensure maximum efficiency in converting wind energy into electricity, a model of a universal step-up/step-down voltage converter AC-DC_MPPT_Wind with the function of maintaining the maximum power point was developed, which serves as a BEV load and a charger, whose output was connected to the battery. The structure of this subsystem is shown in Figure 7.

a) b)

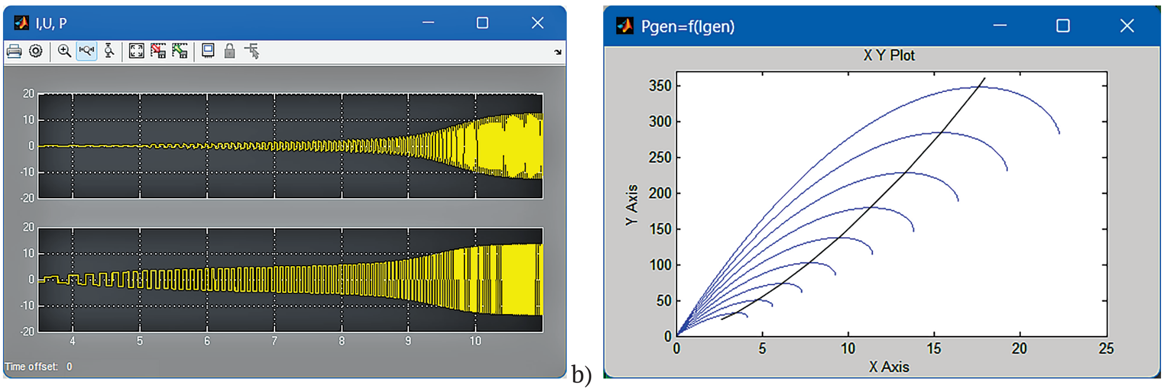


Figure 6. Results of wind turbine modelling

Note: a – current and voltage oscillograms at its output; b – dependence of wind turbine output power on load current for wind speeds of 6-14 m/s

Source: compiled by the authors of this study

The elements of the input load of the AC-DC_MPPT_Wind subsystem were a two-half-period diode voltage rectifier VD1 – VD4, a capacitive filter C1 to reduce input voltage fluctuations, voltage and current meters VM1, IM1, and a controlled current source CCS with a limiting resistance *Ro*. The converter current consumption (input) was determined based on the results of calculations from its output power P'_2 (secondary circuit with losses) by dividing it by the converter input voltage:

$$I(ccs) = P'_2/U_1. \tag{5}$$

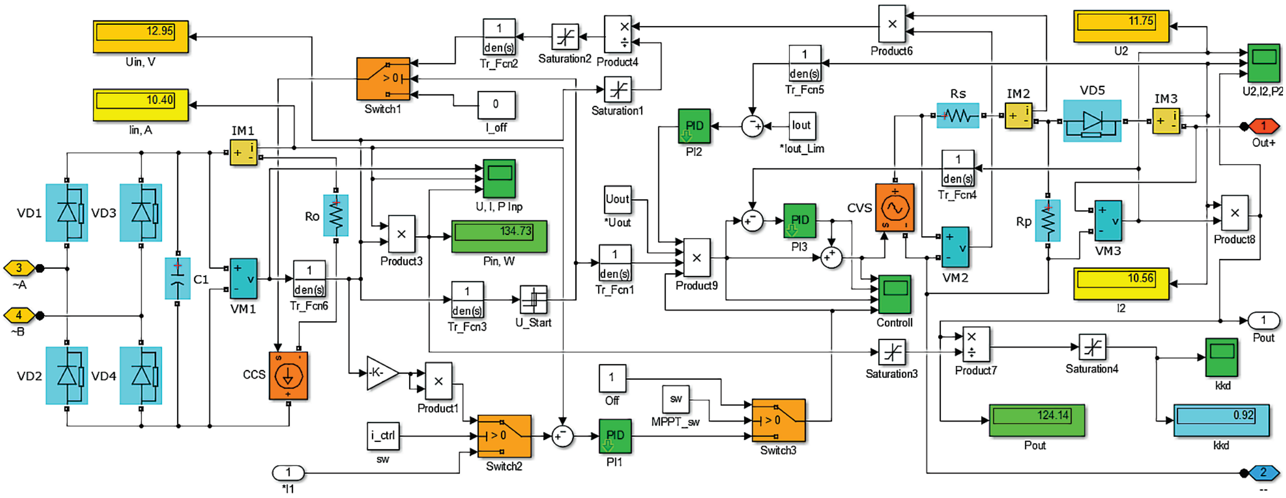
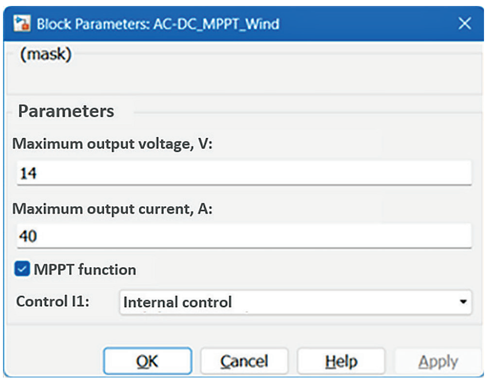


Figure 7. Structure of the AC-DC_MPPT_Wind voltage converter subsystem
Source: compiled by the authors of this study

The calculated current value was set via the external port of the CCS element. The valuable power of the consumer P_2 was defined as the product of the output voltage U_2 (< = 14B) and the load current, which is the battery's charging current. The resistances of the resistive elements set losses in the loaded and idle modes of the converter: series – *Rs*, parallel – *Rp*, as well as the parameters of the diode VD5. I_off sets the power consumption to standby mode.

The MRRT function in the model was implemented as follows: since the power of a wind turbine cubically depends on the wind speed, and its output voltage (EMF) is directly proportional to this speed, the maximum power is achieved when a certain load current is provided at its output, which depends on the square of the wind speed, respectively (for the selected rated mode of the generator at a wind speed of 10 m/s, the value of I_{gen} = 10.4 A according to the modelling results, Figure 6b). Based on this, the task of the MPPT algorithm was to determine and maintain the generator current depending on the wind speed $I_{gen} = f(Ws)^2$ by adjusting the battery charging current. This was achieved by introducing feedback to control the converter's input current, which was compared with the calculated (setpoint) current value calculated from the generator voltage for different wind speeds. The comparison result, with its sign, was fed into the proportional-integral controller (PI1, Fig. 7), whose control signal regulates the converter's output voltage and, associated with affects the battery's charging current and stabilises the input current at the desired level. Under this condition, the generator's output current is directly proportional to the square of its output voltage.

The converter started to operate at a sufficient wind speed when the generator output voltage exceeded the set value (U_{start} > 3 V), according to the MPPT algorithm. The process of charging the battery with a current determined by the wind speed occurred. If it increased to more than 15 m/s, the charging current was limited to the level set in the settings (Fig. 8a) for the selected battery (40 A), and the MRRT function switched to the constant current charging mode. The charging process was completed in the constant voltage mode (14 V), and the current was reduced to the minimum value (0.1 A) (Fig. 8b).

a) 

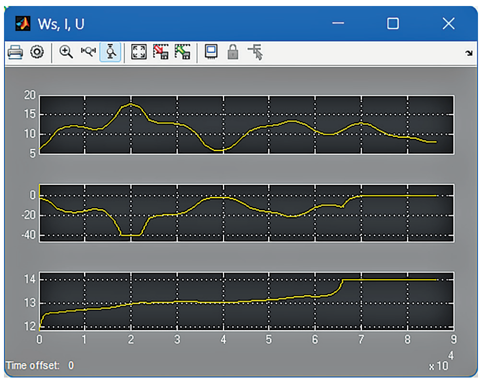
b) 

Figure 8. Settings window
Note: a – AC-DC_MPPT_Wind unit; b – time diagrams of wind speed, charging current, and battery voltage
Source: compiled by the authors of this study

The structure of the input load of the DC-AC_inverter subsystem (Fig. 9) is similar to AC-DC_MPPT_Wind, except for the absence of a diode rectifier. It included a capacitive filter C1, voltage and current meters VM1, IM1, and a controlled current source CCS with a limiting resistance Ro. The converter's input current was calculated as in the AC-DC_MPPT_Wind subsystem, from its output power P'2 (including losses) by dividing it by the converter's input voltage. The valuable power of the consumer P_2 was defined as the product of the practical value of the output voltage U_2 (220B) and the inverter load current. The values of the resistances set losses in the loaded and no-load modes of the inverter: series – *Rs*, parallel – *Rp*. I_off sets the power consumption to standby mode.

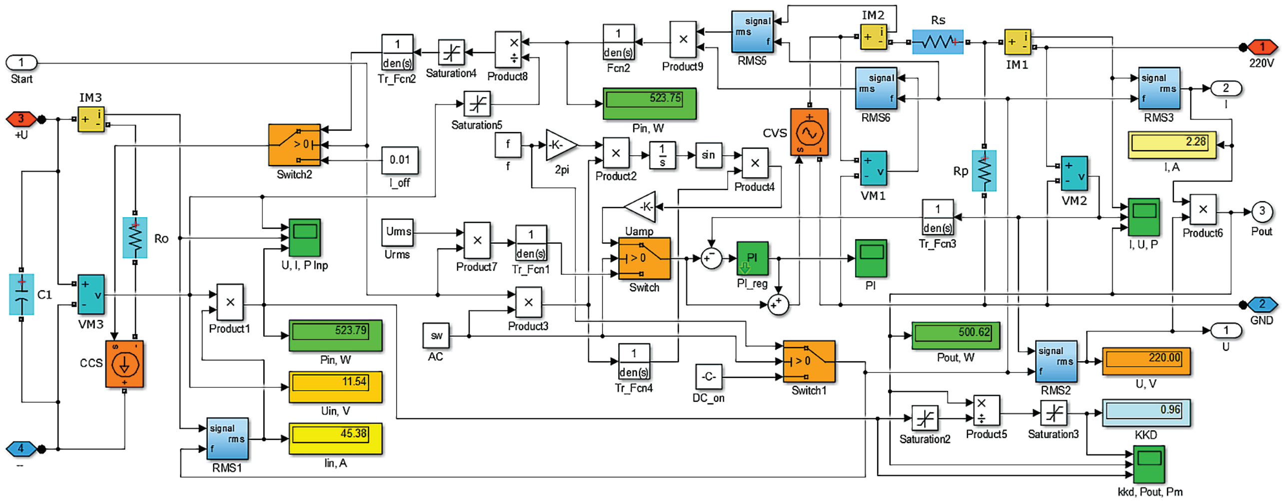


Figure 9. Structure of the DC-AC_inverter voltage converter simulation model
Source: compiled by the authors of this study

The peculiarities of the DC-AC_inverter subsystem model include the ability to set the output voltage and current frequency and select the output current modelling mode - AC or DC, depending on the nature of the research tasks. These modes could be set by selecting the appropriate item from the drop-down menu in the subsystem settings dialogue box (Fig. 10).

The results of modelling the inverter output parameters (current, voltage, power) with the transition from AC to DC are shown in Figure 11.

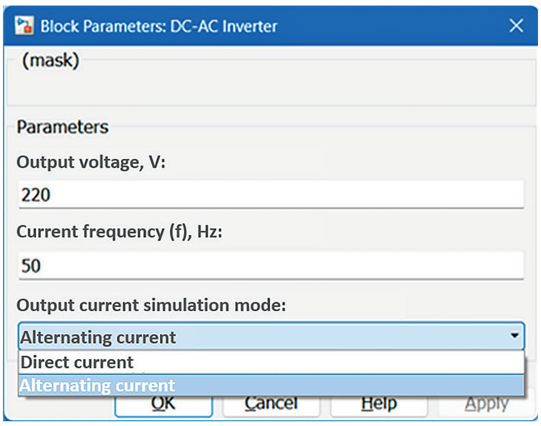


Figure 10. DC-AC_inverter subsystem settings window
Source: compiled by the authors of this study

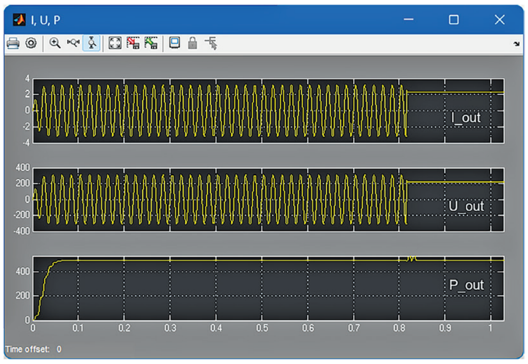


Figure 11. Results of modelling the inverter operation (output parameters)
Note: I_out – current, A; U_out – voltage, V; P_out – power, W
Source: compiled by the authors of this study

The choice of DC mode significantly reduced the model execution time while maintaining the overall balance of the inverter's input and output power, considering losses. It is rationally used in the case of modelling long-term processes.

The study focused on developing a simulation model of an autonomous consumer energy supply system, a subsystem of wind turbine, and alternating current generator models. The model mainly focused on autonomous energy sources, particularly wind energy, as their use is projected to increase. This was also studied in the works of W. Hallgren *et al.* (2014) and F. Porté-Agel *et al.* (2020). The researchers contended that wind energy and other renewable energy sources were projected to experience substantial growth in the upcoming decades, making them indispensable for mitigating climate change and fostering energy sustainability. It is worth noting that according to forecasts, by 2026, solar energy production may increase from 1991 GW to 2708 GW (SolarPower Europe, 2022). J.K. Kaldellis (2002) and O. Apata & D.T.O. Oyedokun (2017) noted that using autonomous power systems was one of the most successful ways to meet the electrification needs of numerous isolated consumers worldwide.

To assess the sustainability and practicality of wind farms compared to other energy sources, it is essential to evaluate their energy use and environmental impact. According to C.K. Gao *et al.* (2019), life cycle analysis has shown that wind farms have a lower carbon footprint than bioenergy plants, making them a more environmentally friendly option. In addition, the efficient design of wind turbines plays a crucial role in reducing the cost of energy production. M.K. McWilliam *et al.* (2012) identified generator structures optimised for energy production costs by considering population density, wind availability, and proximity to power lines. This method ensures efficient use of wind resources in different regions.

Wind energy, a rapidly expanding green technology, provides a clean, safe, and renewable source of electricity generation. The study by F.H. Khan *et al.* (2021) delved into the available methodologies for sustainably harnessing wind energy, scrutinising recent technological advancements and the prospects of the global wind power industry. One promising avenue for wind energy harvesting involves utilising vehicle-induced turbulent airflow generated by highway traffic to power infrastructure such as highway lighting and telecommunication signalling systems. A.A. Al-Aqel *et al.* (2016) focused on assessing the potentiality of implementing small-scale wind turbines along the highways. Devashish & T. Amarnath (2017) mainly studied different technical aspects of harnessing wind energy.

MATLAB/Simulink was used to model a simulation model of an autonomous power supply system for consumers, including wind turbine and alternator subsystems. In the MATLAB/Simulink environment, block libraries (block sets) represent a modern object-oriented, event-driven, user-friendly approach to problem-solving. Researchers R. Andrienko & K. Klen (2022) presented the simulation modelling results of an autonomous power supply system based on solar panels using accurate data in MATLAB Simulink under constant changes in insolation and load. S. Nasri *et al.* (2017), to prove the reliability and effectiveness of the applied control strategy and its impact on the system's operation, simulated the proposed system using Matlab/Simulink.

The model consists of several vital subsystems, such as a wind generator (Wind_Generator), a wind turbine (Wind_Turbine), and an alternating current generator (Generator). These subsystems interact with each other to ensure the efficient transfer of energy from the wind stream to the electrical grid. A controlled ideal voltage source with active and inductive elements allows for accurate generator modelling. This includes working with both constant and variable values of electromotive force (EMF), which enables the generator's performance to be evaluated in different modes. The main output parameters of the model are rotor speed, torque, voltage, and current. These parameters are displayed on the model's oscilloscope and digital displays. Their display allows for accurate real-time system analysis, facilitating control and monitoring. This enables precise real-time system analysis, facilitating advanced control and monitoring. Detailed calculations were performed to determine the amplitude values of the electromotive force (EMF) and the voltage-frequency response coefficient of the generator. Based on the calculated data of the physical model of the generator (for the nominal rotor speed), the total amplitude value of the generator's EMF $Eg = 16.246$ V. At the same time, the coefficient kef of the voltage-frequency characteristic is $k_{ef} = 0.4224$ V/Hz. During the simulation of the generator's operation in the 'direct current' mode (DC out), the input of the CVS source receives the calculated EMF value, which is proportional to the rotor speed by the coefficient kef and equivalent to its current AC value.

The function of maintaining the maximum power point (MPP) in the model is implemented as follows: since the power of the wind generator is cubically dependent on the wind speed, and its output voltage (EMF) is directly proportional to this speed, the maximum power is achieved if the load current at its output is a specific value, which depends on the square of the wind speed, respectively (for the selected nominal mode of the generator at a wind speed of 10 m/s, the value of $I_{gen} = 10.4$ A according to the modelling results. Based on this, the task of the MPPT algorithm is to determine and maintain the generator current depending on the wind speed $I_{gen} = f(Ws)^2$ by adjusting the battery charging current. This is achieved by introducing feedback to control the value of the converter input current, which is compared with the calculated (setpoint) current value calculated from the actual generator voltage for different wind speeds.

The results generally confirm the significant potential of using autonomous energy supply systems, particularly systems based on wind energy sources. The developed simulation model in MATLAB/Simulink demonstrates efficiency in modelling the operation of such systems, particularly their critical subsystems: wind turbine, wind generator, and alternator.

CONCLUSIONS

The research developed a simulation model of an autonomous power supply system using renewable wind energy. The model was built in Simulink (Matlab) using Simscape, SimElectronics, and SimPowerSystem libraries, which enabled realistic and accurate simulation. The model consisted of key subsystems, including a wind generator, wind turbine, and an AC generator, which worked together to transfer energy from wind to the electrical grid efficiently. A controlled ideal voltage source modelled the generator with active and inductive elements, accommodating constant and variable electromotive force (EMF) values.

Outputs such as rotor speed, torque, voltage, and current were displayed in real time, providing precise system monitoring.

Detailed calculations determined the generator's EMF amplitude ($Eg = 16.246$ V) and the voltage-frequency response coefficient ($k_{ef} = 0.4224$ V/Hz) for nominal rotor speed. In DC mode, the input EMF was proportional to rotor speed, ensuring accurate simulation of generator behaviour. The maximum power point (MPP) was maintained through a feedback-controlled MPPT algorithm. Since wind generator power depended cubically on wind speed and EMF was directly proportional to speed, the optimal generator current varied with the square of wind speed. For a nominal wind speed of 10 m/s, the optimal current was $I_{gen} = 10.4$ A. The MPPT algorithm adjusted the battery charging current via converter input current control, ensuring stable operation under varying conditions.

Simulation confirmed the cubic dependence of output power on wind speed, which optimised power supply performance. The DC-AC inverter subsystem adjusted output voltage and frequency, adapting to different loads and enhancing system reliability. The simulation model effectively predicted wind energy utilisation, simulated various operational modes, and optimised mechanical and electrical power balance. It minimised energy losses, ensuring efficient operation of autonomous systems.

Further research is expected to expand the autonomous energy supply system for consumers by integrating additional energy sources, such as solar panels, to create hybrid autonomous energy supply systems with the possibility of effective interaction between different energy sources.

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None.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Автономна система енергозабезпечення споживачів

Анотація. Метою дослідження було розробити структуру імітаційної моделі системи автономного енергопостачання для споживачів, яка включає підсистеми моделей вітротурбін і генераторів змінного струму, а також описати характеристики її компонентів. Розглянуто порядок функціонування компонентів системи автономного електропостачання споживачів, а також особливості їх взаємодії. Імітаційна модель системи автономного електропостачання споживачів створена в програмному середовищі Simulink (Matlab) з використанням стандартних та спеціалізованих блоків бібліотеки Simulink, що дозволить найбільш наочно та детально відобразити механізми взаємодії об'єктів в автоматизованій системі електропостачання споживачів та проаналізувати отримані результати. Розроблено імітаційну модель автономної системи енергопостачання споживача, підсистеми моделей вітрової турбіни та генератора змінного струму. Детально описано отриману імітаційну модель та її основні компоненти. Для забезпечення максимальної ефективності перетворення енергії вітру в електроенергію створено модель універсального підвищувально-знижувального перетворювача напруги AC-DC_MPPT_Wind з функцією підтримання точки максимальної потужності, який виконував функції навантаження вітротурбіни та зарядного пристрою, і вихід якого підключено до акумуляторної батареї. Особливостями моделі підсистеми DC-AC_inverter є можливість регулювання вихідної напруги та частоти струму, а також вибору режиму моделювання вихідного струму - змінного або постійного, залежно від характеру дослідницьких завдань. Також описано та проаналізовано експеримент, проведений з використанням цієї моделі. Результати показали, що імітаційна модель системи автономного електропостачання споживачів працювала коректно і виконувала всі задані функції. Отримані результати можна використати на промислових підприємствах для забезпечення енергетичної незалежності та зниження витрат на електроенергію

Ключові слова: імітаційна модель; енергетична незалежність; джерела вітрової енергії; електроенергія; вітрогенератор

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Optimisation of tower crane rotation mechanism force acceleration mode at steady payload hoisting

Abstract. The process of optimisation of the force acceleration mode of the rotation mechanism of the tower crane with the beam jib at steady payload hoisting was examined in the presented paper. The crane rotation mechanism was presented as a dynamic model with 4DOF in which the main motion of the rotation and payload hoisting mechanisms is considered as well as oscillations of the rotation part of the crane and the payload in the plane of slew. For such a dynamic model, a mathematical model which is a system of ordinary second order differential equations was formulated. The system of equations was reduced to the angular coordinate of the payload slew and was represented by the sixth order equation. The optimisation of the rotation mechanism's acceleration mode at steady payload hoisting was carried out based on the RMS of the drive torque criterion considering constraints on the drive torque and drive power. The optimisation criterion as well as the constraints were reduced to the generalised criterion. When optimising , the movements and velocities of the generalised rotation mechanism coordinates in the beginning and in the end of the acceleration process were chosen as motion boundary conditions. The acceleration mode of the crane rotation mechanism at steady payload hoisting was obtained as the result of optimisation. The obtained mode minimised the action of the dynamic payloads and decreases the maximum values of the crane's mast deformation, drive power, and deviation of the payload cable from the vertical. At that, the crane's elements' and payload's oscillations upon reaching the steady motion mode were eliminated. The results

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of the study may be used in automation systems for controlling the rotation mechanisms of tower cranes, which ensures improved efficiency and stability of work during payloads hoisting

Keywords: jib crane; hoisting and rotation mechanisms; dynamic payloads; optimal control; payload oscillation

INTRODUCTION

A combination of the rotation and payload hoisting mechanisms is performed to increase the capacity of tower cranes. During such motion of mechanisms, significant dynamic payloads occur in the elements of the crane and in drive mechanisms, along with oscillations of the payload on elastic suspension. These payloads exert the greatest undesirable influence when the rotation mechanism carries out the processes of acceleration or braking. During these processes, spatial oscillations of the payload on elastic suspension sharply increase. They influence energy losses, crane's work reliability and complicate the work of the staff and the crane operator. Determining an acceleration mode of the rotation mechanism at steady payload hoisting that decreases dynamic payloads and eliminates oscillations of the payload on elastic suspension is an important problem.

The efficiency of cranes work, tower cranes in particular, is determined based on their capacity, reliability, and safe exploitation. In work M. Michna *et al.* (2020) it was established that a minute decrease of dynamic payloads during the undergoing of transient processes significantly enhances the reliability indicators of cranes. Apart from that, dynamic payloads exert a significant influence on the accuracy of the positioning of the payload (Chwastek, 2021). Dynamic payloads increase significantly in crane structures at combining the work of drive mechanisms. At that, the swinging of the payload on the elastic suspension also increases.

The decrease of the dynamic payloads can be achieved by using fundamental principles of mechanics, based on which the methods of optimisation of motion of the crane mechanisms are built. In study by S. Chwastek (2020), criteria of optimisation as quadratic functionals for each mechanism of the tower crane were formulated based on the built mathematical model. The minimisation of the functionals allowed for obtaining a set of optimal parameters for crane mechanisms at which their interaction had to be effective. An innovative feature of the presented solution was the complex approach to the optimisation of the crane mechanisms with separate drives. This approach was focused on decreasing the oscillations of the payload on elastic suspension and minimising the forces that act in the haulage elements (cables). Much attention was given to the problems of optimisation of the parameters of the crane mechanisms and securing the reliability and safety of handling processes. At that, various programs and methods of study were employed, metaheuristic methods in optimisation problems for crane mechanisms in particular P. Adam *et al.* (2020).

The work by M. Ambrosino *et al.* (2020) established that productivity depends on the magnitude of dynamic payloads in the crane elements. The authors of the article O. Podolyak *et al.* (2022) noted the presence of dynamic payloads in the crane structure, which depend on the oscillations of the payload on the flexible suspension. Here, a mathematical model is presented that describes the processes of starting and braking of a crane and its dynamic payloads are determined. In the work by Q. Wu *et al.* (2020), a mathematical model is built and the dynamics of the movement of a crane with a double pendulum and with a distributed mass of the bridge girder are analysed.

The choice of motion modes for drive mechanisms that decrease the oscillations of the elements and increase the efficiency of cranes is quite a relevant problem and requires more comprehensive research.

The research purpose lied in increasing the efficiency of joint work of the tower crane rotation and payload hoisting mechanisms through optimising the acceleration mode of the rotation mechanism at steady operation of the payload hoisting mechanism.

MATERIALS AND METHODS

The jib system with a beam jib of the tower crane at joint rotation and payload hoisting mechanisms may be presented as a discrete dynamic model (Fig. 1). Such model comprises brought to the crane slew axis absolutely solid masses of the drive rotation mechanism with the inertia moment J_1 and the rotation part of the crane with the inertia momentJ_2 that are connected together by an elastic element with the stiffness coefficient C. A trolley with the mass m_2 to the centre of gravity of which with the help of a variable length elastic suspension a payload with the mass m is attached. It is located on a beam jib in a stationary position. Drive torque M and resistance forces torque M_0 that are brought to the crane slew axis act in the drive rotation mechanism. The main motion of the drive mechanisms, elastic displacements of the rotation mechanism and oscillations of the payload on elastic suspension in the plane of the crane slew are considered in the presented dynamic model. Deviations of the elastic payload suspension from the vertical in the plane of the trolley movement were not considered, as they depend on the magnitude of centrifugal force that acts on the payload rather than on the crane rotation mode. Thus, the provided dynamic model of the jib system has 4DOF.

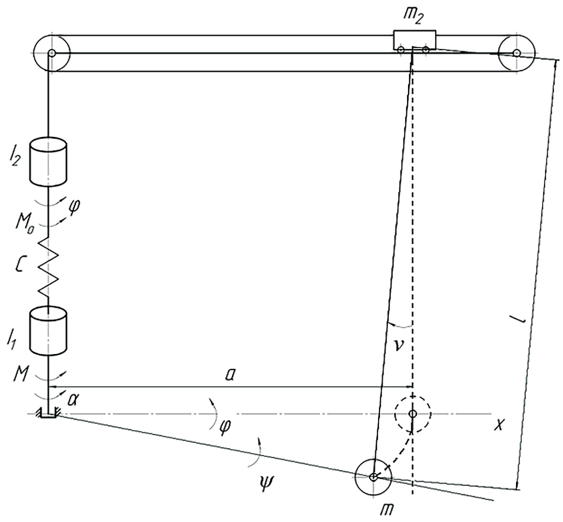

Figure 1. Dynamic model of the tower crane slew at steady payload hoisting

Note: J_1 – drive rotation mechanism with the inertia moment; J_2 – rotation part of the crane with the inertia moment; m_2 – trolley with the mass; m – payload with the mass; C – stiffness coefficient; M – drive torque; M_0 – resistance forces torque; l – length of the elastic suspension; a – payload outreach (parameter); v – angular coordinate of deviation of a flexible payload suspension from the vertical; α – generalised coordinate of the rotation mechanism drive; φ – generalised coordinate rotation part of the crane; ψ – generalised coordinate slew of the payload

Source: compiled by the authors

At that, the coordinate of the payload hoist (the length of the elastic suspension) changes with a constant rate v. It is determined by the dependency:

$$l = l_0 + vt, \tag{1}$$

where l_0 – the initial length of the elastic payload suspension; t – time; v – the constant velocity of the payload hoist.

It was chosen angular coordinates of the brought mass of the rotation mechanism drive α, rotation part of the crane φ, and slew of the payload ψ as generalised coordinates of the dynamic model of the jib system at the rotation mechanism operation. At the same time, the trolley's position is unchanged, it is determined by the parameter a. The angular coordinate of the elastic payload suspension deviation from the vertical was determined by the following dependency:

$$v = \frac{a(\phi-\psi)}{l_0+vt}. \tag{2}$$

The second order Lagrange equations were used to build a mathematical model of the crane rotation mechanism motion at steady payload hoisting:

$$\frac{d}{dt}\frac{\partial T}{\partial \dot\alpha} - \frac{\partial T}{\partial \alpha} = \mathrm{M} - \frac{\partial \Pi}{\partial \alpha};\ \frac{d}{dt}\frac{\partial T}{\partial \dot\phi} - \frac{\partial T}{\partial \phi} = M_0 - \frac{\partial \Pi}{\partial \phi};$$
$$\frac{d}{dt}\frac{\partial T}{\partial \dot\psi} - \frac{\partial T}{\partial \psi} = -\frac{\partial \Pi}{\partial \psi}, \tag{3}$$

where, T and Π are the kinetic and potential energy, respectively, expressed as:

$$T = \frac{1}{2}J_1\dot\alpha^2 + \frac{1}{2}(J_2 + m_2a^2)\dot\phi^2 + \frac{1}{2}m\left(a^2\dot\psi^2 + v^2\right), \tag{4}$$

$$\Pi = \frac{1}{2}C(\alpha-\phi)^2 - \mathrm{mglcosv} = \frac{1}{2}C(\alpha-\phi)^2 - \mathrm{mg}\,(l_0+vt)\cos\frac{a(\phi-\psi)}{l_0+vt}. \tag{5}$$

Taking derivatives of expressions (4) and (5) according to system (3), the following results were obtained:

$$\frac{\partial T}{\partial \alpha} = \frac{\partial T}{\partial \phi} = \frac{\partial T}{\partial \psi} = 0;\ \frac{\partial T}{\partial \dot\alpha} = J_1\dot\alpha;$$
$$\frac{\partial T}{\partial \dot\phi} = (J_2 + m_2a^2)\dot\phi;\ \frac{\partial T}{\partial \dot\psi} = ma^2\dot\psi; \tag{6}$$

$$\frac{d}{\mathrm{d}t}\frac{\partial T}{\partial \dot\alpha} = J_1\ddot\alpha;\ \frac{d}{\mathrm{d}t}\frac{\partial T}{\partial \dot\phi} = (J_2 + m_2a^2)\ddot\phi;$$
$$\frac{d}{\mathrm{d}t}\frac{\partial T}{\partial \dot\psi} = ma^2\ddot\psi; \tag{7}$$

$$\frac{\partial \Pi}{\partial \alpha} = C(\alpha-\phi); \tag{8}$$

$$\frac{\partial \Pi}{\partial \phi} = -C(\alpha-\phi) + m\cdot g\cdot a\cdot\sin\frac{a(\phi-\psi)}{l_0+vt} =$$
$$-C(\alpha-\phi) + \frac{\mathrm{mg}a^2}{l_0+vt}(\phi-\psi); \tag{9}$$

$$\frac{\partial \Pi}{\partial \psi} = -m\cdot g\cdot a\cdot\sin\frac{a(\phi-\psi)}{l_0+vt} = -\frac{\mathrm{mg}a^2}{l_0+vt}(\phi-\psi). \tag{10}$$

After substitution of expressions (6), … (10) into the system (3) the equations of the tower crane rotation mechanism motion at steady payload hoisting the following expression was obtained:

$$J_1\ddot\alpha = \mathrm{M\text{-}C}(\alpha-\phi);$$
$$(J_2 + m_2a^2)\phi = -M_0 + C(\alpha-\phi)\mathrm{ma}^2\frac{g}{l_0+vt}(\phi-\psi);$$
$$\ddot\psi = \frac{g}{l_0+vt}(\phi-\psi). \tag{11}$$

Significant dynamic payloads that lead to swinging of the payload on elastic suspension appear in the elements of the structure and drive mechanism in the rotation mechanism acceleration process, which decreases the reliability of the crane operation and increases energy losses. Thus, the need for optimising the motion mode of the drive rotation mechanism of the crane which would decrease the action of the dynamic payloads to minimum has appeared. Dynamic payloads largely depend on the magnitude and nature of the torque change of the drive mechanism. Thus, it was chosen the RMS (Root Mean Square) value of the drive torque during acceleration as a criterion of optimisation of the rotation mechanism acceleration mode at steady payload hoisting. It was determined by the following dependency:

$$M_{ck} = \left[\frac{1}{t_1}\int_0^{t_1} M^2\,dt\right]^{1/2} \rightarrow min. \tag{12}$$

Criterion (12), which is an integral functional, must be minimised when meeting the following boundary conditions of the rotation mechanism motion:

$$\begin{aligned} &t=0:\ \alpha=\frac{M_0}{C},\ \dot{\alpha}=0, \phi=0,\ \dot{\phi}=0, \psi=0,\ \dot{\psi}=0;\\ &t=t_1:\ \alpha=\frac{M_0}{C}+\frac{\omega t_1}{2},\ \dot{\alpha}=\omega,\ \phi=\frac{\omega t_1}{2},\ \dot{\phi}=\omega, \psi=\frac{\omega t_1}{2},\ \dot{\psi}=\omega; \end{aligned} \tag{13}$$

and constraints on the drive torque M and the power of rotation mechanism drive P:

$$M_{\min} \leqslant M \leqslant M_{\max}; \tag{14}$$
$$P_{\min} \leqslant P \leqslant P_{\max}. \tag{15}$$

where t_1 – the duration of the rotation mechanism acceleration process; ω – the steady angular velocity of the rotation part of the crane; $M_{\min}$ and $M_{\max}$ – the minimum and maximum permissible values of the rotation mechanism drive torque; $P_{\min}$ and $P_{\max}$ – the minimum and maximum permissible values of the rotation mechanism drive power.

It was necessary to determine a tower crane rotation mechanism motion mode that ensures an extreme value of criterion (12) and meets boundary conditions (13) and constraints (14) and (15) in optimisation problem (12), ..., (15).

The criterion (12) was expressed using the generalised coordinate of the payload slew ψ and its derivatives with respect to time. For this, the expression for the drive torque from the first equation of system (11) was found:

$$M = J_1\ddot{\alpha} + C(\alpha - \phi). \tag{16}$$

The expression of the angular coordinate of the rotation part of the crane from the last equation of system (11) was determined. In further it was expressed by using the payload slew coordinate and its second derivative with respect to time:

$$\phi = \psi + \frac{l_0+vt}{g}\ddot{\psi}. \tag{17}$$

The angular velocity and acceleration of the rotation part of the crane by taking the first and the second derivatives with respect to time of expression (17) were determined:

$$\dot{\phi} = \dot{\psi} + \frac{v}{g}\ddot{\psi} + \frac{l_0+vt}{g}\dddot{\psi}. \tag{18}$$

$$\ddot{\phi} = \ddot{\psi} + 2\frac{v}{g}\dddot{\psi} + \frac{l_0+vt}{g}\psi^{\mathrm{IV}}. \tag{19}$$

From the second equation, considering the third equation of system (11), the last expression that belongs to dependency (16) was determined:

$$C(\alpha - \phi) = (J_2 + m_2a^2)\ddot{\phi} + \mathrm{m}a^2\ddot{\psi} + M_0.$$

After substitution of expression (19) into the obtained dependency, the following expression may be obtained:

$$C(\alpha - \phi) = (J_2 + m_2a^2)\left[\ddot{\psi} + 2\frac{v}{g}\dddot{\psi} + \frac{l_0+vt}{g}\psi^{\mathrm{IV}}\right] + \mathrm{m}a^2\ddot{\psi} + M_0. \tag{20}$$

From equation (20) the angular coordinate of the drive brought to the axis of the crane slew was expressed:

$$\begin{aligned} \alpha = \psi + &\left[\frac{l_0+vt}{g} + \frac{J_2+(m+m_2)a^2}{C}\right]\\ &\ddot{\psi} + \frac{J_2+m_2a^2}{C}\left[2\frac{v}{g}\dddot{\psi} + \frac{l_0+vt}{g}\psi^{\mathrm{IV}}\right] + \frac{M_0}{C}. \end{aligned} \tag{21}$$

The first and the second derivatives with respect to time of expression (21) were obtained, the angular velocity and acceleration of the rotation mechanism drive that are reduced to the rotation part of the crane were determined:

$$\begin{aligned} \dot{\alpha} = \dot{\psi} + \frac{v}{g}\ddot{\psi} + &\left[\frac{l_0+vt}{g} + \frac{J_2+(m+m_2)a^2}{C}\right]\\ &\dddot{\psi} + \frac{J_2+m_2a^2}{C}\left[3\frac{v}{g}\psi^{\mathrm{IV}} + \frac{l_0+vt}{g}\psi^{V}\right]; \end{aligned} \tag{22}$$

$$\begin{aligned} \ddot{\alpha} = \ddot{\psi} + 2\frac{v}{g}\dddot{\psi} + &\left[\frac{l_0+vt}{g} + \frac{J_2+(m+m_2)a^2}{C}\right]\\ &\psi^{IV} + \frac{J_2+m_2a^2}{C}\left[4\frac{v}{g}\psi^{V} + \frac{l_0+vt}{g}\psi^{\mathrm{VI}}\right]. \end{aligned} \tag{23}$$

As a result of substitution expressions (20) and (23) into dependency (14) the function of the drive torque as the function of the angular coordinate of the payload slew and its derivatives with respect to time was obtained:

$$\begin{aligned} M = M_0 &+ [J_1 + J_2 + (m_2 + m)a^2]\ddot{\psi} +\\ &+ 2(J_1 + J_2 + m_2a^2)\frac{v}{g}\dddot{\psi} +\\ &+ \left\{J_1\left[\frac{l_0+vt}{g} + \frac{J_2+(m+m_2)a^2}{C}\right] + (J_2 + m_2a^2)\frac{l_0+vt}{g}\right\}\\ &\psi^{IV} + \frac{J_2+m_2a^2}{C}\left[4\frac{v}{g}\psi^{V} + \frac{l_0+vt}{g}\psi^{\mathrm{VI}}\right]. \end{aligned} \tag{24}$$

In order to consider constraints (14) and (15) in the stated optimisation problem the objective function to minimise was designed:

$$\begin{aligned} &\mathrm{Cr} = M_{\mathrm{ck}} + I min, P_{max}P_{min}M_{max\,M_{min}}\\ &I\begin{cases} 0, if\ \min(M) \geq M_{\min};\\ min(M)\ \delta_M, if \min(M) < M_{\min}; \end{cases}{}_{M_{min}}\\ &I\begin{cases} 0, if\ \max(M) \geq M_{\min};\\ max(M)\ \delta_M, if \max(M) < M_{\max}; \end{cases}{}_{M_{max}}\\ &I\begin{cases} 0, if\ \min(P) \geq P_{\min};\\ min(P)\ \delta_P, if \min(P) < P_{\min}; \end{cases}{}_{P_{min}}\\ &I\begin{cases} 0, if\ \max(P) \geq P_{\min};\\ max(P)\ \delta_P, if \max(P) < P_{\max}; \end{cases}{}_{P_{max}} \end{aligned} \tag{25}$$

where I_{Mmin} and I_{Mmax} the penalty components of the criterion that regulate the compliance with the first and the second inequalities of constraints (14), respectively; I_{Pmin} and I_{Pmax} are the penalty components of the criterion that correspond to the compliance with the first and the second inequalities of constraints (15), respectively; δ_M and δ_P are the weight coefficients that determine the magnitude of the penalties for non-compliance with constraints (14) and (15), respectively (within this study, it was assumed that $\delta_M = 10^{10}$ and $\delta_P = 10^{8}$).

The boundary conditions (13) were reduced to the generalised coordinate of the payload slew ψ and its derivatives with respect to time:

$$t=0:\psi=0, \dot{\psi}=0;\ \ddot{\psi}=0,\ \dddot{\psi}=0,\ \psi^{IV}=0,\ \psi^{V}=0;$$
$$t=t_1:\psi=(\frac{\omega t_1}{2}), \dot{\psi}=\omega;\ \ddot{\psi}=0,\ \dddot{\psi}=0,\ \psi^{IV}=0,\ \psi^{V}=0. \quad (26)$$

where, ω – the steady angular velocity of the crane slew.

Integral functional (12) along with expressions (14), ..., (24) and boundary conditions (25) represent an optimisation problem, in which it was necessary to determine the law of change of the angular coordinate of the payload slew $\psi(t)$ that minimises the value of criterion (12) and meets constraints (14), (15), as well as boundary conditions (26).

The presented variational problem was nonlinear, therefore an approximate method to solve it was used. The unknown function $\psi(t)$ was presented as polynomial with two terms to solve the variational problem:

$$\psi(t)=\psi_1(t)+\psi_2(t). \quad (27)$$

In dependency (27), the first term $\psi_1(t)$ was the selected as a polynomial that meets boundary conditions (26), and the second one – $\psi_2(t)$ – was a polynomial that includes free unknown coefficients, and the following zero boundary conditions are met:

$$\psi_2(0)=\dot{\psi}_2(0)=\ddot{\psi}_2(0)=\dddot{\psi}_2(0)=\psi_2^{IV}(0)=\psi_2^{V}(0)=0;$$
$$\psi_2(t_1)=\dot{\psi}_2(t_1)=\ddot{\psi}_2(t_1)=\dddot{\psi}_2(t_1)=\psi_2^{IV}(t_1)=\psi_2^{V}(t_1)=0. \quad (28)$$

The function $\psi_1(t)$ was preцsented as the eleventh order polynomial that allows for meeting boundary conditions (26):

$$\psi_1(t)=\sum_{k=0}^{11}C_k t^k. \quad (29)$$

Since in boundary conditions (26) the derivatives with respect to time of the function $\psi(t)$ were included up to and including the fifth order, the higher derivatives were determined:

$$\begin{aligned}
&\dot{\psi}_1(t)=C_1+2C_2t+3C_3t^2+4C_4t^3+5C_5t^4+6C_6t^5+\\
&+7C_7t^6+8C_8t^7+9C_9t^8+10C_{10}t^9+11C_{11}t^{10};\\
&\ddot{\psi}_1(t)=2C_2+6C_3t+12C_4t^2+20C_5t^3+30C_6t^4+\\
&+42C_7t^5+56C_8t^6+72C_9t^7+90C_{10}t^8+110C_{11}t^9;\\
&\dddot{\psi}_1(t)=6C_3+24C_4t+60C_5t^2+120C_6t^3+210C_7t^4+\\
&+336C_8t^5+504C_9t^6+720C_{10}t^7+990C_{11}t^8;\\
&\psi_1^{IV}(t)=24C_4+120C_5t+360C_6t^2+840C_7t^3+\\
&+1680C_8t^4+3024C_9t^5+5040C_{10}t^6+7920C_{11}t^7;\\
&\psi_1^{V}(t)=120C_5+720C_6t+2520C_7t^2+6720C_8t^3+\\
&+15120C_9t^4+30240C_{10}t^5+55440C_{11}t^6,
\end{aligned} \quad (30)$$

where, C_0, C_1, ... C_{11} – the constants that were determined based on motion boundary conditions (26). As a result of the substitution of boundary conditions (26) into expressions (29) and (30), the following values might be obtained:

$$C_0=C_1=C_2=C_3=C_4=C_5=0. \quad (31)$$

The constants C_6, C_7, ..., C_{11} were determined based on the following system of linear algebraic equations:

$$\begin{aligned}
&C_6+C_7t_1+C_8t_1^2+C_9t_1^3+C_{10}t_1^4+C_{11}t_1^5=\frac{\omega}{2t_1^5};\\
&6C_6+7C_7t_1+8C_8t_1^2+9C_9t_1^3+10C_{10}t_1^4+11C_{11}t_1^5=\frac{\omega}{t_1^5};\\
&30C_6+42C_7t_1+56C_8t_1^2+72C_9t_1^3+90C_{10}t_1^4+110C_{11}t_1^5=0;\\
&120C_6+210C_7t_1+336C_8t_1^2+504C_9t_1^3+720C_{10}t_1^4+990C_{11}t_1^5=0;\\
&360C_6+840C_7t_1+1680C_8t_1^2+3024C_9t_1^3+\\
&+5040C_{10}t_1^4+7920C_{11}t_1^5=0;\\
&720C_6+2520C_7t_1+6720C_8t_1^2+15120C_9t_1^3+\\
&+30240C_{10}t_1^4+55440C_{11}t_1^5=0.
\end{aligned} \quad (32)$$

As a result of the substitution of constants (31) as well as the ones determined when solving the system of linear algebraic equations (32) into dependency (29), the function that meets boundary conditions with respect to the coordinate ψ and its derivatives with respect to time were determined.

The $\psi_2(t)$ polynomial is represented as follows:

$$\psi_2(t)=\left(\frac{t}{t_1}\right)^6\left(\frac{t_1-t}{t_1}\right)^6\cdot$$
$$\cdot\sum_{k=0}^{n}D_k\left(\frac{t}{t_1}\right)^k\frac{\omega t_1}{2},\ 0\le t\le t_1, \quad (33)$$

where D_0, D_1, ..., D_n – the free coefficients, on which the value of optimisation criterion (12) depends; the multiplier that ensures compliance with zero boundary conditions (27) at arbitrary values of the coefficients D_0, D_1, ..., D_n. These coefficients are free and they ensure the determination of the minimum value of criterion (12).

As a result of the substitution of expressions (29), ..., (33), considering boundary conditions (28), into dependency (27) the expression of function $\psi(t)$ which includes the unknown free coefficients D_0, D_1, ..., D_n was obtained.

Using dependencies (17) and (21) the expressions of the angular coordinates of the drive mechanism slew and the rotation part of the crane according to i that also depend on the free coefficients D_0, D_1, ..., D_n were found. At integration, criterion (12) also became the function of the free coefficients D_0, D_1, ..., D_n. Thus, the approximate solution of the optimisation problem (12), ..., (15) was reduced to determining the optimisation criterion minimum as a function of many variables D_0, D_1, ..., D_n.

The metaheuristic *VCP-PSO* method (Romasevych *et al.*, 2022) was applied to solve the formulated optimisation problem. At that, the generalised criterion of optimisation (25), considering the expression (12), as the function that depended on 6 free coefficients was represented:

$$C_r=C_r(D_0, D_1, ..., D_5). \quad (34)$$

The calculations of the optimal force acceleration mode of the tower crane rotation mechanism at steady payload hoisting based on the criterion of the RMS value of the drive torque (12) and constraints on the drive torque (14) and the power (15) of the drive when meeting the boundary conditions (26) were carried out at such values of the parameters of the jib system: $m = 5000$ kg, $m_2 = 300$ kg, $J_1 = 5{,}51 \cdot 10^5$ kg $\cdot$ m², $J_2 = 4{,}92 \cdot 10^6$ kg $\cdot$ m², $M_0 = 39890$ Nm, $C = 6{,}63 \cdot 10^6$ Nm/rad, $a = 20$ m, $v = 0{,}5$ m/s, $\omega = 0{,}075$ rad/s, $l_0 = 10$ m, $t_1 = 5{,}0$ s, $g = 9{,}81$ m/s², $M_{min} = 0$, $M_{max} = 260000$ Nm, $P_{min} = 0$, $P_{max} = 14000$ W.

RESULTS AND DISCUSSION

The following values of the free coefficients were obtained as a result of solving the optimisation problem:

$$D_0 = 61.88;\ D_1 = -47.38;\ D_2 = 3.58;$$
$$D3 = -9.66;\ D_4 = 1.52;\ D_5 = 90.33.$$

Based on the obtained solution of the optimisation problem of the acceleration process of the tower crane rotation mechanism at steady payload hoisting, graphic dependencies of kinematic (Fig. 2-4), dynamic, and energy characteristics of the jib system of the tower crane in the process the rotation mechanism acceleration were built.

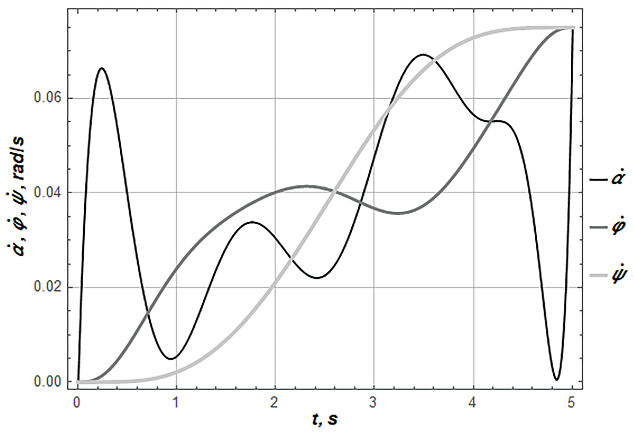

Figure 2. Plots of angular velocities of the rotation mechanism drive , rotation part of the crane and slew of the payload
Source: compiled by the authors

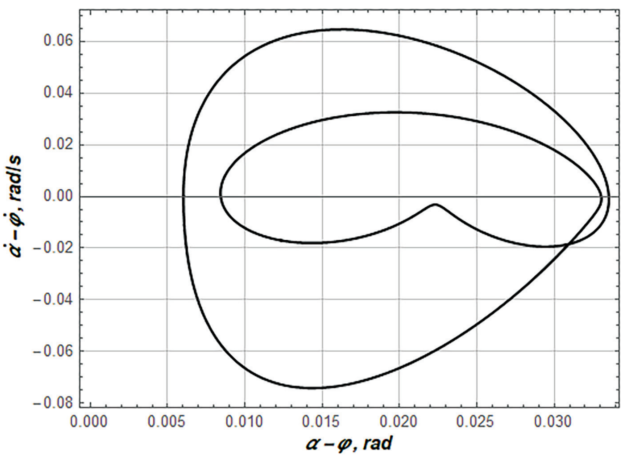

Figure 2. Phase portrait of the elastic deformation of the crane's mast
Source: compiled by the authors

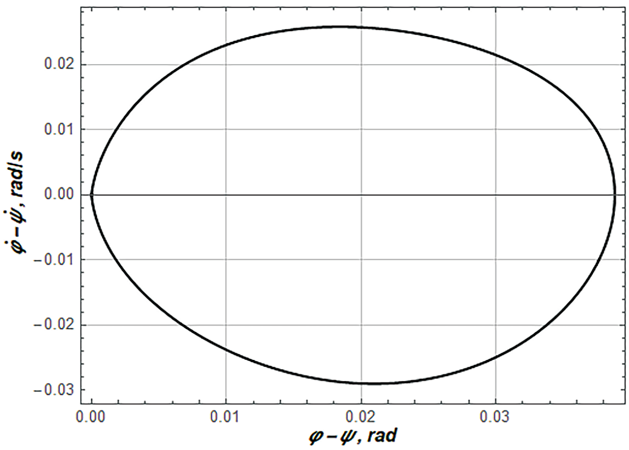

Figure 4. Phase portrait of the cable deviation from the vertical in the plane of the slew
Source: compiled by the authors

From graphic dependencies of the angular velocities of the elements of the jib system of the crane (Fig. 2) conclusion can be drawn that the velocity of the payload slew changes smoothly according to an S-shaped diagram. The velocity of the rotation part of the crane also exhibits a pattern similar to a smooth change. Along with that, the velocity of the drive rotation mechanism exhibits an oscillatory pattern with abrupt increases and decreases of the motion rate. Such a mode of the crane's motion ensures optimal technological characteristics of the crane's performance. At that, the reliability of the drive mechanism's performance may be substantially decreased. This was caused by an abrupt change of motion velocity, it led to the appearance of significant dynamic payloads in the elements of the drive.

Phase portrait of oscillations in the rotation mast of the crane (Fig. 3) shows that oscillations attenuate quite rapidly (within the course of two periods of oscillation). Overall, such motion mode ensures a stable mode of operation of the crane structure. From the phase portrait of oscillations of the payload on the elastic suspension (Fig. 4) it can be observed that during the acceleration process, the oscillations of the payload attenuate smoothly within the course of one period of oscillation and completely disappear upon reaching the steady motion of the rotation mechanism. The obtained phase portrait confirmed the smooth motion of the payload during the operation of the crane rotation mechanism.

The drive torque of the crane rotation mechanism drive exhibits an oscillatory pattern, increasing and decreasing twice from the steady to the maximum value. At that, the maximum value of the drive torque corresponds to the maximum permissible value, which is *260 kNm*. Elastic torque in the rotation mast of the crane also exhibits a similar pattern of change in the process of rotation mechanism acceleration (Fig. 5). However, it takes slightly smaller numerical values in comparison to the drive torque.

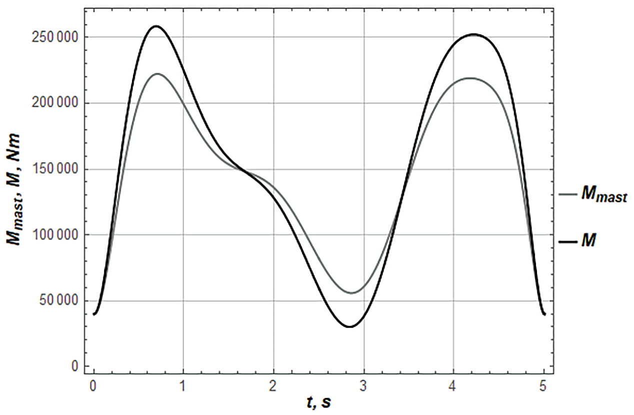

Figure 5. Plots of the drive torque of the crane rotation mechanism drive M and the elastic torque in the rotation mast of the crane
Source: compiled by the authors

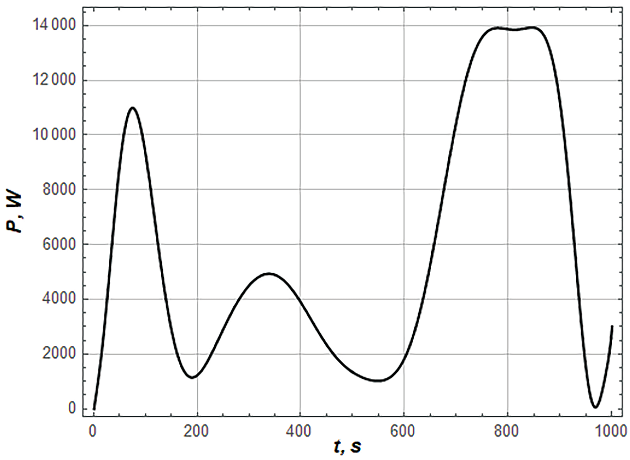

Figure 6. Crane rotation mechanism drive power plot
Source: compiled by the authors

The power of the crane rotation mechanism drive (Fig. 6) exhibits an aperiodic oscillatory pattern with variable frequency and amplitude, reaching the maximum permissible value of *14 kW* in the end of the acceleration process. Upon reaching the steady motion mode of the crane rotation mechanism, the power consumption was *3.0 kW*. The power component of the drive consumed by the deformation of the mast (Fig. 7) initially sharply increases to the maximum value of *9.5 kW* and then decreases to *9.0 kW*. At that, during the acceleration process, all the energy of the crane's mast deformation is returned to the system.

As a result of solving optimisation problem (12), ..., (15), numerical values of kinematic, dynamic, and energy indicators were calculated for the base case (boundary conditions of the rotation mechanism acceleration are ensured) and for the optimal acceleration mode, where additionally a minimum value of generalised criterion (25) is ensured (Table 1).

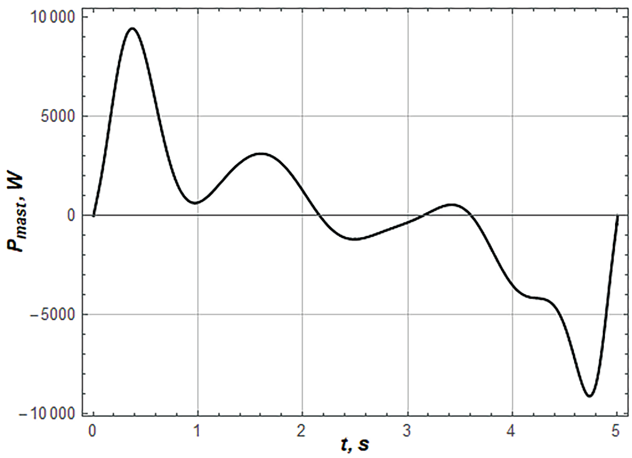

Figure 7. Plot of the change of the component of the drive power that is consumed by the deformation of the rotation mast of the crane
Source: compiled by the authors

Table 1. Numerical values of indicators that correspond to the base and optimal solutions of problem (12), ..., (15)

Estimate evaluation	Unit of measure	Magnitude of the indicator obtained for the solution	
		base	optimal
RMS indicators domain			
Payload deviation	rad	0.0232	0.0223
Elastic deformation of the mast	rad	0.0250	0.0235
Torque in the mast	Nm	165494	155684
Drive torque	Nm	184731	170555
Drive power	W	7892	7378
Maximum indicators domain			
Payload deviation	rad	0.0424	0.0388
Elastic deformation of the mast	rad	0.0386	0.0335
Torque in the mast	Nm	255618	222343
Drive torque	Nm	295608	258573
Drive power	W	17547	13924

Source: compiled by the authors

Analysis of Table 1 showed that compared to the base motion case, the optimal acceleration mode is better in all defined indicators. So, for example, the RMS deviation from the vertical for the elastic payload suspension decreases by

4.0%, and the maximum – by 9.3%. The RMS value of the mast elastic deformation decreases by 6.4%, and the maximum – by 15.2%. The RMS value of the drive torque decreases by 10.8%, and the maximum – by 14.3%, while the RMS value of the drive power decreases by 7.0%, and the maximum – by 26.0%.

In the work by R. Buczkowski & B. Żyliński (2021) the strength and wear characteristics of crane elements were evaluated using numerical analysis. The authors of the article I. Umaru *et al.* (2021) developed a control system that eliminates vibrations and ensures the desired positioning of the payload in gantry cranes. A. Mohammed *et al*. (2023) proposed a method for eliminating residual oscillations of the payload when moving the crane by using a modified controller. In the work by E. Jarzębowska *et al.* (2020) the vibrations of rigid and flexible elements of the crane and the payload with given constraints were analysed. J. Wang *et al.* (2022) proposed a method for eliminating oscillations of the payload and the structure of a floating crane with 3-DOF. In the study by I.A. Martin *et al.* (2021), a controller was developed to monitor oscillations in the payload of a floating crane with a specified number of degrees of freedom (DOF).

The paper by J. Ye & J. Huang (2023) investigated the dynamics of payload transportation by crane reloaders. Here, the main focus was on the influence of oscillations of the payload on a flexible suspension on the dynamics of the structure and the positioning of the payload. The authors M. Bello *et al.* (2024) presented modelling and analysis of the dynamic characteristics of a double-pendulum overhead crane model. The study of the dynamics of motion of an overhead crane with a new wheel design was the subject of the work by N. Fidrovska *et al.* (2021), where stresses in the crane structure elements were determined. In the work by R. Miranda-Colorado (2021) presented a new robust controller to dampen the oscillation of the deflection angle of a crane payload suspension with a variable cable length. Dynamic payloads and swinging of the payload on a flexible suspension also affect its positioning accuracy during loading, unloading, and assembly operations (Kovalenko *et al*., 2023). In the article by S.M. Fasih *et al.* (2020), control of the payload rotation mechanism was carried out by using a neural network to generate the input data for a jib crane. In the work by S. Tong *et al.* (2024), a method for controlling the dynamic sliding mode has been proposed, and a dynamic model of a double-pendulum cable crane with wind disturbance was developed. The authors of the article by Y. Qian *et al.* (2022) developed a method for controlling the movement of jib crane mechanisms. The work by F. Lui *et al.* (2021) deals with the issues regarding the control of payload swinging and the vibration characteristics of jib cranes, which allowed reducing the payloads on the structural elements. Achievements of optimisation using swarm intelligence methods were presented in the works of another studies by E.H. Houssein *et al.* (2021), T.M. Shami *et al. (*2022) and M. Isiet & M. Gadala (2020).

In work by S.M. Fasih *et al.* (2020), the dynamics of the rotation mechanism of the jib crane were modelled and the deviation from the vertical of the flexible suspension of the payload was determined. To reduce the payload oscillations, the length of the flexible suspension with the payload was changed. Its maximum deviation from the vertical was 10 degrees without changing the length of the flexible payload suspension. The authors managed to reduce its maximum deviation from the vertical to 6 degrees, and with an additional reduction of its oscillations – to 3 degrees by varying the length of the flexible suspension of the payload. The optimisation of the process of starting the rotation mechanism during steady hoisting of the payload made it possible to reduce the maximum deviation from the vertical of the flexible suspension to 2.3 degrees. The authors of the article F. Lui *et al.* (2021) conducted a study of the dynamics of the movement of a jib crane, where the maximum deviation from the flexible suspension of the payload at a steady mode of movement was determined, which is 0.01 radian, and the oscillations of the payload practically do not subside until the end of the movement cycle. As a result of optimising the starting mode of the rotation mechanism when entering the steady mode of movement, the oscillations are completely eliminated. In work by S. Chwastek (2020), the parameters of the jib hoisting mechanism were optimised, where integral quadratic functionals were used as optimisation criteria. In the article, the optimisation of the movement mode of the rotation mechanism was carried out, where also the integral quadratic functional was used as the optimisation criterion, which is the RMS value of the driving torque. This indicates the relevance and expediency of using integral quadratic functionals as criteria in crane mechanism optimisation problems. The article's authors Q. Wu *et al.* (2020) carried out a dynamic analysis and optimisation of the motion mode of the trolley of the bridge crane with a two-pendulum payload suspension. The dynamic analysis showed that practically undamped oscillations of the payload on the flexible suspension are observed. By choosing the start-up duration, it was possible to eliminate the oscillations of the payload on the flexible suspension during the steady motion, but at the same time, in the start-up mode, the maximum deviation from the vertical of the flexible suspension of the payload increased by 1.14 times. In the article, as a result of the optimisation of the start-up mode, the oscillations of the payload on the flexible suspension in the section of steady motion are also eliminated. At the same time, the duration of the start-up process and the maximum value of the deviation from the vertical of the flexible payload suspension do not increase. In the work I. Umaru *et al.* (2021), a dynamic analysis of the movement of a trolley with a payload was performed without and with the use of a PID controller. The analysis of the obtained research results showed that without the use of the controller, the oscillations of the payload are practically not dampened and the maximum value of the deviation from the vertical of the flexible suspension of the payload is 0.11 radians. When using the controller, the maximum value of the deviation from the vertical of the flexible suspension of the payload decreased to 0.06 radians in the start mode, and in the steady mode, these oscillations are practically eliminated. In the article, the oscillations of the payload on the flexible suspension after the start process are also eliminated, but the maximum value of the deviation from the vertical of the flexible payload suspension in the start area is smaller and is 0.04 radians.

The results obtained in the article and in the articles of other authors are close in terms of content and numerical characteristics, and in some cases are even slightly better in similar studies.

CONCLUSIONS

The article provides the results of optimising the motion mode of the rotation mechanism of the tower crane with a beam jib at steady payload hoisting. The tower crane rotation mechanism at steady payload hoisting was presented as the dynamic model with 4DOF, where the main motion of the drives and oscillations of the crane mast and payload on elastic suspension in the plane of the slew were considered. At that, the payload hoisting coordinate was known since the hoist was performed at a constant velocity.

For such a model a system of differential equations of motion of the rotation mechanism at steady payload hoisting is formulated which was reduced to the angular coordinate of the payload slew and its derivatives with respect to time up to and including the sixth order. To decrease dynamic payloads in the elements of the crane and drive structure, an optimisation problem was stated and solved. In this problem the acceleration mode of the rotation mechanism at minimisation of the integral criterion and ensuring the necessary boundary conditions for the jib system motion and constraints on force and energy characteristics was determined. The optimisation criterion used was the RMS value of the drive torque of the rotation mechanism drive during the acceleration process. The constraints included minimum and maximum values of the drive torque and drive power. The integral criterion along with the constraints on the drive torque and drive power was presented as a generalised criterion which was minimised as it reflects undesirable properties of the system.

The presented optimisation problem for selecting the acceleration mode of the rotation mechanism at steady payload hoisting is nonlinear, so an approximate method was applied for its solution. In this problem, the unknown function of the payload slew was represented by a sum of two polynomials. The first polynomial was selected from the condition of meeting the boundary conditions of the rotation mechanism acceleration, and the second polynomial included free coefficients and ensures zero boundary conditions. The values of the free coefficients were determined based on the condition of the minimisation of the generalised criterion using the modified metaheuristic *VCP-PSO* method.

Based on the performed optimisation, an acceleration mode of the crane rotation mechanism which minimises dynamic payloads, reduces the drive mechanism power, and eliminates oscillations of the elements and payload in the steady motion region was obtained. The analysis of the base and optimal acceleration modes of the rotation mechanism shows that in the latter motion mode compared to the former the maximum values of the elastic payload suspension deviation from the vertical decrease by 9.3%, mast deformations by 15.2%, drive torque by 14.3%, and drive power by 26.0%.

Prospects for further research are aimed at optimising the operation of tower cranes through the improvement of dynamic models of their mechanisms. It is proposed to pay special attention to the development of intelligent control systems that allow the implementation of the determined optimal modes of motion of the tower crane rotation mechanism in practice.

An important direction is to increase the energy efficiency of cranes by optimising energy consumption by mechanism drives. The development of hybrid control systems that combine classical PID controllers with fuzzy logic algorithms is promising. This will allow more effective adaptation of systems to changing operating conditions.

Further research involves experimental verification of models in real conditions to confirm their adequacy. This will help optimise the design, reduce wear of elements and increase the safety of crane operation. Modelling taking into account a larger number of factors that will allow more accurate prediction of the behavior and reliability of the crane.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Оптимізація силового режиму пуску механізму повороту баштового крану при усталеному підйомі вантажу

Анотація. Метою роботи було оптимізувати силовий режим пуску механізму повороту при усталеному підйомі вантажу баштового крана з балочною стрілою. Механізм повороту крана представлено динамічною моделлю з чотирма ступенями вільності, де враховано основний рух механізмів повороту та підйому вантажу, а також коливання поворотної частини крана та вантажу в площині повороту. Для такої динамічної моделі складено математичну модель, яка представляла собою систему звичайних диференціальних рівнянь другого порядку. Систему рівнянь зведено до кутової координати повороту вантажу і представлено рівнянням шостого порядку. Оптимізацію режиму пуску механізму повороту при усталеному підйомі вантажу здійснено за критерієм середньоквадратичного значення рушійного моменту приводу. При цьому враховано обмеження на рушійний момент та потужність приводу. Критерій оптимізації разом з обмеженнями зведено до узагальненого критерію. При оптимізації за крайові умови руху взяті переміщення та швидкості узагальнених координат механізму повороту на початку та в кінці процесу пуску. За результатами оптимізації отримано режим пуску механізму повороту крана при усталеному підйомі вантажу. Отриманий режим мінімізує дію динамічних навантажень, зменшує максимальні значення деформації колони крана, потужності приводу та відхилення вантажного канату від вертикалі. При цьому усуваються коливання ланок крана і вантажу при виході на усталений режим руху. Результати дослідження можна використати у системах автоматизації для керування механізмами повороту баштових кранів, що забезпечує покращену ефективність і стабільність роботи при підйомі вантажу

Ключові слова: стріловий кран; механізми підйому та повороту; динамічні навантаження; оптимальне керування; коливання вантажу

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Introduction of neural network technologies to optimise the control of the operating modes of a sucker-rod pump installation

Abstract. The study was conducted to identify the possibilities of implementing neural network technologies to optimise the control of the operating modes of the sucker-rod pump (SRP), which will help to increase the efficiency of oil production and reduce operating costs. The study used data analysis and adaptive management methods to optimise the operation of the SRP. As a result of the study, it was found that the introduction of neural network technologies in the SRP management system can significantly increase their efficiency. Analysis of data from the unit's sensors using neural networks helped to identify optimal operating modes that ensure maximum production with minimal energy consumption. A forecasting model has been developed that can detect potential equipment failures in advance, which reduces the risks of emergencies and maintenance costs. The study also showed that adaptive control algorithms based on artificial intelligence can automatically adjust the operating modes of the SRP depending on variable conditions, such as pressure fluctuations or changes in the properties of the oil produced. Based on the integration with the Internet of Things, the system has the ability to perform real-time monitoring, which increases the efficiency of decision-making. As a result, the introduction of neural network technologies not only optimises mining processes, but also helps to reduce operating costs. In addition, the study revealed that the use of neural networks in control systems can significantly reduce the time required to configure and optimise processes, which increases the overall productivity of the SRP

Keywords: forecasting model; adaptive algorithms; operating costs; emergencies; potential failures

INTRODUCTION

The introduction of the latest technologies in various industries has become a necessary condition for improving the efficiency and competitiveness of enterprises. This problem is particularly relevant in the field of oil production, where sucker-rod pumps (SRPs) play a key role in the process of lifting hydrocarbons from great depths. The SRP consists of several components, including a pump, rod, and electric motor, that work together to ensure efficient oil production. Conventional management methods for such installations often face problems related to low productivity, high energy costs, and the risk of accidents. Modern neural network technologies that can analyse large amounts of data and adapt to changing conditions offer new solutions for optimising the operation of SRPs. They can not only increase the efficiency of mining, but also reduce the cost of equipment maintenance.

In the field of SRP management, it is important to strike a balance between improving productivity and reducing costs. Conventional management methods are often unable to respond effectively to changes in working conditions, which leads to irrational use of energy resources. M. Sabah *et al*. (2021) showed that adaptive control algorithms can improve mining efficiency. They also noted that such algorithms reduced system setup time, which was crucial for reducing costs. B. Cao *et al*. (2023) found that neural networks were able to predict equip-

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ment failures, which significantly reduced the risk of field accidents. Their study demonstrated how such forecasts can reduce maintenance costs and improve overall system reliability. A. Sircar *et al*. (2021) focused on the possibilities of optimising energy costs through automation of control processes. They emphasised that the introduction of neural networks could significantly reduce energy costs, which was an important aspect in the modern oil production industry. K. d'Obyrn *et al*. (2024) developed models that considered geological conditions, which made it possible to change the management strategies of SRP. These models helped to adapt management decisions to the specifics of each field, increasing production efficiency. Z. Huang *et al*. (2023) emphasised the importance of integrating neural networks with the Internet of Things (IoT) for real-time performance monitoring. They noted that such integration could significantly increase the speed of response to changes in production conditions.

R. Al-Shabandar *et al*. (2021) evaluated the economic benefits of implementing neural network technologies in production processes. Their study demonstrated how economic efficiency can increase by reducing the cost of energy resources and maintenance. A Brendel *et al*. (2021) drew attention to the ethical aspects of the use of artificial intelligence in industry. They stressed the need to create transparent and understandable algorithms that would avoid possible risks and ensure trust in new technologies. A. Sheikhoushaghi *et al*. (2022) analysed the impact of neural networks on mining management decision-making. They pointed out the ability of these technologies to adapt to changing conditions, which was important for management effectiveness. Z. Liu *et al*. (2021) emphasised the importance of training neural networks on historical data to improve forecasting. They noted that this practice helped to improve the accuracy of models and provide better resource management. A. Drewek-Ossowicka *et al*. (2021) investigated security aspects of the use of neural networks in control systems. They stressed the need for an integrated approach to risk assessment, which would help to ensure the safe introduction of new technologies in industry. However, despite the results achieved, gaps remain that require further study. For example, aspects of integrating neural networks with the IoT and their impact on real-time response speed are not sufficiently studied, which can significantly affect management decisions in a rapidly changing environment.

The purpose of the study was to evaluate neural network models for predicting optimal operating modes of the SRP to increase oil production, reduce energy consumption, and increase the economic efficiency of the management system. Objectives of the study:

1. To evaluate the impact of neural network technologies on improving the efficiency of SRP management in terms of performance and power consumption.

2. To investigate how adaptive control algorithms can help to optimise oil production processes in conditions of variable geological and operational parameters.

3. To conduct an economic assessment of the effectiveness of implementing neural networks in management systems, in particular, to identify how these technologies reduce energy consumption and maintenance costs while improving productivity.

MATERIALS AND METHODS

The study conducted a comprehensive analysis of the implementation of neural network technologies to optimise the management of SRPs, which are critical for oil production from great depths. The first important aspect that was analysed was the optimisation of the work of the SRP. The use of the method of processing large amounts of data using neural networks enabled the analysis of information obtained from sensors installed at the plants, including rotational speed, pressure, temperature and other parameters. Based on this analysis, models were developed that predict the optimal modes of functioning of the SRP. This allows achieving maximum oil production with minimal energy consumption, identifying the most efficient operating parameters and significantly increasing the overall productivity of units.

The next aspect considered in the study was the prediction of equipment failures. The use of the method of analysing historical data using neural networks identified patterns that preceded failures in the operation of installations. Based on this analysis, predictive models were developed that can predict possible equipment failures. Based on this, enterprises can take preventive measures in advance, which helps to reduce the risk of accidents and minimise serious consequences for production. The study also focused on adaptive management, which was crucial in the context of variable geological factors and mining properties. The use of the adaptive algorithm modelling method demonstrated the ability of neural networks to adapt to changes in the operating conditions of the SRP. In cases where parameters such as pressure or oil properties change, these algorithms automatically adjust the operating modes of the plants, which ensured that a high level of efficiency is maintained in various operational scenarios.

An important element of the study was the assessment of the economic benefits of implementing neural networks in management systems. Optimisation of SRP operating modes not only improves production, but also reduces energy and maintenance costs. The cost analysis of "Ukrnafta" was carried out, which showed that optimisation of management processes can reduce operating costs, which, in turn, will have a positive impact on the overall economy of the enterprise (Audited financial statements..., 2021). An equally important aspect was the study of the integration of neural network technologies with the IoT. Using the system analysis method, it was shown how the integration of neural network technologies and the IoT contributes to the improvement of monitoring and management systems of SRP. Based on this integration, enterprises can perform real-time monitoring, which increased the efficiency of decision-making and allowed them to respond in a timely manner to changes in operating conditions.

The last aspect of the study was specific examples of the use of neural networks in Ukrainian and foreign enterprises. The study focused on the introduction of neural network technologies in oil production processes to determine their impact on the effectiveness of SRP management. At "Ukrnafta", which is based in Ukraine, the introduction of neural network technologies has made it possible to optimise oil production processes, reducing energy costs, and increasing productivity. Similarly, the US oil company "ExxonMobil" used neural networks to predict equipment failures, which helped to identify potential problems in time. "Saudi Aramco", the national oil company of Saudi Arabia, used adaptive control algorithms based on neural networks, which helped to effectively respond to changes in geological conditions. "Equinor", a Norwegian company, also integrated neural networks for analysing data from sensors, which helped to optimise the operating modes of the SRP. This analysis identified best practices and the most effective methods in a variety of environments, which helped to improve productivity and reduce risks in mining processes.

RESULTS

The introduction of neural network technologies in the field of oil and gas production is extremely relevant, as it opens up new opportunities for optimising the operation of SRP. SRPs are key elements in production systems designed to lift oil from great depths, where conventional methods may be ineffective.

Recurrent neural networks are powerful tools for processing sequential data with temporal or spatial dependencies, and can store information from previous stages to predict subsequent results. They are used to analyse the parameters of the SRP operation in real time, such as temperature, pressure, and flow rate, which allows more accurately predicting changes in these indicators at each stage of the plant's operation and adjust the parameters to ensure efficient and safe operation (Abdalla *et al*., 2023).

Deep neural networks, in particular the long-term memory architecture, are a subtype of recurrent neural networks and can handle complex, long-term dependencies in data, which allows working effectively with large amounts of information. They are used to predict pump saturation needs and optimise energy consumption, helping to more accurately estimate energy costs and provide cost-effective operating modes of installations (Kristian *et al*., 2024).

Convolutional neural networks are effective for processing images or video data and are used to monitor the state of equipment using video sensors. They allow detecting anomalies in pump operation, such as mechanical damage or leaks, and analysing equipment stops and damages based on video analysis (Ma *et al*., 2023).

Generative neural networks are used to create simulation data that helps to simulate different operating conditions and adapt systems to changes in geological characteristics. They allow creating new data sets necessary for training other models when real data is limited or unavailable, and predicting possible changes in the operating conditions of the SRP, ensuring the reliability and efficiency of systems under conditions of uncertainty (Ma *et al*., 2024). Each of these approaches has its own advantages and application specifics, depending on the task, which allows a comprehensive approach to solving problems in the operation of pumping units.

In today's environment, when competition in the energy market is growing, and the requirements for reducing costs and improving productivity are becoming more stringent, the use of innovative technologies, such as neural networks, is becoming necessary. Neural networks have the ability to analyse large amounts of data received from sensors and identify patterns that are difficult for a person to notice. This allows predicting the optimal operating modes of the SRP, ensuring stable and efficient operation of the installation.

The introduction of neural network technologies in the management of SRPs can lead to significant improvements in efficiency, lower energy costs, reduced installation and maintenance time, and increased oil production. In particular, neural networks can detect potential equipment failures, which allows taking timely measures to eliminate them and prevent accidents.

Optimisation of the SRP operation using neural networks opens up new opportunities for improving the efficiency of the oil industry. Modern installations collect huge amounts of data from numerous sensors that record indicators of such key parameters as speed, pressure, and temperature. As a rule, processing such data manually is complex and slow, which often leads to inefficient use of resources and an increased risk of accidents. However, the introduction of neural network technologies allows automating the analysis of this data and configure the system in real time (Swain *et al*., 2022).

Neural networks are able not only to process information flows from sensors, but also to learn from this data, forming forecasts about the optimal operating modes of the installation. For example, real-time analysis of pressure and temperature changes allows the neural network to determine the best performance for the speed of pumping equipment. This allows not only improving performance, but also reducing power consumption, as the system automatically adapts to changing conditions. Thus, the use of artificial intelligence in the management of SRPs becomes a key factor for achieving a balance between maximum oil production and saving energy resources (Kolakoti *et al*., 2023).

In addition, the ability of neural networks to predict possible hardware failures based on analysis of historical data and current indicators helps to reduce the likelihood of accidents. This significantly reduces maintenance costs, because the intended repair is less expensive than eliminating the consequences of breakdowns. As a result, neural network management models not only optimise mining processes, but also increase the overall reliability of SRPs.

When implementing neural networks in industry, several technical and organisational difficulties may arise. Technical difficulties include integration with existing management systems, as many businesses use legacy technologies, and adapting them to new data standards can require significant effort. In addition, training neural networks requires large amounts of high-quality data, which can be a problem if existing data in the enterprise is incomplete or unstructured. Neural networks also require significant computing power, which can be a problem for businesses with limited access to high-performance computing platforms (Malhan & Gupta, 2023).

Organisational difficulties include the need for machine learning specialists, which may not be enough in the labour market, and the need to adapt existing business processes. This can cause resistance among employees and require staff retraining. Implementing new technologies also requires significant initial investment in technology, equipment, and training, which can be difficult for businesses on a tight budget (Guo *et al.*, 2024).

In addition, there are problems with data security, since the use of large amounts of sensitive information requires strict compliance with security and confidentiality standards. Regulatory restrictions, especially in industries subject to strict controls, such as the oil and gas industry, can make it difficult to implement neural networks. Thus, the introduction of neural networks in industry requires a comprehensive approach, including technical modernisation, personnel training, and consideration of regulatory aspects. Predicting failures in the SRP using neural network technologies is a key factor in improving the security and efficiency of their work. One of the main problems in the operation of SRPs is unpredictable equipment failures, which can lead not only to downtime in operation, but also to significant financial losses due to repairs and stopping oil production. The use of neural networks for analysing historical data opens up opportunities for early prediction of potential failures and, thus, makes it possible to take timely measures to prevent accidents.

Neural networks are able to learn from large amounts of data that include the installation's performance over a long period of time: vibration levels, pressure, temperature, power consumption, and other parameters. By analysing this data, the neural network identifies patterns that may indicate the beginning of degradation of individual components or the approach of their failure. As a result, the system can automatically provide a warning about a possible failure of a certain element, which allows performing preventive maintenance before real problems occur (Pérez-Gomariz *et al.*, 2023).

This ability to predict failures significantly increases the reliability of the SRP, reducing the likelihood of accidents. Due to early maintenance measures, companies can avoid unexpected costs associated with urgent repairs and emergency production stops. In addition, planned technical measures are usually cheaper than eliminating the consequences of unexpected accidents. In this context, neural networks not only improve the plant management process, but also help to reduce operating costs and increase the productivity of the oil and gas industry (Silvia *et al.*, 2023).

Adaptive management is one of the most promising areas in the development of modern technologies in the oil and gas industry. The operating conditions of pumping equipment can vary depending on many factors, in particular, due to changes in the geological conditions of the field, the properties of the oil produced, or unpredictable fluctuations in pressure and temperature levels. Neural network technologies provide flexible and adaptive management of installations, which allows them to maintain their efficiency even in changing and unstable environments (Fakher *et al.*, 2022).

One of the key advantages of neural networks is the ability to continuously learn based on the obtained data and adapt to new conditions. This means that the system can automatically adjust the operating modes of the installation in accordance with the current indicators, without requiring manual intervention. For example, when oil properties change, such as viscosity or impurity content, the neural network can independently adjust the optimal pressure and speed parameters of pumping equipment. This adaptability allows avoiding system failures and maintaining high production performance regardless of external changes (Abdolrasol *et al.*, 2021). In addition, in cases of changes in geological conditions, such as a decrease in reservoir pressure or a complication of rock structure, neural network models can quickly respond to these changes. Based on integration with monitoring systems, neural networks constantly receive data on the state of the installation and the environment, which allows them to adapt their work to new conditions in a timely manner. This ability to adapt quickly is particularly important in large oil and gas fields, where the geological structure can be extremely variable and standard control algorithms are often not effective enough.

Adaptive control also helps to minimise energy costs, as the neural network adjusts the operation of the installation so as to maximise the use of resources. As a result, companies implementing such systems can achieve not only stable performance, but also energy savings, which is a key factor in modern industry (Table 1).

Table 1. Comparison of key indicators before and after the introduction of neural network technologies for SRPs at "Ukrnafta"

Parameter	Before implementing neural network	After implementing neural network	Change (%)	Explanation
Power consumption (kW)	10,000	8,000	-20	Reduced power consumption is achieved by optimising operating modes by a neural network that adjusts the parameters of installations depending on conditions in real time, which reduces unnecessary energy consumption

Continued Table 1.

Parameter	Before implementing neural network	After implementing neural network	Change (%)	Explanation
Energy costs (UAH)	200,000	160,000	-20	The reduction in energy costs is the result of reduced energy consumption, which is made possible by the adaptive operation of the neural network, which minimises the use of energy required to maintain stable operation of installations
Capacity (units/hour)	50	65	+30	The increase in productivity is conditioned by more precise adjustment of operating modes, which optimises equipment performance and minimises losses due to inefficient load
Downtime (hour/month)	15	5	-66	Downtime reduction is achieved due to proactive monitoring and forecasting of failures by the neural network, which detects possible failures in a timely manner and makes it possible to conduct preventive maintenance without stoppin
Service cost (UAH)	50,000	35,000	-30	Reduced maintenance costs are associated with fewer emergency downtime and preventive maintenance based on neural network forecasts, which reduces the need for expensive repairs

Source: compiled by the author

Reduction of the cost of operating SRP is one of the key aspects that ensure sustainable competitiveness of oil and gas enterprises. One of the most effective ways to reduce costs is to optimise the operating modes of installations, which can significantly reduce costs of energy and maintenance. The use of neural networks to control mining processes allows achieving this goal, providing more precise configuration of the plant's operation depending on the actual operating conditions (Zhu *et al.*, 2021).

The use of neural network technologies allows automatically adjusting the operation of pumping equipment, considering changes in pressure, temperature, and properties of the oil produced. This results in the system running more efficiently, using only the necessary amount of energy to ensure optimal performance. Reducing energy costs has a direct impact on the overall economy of the enterprise, since energy costs account for a significant part of operating costs in the oil and gas industry. Efficient energy consumption not only reduces costs, but also helps to reduce greenhouse gas emissions, which is important for compliance with environmental standards (Skillington *et al.*, 2022).

In addition, neural networks help to reduce maintenance costs by being able to predict hardware failures. Automated data monitoring and analysis systems allow identifying potential problems long before they lead to serious failures. This allows planning maintenance ahead of time, minimising the need for expensive emergency repairs and reducing the duration of equipment downtime. Regular preventive maintenance is less expensive and allows businesses to use their resources more efficiently.

Optimising operating modes and reducing maintenance costs also affects the service life of the equipment. Maintaining stable and efficient operating conditions prevents excessive wear on plant components, allowing them to continue operating without the need for frequent replacement of expensive parts. This, in turn, reduces capital expenditures and improves the economic performance of the enterprise. The integration of neural network technologies with IoT opens up new prospects for creating highly efficient monitoring and management systems for SRP. Conventional methods of managing oil production systems are often reactive, meaning that the response to changes or malfunctions occurs only after they occur. In turn, the integration of IoT with neural networks enables a proactive approach to management, which helps to more effectively control all processes in real time (Wang *et al.*, 2022).

IoT technologies allow collecting huge amounts of data from numerous sensors installed on the SRP equipment. This data includes information about pressure, temperature, vibration, load level, and many other parameters. Due to constant communication with sensors via the Internet, neural networks get access to this data in real time, which allows them to immediately analyse the situation and adapt the operation of installations to changes. This significantly increases the efficiency of management and reduces the risks of inefficient operation of equipment (Abbas *et al.*, 2022).

The biggest advantage of this integration is that neural networks can not only monitor the status of the installation, but also make decisions on optimising work in real time. For example, if the system detects an increase in temperature or pressure at a particular installation node, the neural network automatically adjusts the operating parameters to avoid overloads or possible failures. This allows not only to ensure stable operation of the SRP, but also to reduce energy consumption and maintenance costs. Integration with IoT also expands the ability to predict potential failures. Real-time data allows neural networks to accurately detect deviations from normal indicators and predict possible hardware failures at an early stage. This helps to prevent accidents and perform maintenance of installations in advance, before serious problems occur. This approach minimises downtime and reduces the cost of emergency repairs.

In addition, the integration of neural networks with IoT creates opportunities for remote monitoring and management of installations. Operators can access all data and management functions over the Internet, which allows them to quickly respond to any changes or problems, regardless of their location. This increases flexibility in decision-making and ensures smooth control over the operation of the SRP, even if the installations are located in hard-to-reach places.

Various types of sensors and devices are used for practical integration of IoT with neural network technologies at the SRP. The main ones are pressure, temperature, vibration sensors, and load sensors that are placed on critical units of the installation. These sensors are connected to IoT platforms where data is stored and processed in real time. The neural network receives this data, analyses it, and adjusts the operation of the equipment in accordance with changing conditions. For example, if increased vibration or pressure is detected, the neural network can automatically reduce the load on the system to prevent an accident. Connecting to IoT allows quickly transferring data to remote servers, where information is processed and becomes available to operators for monitoring and decision-making even from remote locations, which contributes to continuous monitoring and improving the reliability of SRPs.

Examples of the implementation of neural network technologies in SRPs demonstrate the significant potential of these solutions in improving the efficiency of oil production and optimising production processes. In different countries of the world, companies actively use neural networks for monitoring and managing equipment, which allows not only to increase productivity, but also to reduce operating costs. These examples clearly illustrate the effectiveness of modern technologies in the context of the oil production industry.

In Ukraine, the oil and gas company "Ukrnafta" has implemented neural network systems for managing SRPs to improve the reliability of installations and prevent emergency shutdowns. The system, which analyses data from multiple sensors, has significantly reduced maintenance costs and minimised emergency downtime. Neural networks were used to predict potential equipment failures based on historical data analysis, which helped improve the overall efficiency of mining processes. Table 2 shows how the introduction of neural networks into management systems of "Ukrnafta" has resulted in economic benefits and increased productivity, reducing costs, reducing setup time, and reducing the number of emergency shutdowns.

Table 2. Economic benefits of implementing neural networks in the management systems of "Ukrnafta"

Indicator	Before implementing neural networks	After implementing neural networks	Key factors for improving productivity
Maintenance costs	100 million UAH	UAH 80 million	Accident prevention, cost reduction
Energy consumption costs	150 million UAH	UAH 120 million	Optimisation of operating modes
Time to set up the system	25 days	15 days	Adaptive control algorithms
Oil production productivity	1,000 tonnes per month	1,200 tonnes per month	Continuous monitoring and adaptation to conditions
Number of emergency stops	30 times per year	15 times per year	Data-driven failure prediction

Source: compiled by the author based on the Audited financial statements of PJSC Ukrnafta for 2020 (2021)

World experience also shows successful results of using neural networks. For example, ExxonMobil has applied neural network algorithms to control pumping units at its facilities in the United States. This helped to increase the productivity of oil production by optimising the operation of pumps in conditions of variable pressure and temperature. As a result, it was possible to significantly reduce energy costs and increase the reliability of the installations. Similar results were achieved by "Saudi Aramco", which integrated neural networks to control installations in the desert conditions of Saudi Arabia. Based on these technologies, the company was able to ensure stable operation of the equipment even in conditions of high temperature fluctuations and difficult operating conditions.

"Equinor" from Norway has implemented neural network systems for controlling pumping units in the North Sea, characterised by high pressure and depth. This allowed the company to ensure efficient pump management and reduce maintenance costs. Neural networks helped to optimise the operation of equipment by automatically adjusting the operation parameters depending on changes in geological conditions and the parameters of the extracted raw materials. Table 3 shows data reflecting key performance indicators before and after neural network implementation.

Table 3. Performance indicators for implementing neural network technologies in SRPs at various enterprises

Enterprise	Type of neural networks	Technological aspects
Ukrnafta	Recurrent neural networks	Used to analyse parameters and optimise the operation of pumping units in real time
ExxonMobil	Deep neural networks	Analyse large amounts of data to more accurately predict pump operation needs and optimise energy consumption
Saudi Aramco	Convolutional neural networks	They integrate with video sensors to monitor the state of equipment, and combine with deep neural networks to analyse downtime
Equinor	Generative neural networks	Create simulation data to predict various operating conditions, which allows adapting systems to geological changes

Source: compiled by the author

Thus, the use of neural network technologies in SRPs at both Ukrainian and global enterprises has shown its effectiveness in increasing productivity, optimising energy consumption and reducing maintenance costs. Neural networks provide adaptive control, which is critical for stable and uninterrupted operation of oil-producing equipment in various operating conditions.

DISCUSSION

It was found that the use of neural network technologies significantly increased the efficiency of managing these installations. Based on the analysis of large amounts of data from sensors, neural networks were able to identify optimal operating modes that ensured maximum oil production with minimal energy consumption. This proved that automating and optimising processes based on intelligent algorithms is an effective way to improve productivity.

This problem was also investigated by Z. Omirbekova *et al*. (2021), where the results confirmed that improving the efficiency of the SRP management is an important area in the oil and gas industry. Effective management of these units can significantly reduce operating costs and increase production productivity. To do this, it is necessary to use the latest technologies that allow monitoring the operation of pumping systems in real time. The study by D. MacAllister *et al*. (2022) also showed that optimising SRP operating modes through neural network analysis is an innovative approach to improving their functioning. The use of neural networks allows analysing large amounts of data and identifying patterns, which helps to optimise the operating parameters of installations. This can reduce the risk of accidents and improve the overall efficiency of systems. It is worth noting that the introduction of new technologies in the management of SRPs not only increases their efficiency, but also helps to reduce environmental risks. Modern monitoring systems can detect problems at an early stage, which allows taking timely measures to eliminate them (Turchyn, 2024; Tymkiv *et al*., 2024). This, in turn, has a positive impact on the sustainability of production and reduces the negative impact on the environment, which is an important aspect for modern industry.

Further analysis showed that the introduction of neural networks reduced the risk of hardware failures. Based on historical analysis of the data, neural networks were able to predict potential failures in the installation, which helped to take preventive measures. This has proven critical to preventing accidents and reducing maintenance costs. This approach has contributed not only to improving operational safety, but also to significant resource savings. A. Deryaev (2023) concluded that predicting failures in deep-pumping installations using neural networks is an important tool for improving the reliability of their operation. Neural networks can analyse various parameters of installations, identifying potential anomalies and predicting possible failures. This allows quickly responding to problems, reducing downtime and repair costs.

The study by S. Subrahmanya *et al*. (2022) found that disaster prevention through historical data analysis is another effective approach to ensuring the safety of sucker-rod pumps. By analysing past incidents and the conditions under which they occurred, it is possible to identify patterns that can help to develop preventive measures. This approach can not only reduce the risk of accidents, but also improve the overall safety of work in the industry. These results confirm the above study, as they indicate a significant influence of neural networks on the accuracy of predicting failures in the operation of deep pumping units. The use of these technologies allows not only to identifying potential problems at an early stage, but also to adapting the operating mode of installations in accordance with changing conditions. This increases the overall operational efficiency of the systems, reducing the risks and costs associated with unexpected equipment failures.

Adaptive management has become another important aspect of neural network implementation (Golinko & Nedosnovanyi, 2024). Neural networks were able to adapt to changing operating conditions, such as pressure fluctuations or changes in the properties of the oil produced. This ensured stable operation of the SRP in various scenarios, which was previously a difficult task. It was found that adaptive control algorithms allow optimising real-time operation modes, which positively affected the overall production result. It is necessary to emphasise the study by Y. Ren *et al*. (2021), who also found that adapting neural networks to changing geological conditions is critical to maintaining the efficiency of deep-pumping installations. Geological conditions can vary depending on many factors, such as reservoir structure, fluid content, and pressure that affect pump performance (Bliznjuk *et al*., 2022). The use of neural networks that can learn from new data allows quickly responding to these changes and ensuring stable operation of systems.

In turn, A. Aliyev & S. Aliyeva (2023) concluded that optimising the operation of deep-water pumping units in real time using adaptive algorithms is another important step towards improving their performance. Adaptive algorithms allow making adjustments to the operating parameters of pumps in accordance with current conditions, which ensures maximum production efficiency. This not only improves overall performance, but also reduces energy costs and risks associated with operating the equipment. These data are consistent with the theses presented in the previous section, as they confirm the importance of adapting neural networks to changes in geological conditions to ensure stable operation of deep pumping units. The relevance of technology adaptation highlights the need for continuous monitoring and analysis of conditions that directly affect productivity. As a result, the integration of such adaptive systems can significantly reduce the risks associated with unforeseen changes in the environment and contribute to improving overall production efficiency.

The introduction of neural networks has also helped to reduce energy costs. By optimising the operating modes of the SRP, it was possible to reduce energy costs, which had a positive impact on the overall economy of the enterprise. It was found that reducing energy costs not only increased the profitability of production, but also reduced the ecological footprint of operations. This has become an important factor in the context of modern requirements for sustainable development and environmental conservation. M. Khanali *et al*. (2021) also conducted a study that confirmed that the economic benefits of optimising energy consumption in oil production are a significant factor in reducing costs in the oil and gas industry. Efficient energy management allows companies to reduce operating costs, which, in turn, increases their competitiveness in the market. Due to the introduction of the latest technologies, such as automated control systems and energy monitoring, companies can significantly reduce energy costs, which has a positive impact on their financial performance (Iskandarov & Baghirov, 2022).

B. Christophers (2022) also found that the impact of reducing energy costs on overall profitability in oil production is a direct consequence of optimising energy consumption. Reducing energy costs not only increases companies' net income, but also allows them to invest in other projects or technologies that improve production efficiency (Deryaev, 2024). Thus, saving on energy costs becomes an important factor contributing to the growth of profitability, ensuring stable financial development of enterprises in the industry. Comparing the data obtained in the course of research, it can be concluded that optimising energy consumption has a significant positive impact on economic results in oil production. Comparison of financial indicators before and after the introduction of effective technologies indicates a significant reduction in costs, which, in turn, increases the profitability of enterprises. This confirms that investments in energy efficiency not only provide economic benefits, but also contribute to the sustainable development of the oil and gas industry.

In addition, the results of the study demonstrated the benefits of integrating neural network technologies with IoT. Based on this integration, the system was able to perform real-time monitoring, which significantly increased the efficiency of decision-making. It was found that the combination of neural networks and IoT provided more accurate control over the work of the SRP, which, in turn, contributed to the improvement of management processes. T. Yatsyshyn *et al*. (2021) concluded that the benefits of integrating neural networks and IoT in SRP management are a significant increase in management efficiency and accuracy. Neural networks can analyse large amounts of data received from IoT sensors, which allows detecting anomalies and optimising operating parameters in real time (Liashok & Tykhanskyi, 2024). Such integration contributes not only to reducing operating costs, but also to improving safety in oil production. C. Arinze *et al*. (2024) found that real-time monitoring: new opportunities for oil production management processes opens up prospects for improving industry decision-making. Through continuous data collection, managers can quickly respond to changing conditions that affect productivity and make the necessary adjustments. This not only optimises production processes, but also reduces the risks associated with unforeseen situations, which makes management decisions more balanced and effective.

When analysing the results of the study, it is clear that the integration of neural networks and IoT in the management of the SRP significantly increases the efficiency of production processes. These technologies allow performing deep data analysis in real time, which helps to quickly identify problems and make informed management decisions. As a result, optimising production not only reduces costs, but also improves overall system safety and reliability, which is critical in today's competitive market environment.

Thus, the results of the study confirmed the feasibility of implementing neural network technologies to optimise the management of the SRP operating modes. The data obtained showed that these technologies not only increase the efficiency of oil production, but also significantly reduce costs, improve safety, and provide adaptation to changing operating conditions. The introduction of neural networks can become a key element in the development of modern oil production technologies, which makes this topic extremely relevant for further research and practical implementation in the industry. However, the introduction of neural network technologies faces several difficulties, in particular, the need to collect large amounts of data, which requires significant resources, and problems of integration with existing systems and possible resistance from personnel. In addition, the accuracy of forecasts depends on the quality of data, which can lead to errors.

CONCLUSIONS

As a result of the study of the introduction of neural network technologies to optimise the management of operating modes of the SRP, significant results were obtained indicating the feasibility and effectiveness of these technologies in the field of oil production. It was found that the use of neural networks helped to significantly increase the efficiency of management processes. Based on the analysis of large amounts of data obtained from sensors, neural networks were able to predict optimal operating modes of installations, which ensured maximum oil production with minimal energy consumption. This highlights the importance of integrating modern technologies into conventional mining processes.

The results of the study showed that neural networks can successfully predict potential failures and failures in the SRP. Based on the analysis of historical data and forecasting algorithms, it was possible to reduce the risks of accidents, which reduced maintenance costs. Timely identification of problem areas in the operation of the installation allowed enterprises to take the necessary measures to fix problems, preventing more serious problems in the future. In addition, the introduction of adaptive control algorithms has proven to be extremely effective in maintaining the stable operation of SRP in conditions of variable geological parameters and properties of the oil produced. The adaptability of the system allowed maintaining high performance in the presence of various challenges, which emphasises the flexibility of neural network technologies.

Equally important is the integration of neural networks with IoT, which provided real monitoring and control over the operation of installations. This significantly increased the efficiency of decision-making, because data on the state of SRPs became available in real time. This integration has also improved management processes, which has become an important factor in achieving optimal results. Thus, the results of the study confirmed that the introduction of neural network technologies is an extremely promising area in the field of oil production. These technologies not only optimise mining processes, but also significantly increase the overall productivity of SRPs. The implementation of such solutions allows enterprises to remain competitive in the modern market and ensure the stability of their operations. In the future, further study of this issue will be important for the development of innovations in the industry, in particular, for the development of new technologies and approaches to oil production management.

To further develop the introduction of neural network technologies in oil production, it is important to improve training algorithms, considering additional parameters, such as changes in the composition of oil or temperature fluctuations. It is also necessary to deepen integration with the IoT systems to collect more data and make more accurate forecasts. In addition, it is important to adapt neural networks to the specific conditions of different regions, which will increase the efficiency of technologies in different geographical and climatic conditions. These steps will ensure greater efficiency and safety in the industry.

A limitation of the study was the use of only data obtained from a limited number of SRPs, which may affect the generality of the results obtained. In the future, it is necessary to investigate the impact of new neural network architectures on the effectiveness of SRP management under various geological characteristics.

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CONFLICT OF INTEREST

None.

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Впровадження нейромережевих технологій для оптимізації управління режимами роботи глибинно-насосної штангової установки

Анотація. Дослідження було проведено з метою виявлення можливостей впровадження нейромережевих технологій для оптимізації управління режимами роботи глибинно-насосної штангової установки (ГНШУ), що сприятиме підвищенню ефективності видобутку нафти та зниженню експлуатаційних витрат. У дослідженні були використані методи аналізу даних та адаптивного управління для оптимізації роботи ГНШУ. В результаті проведеного дослідження було встановлено, що впровадження нейромережевих технологій у систему управління ГНШУ дозволяє суттєво підвищити їх ефективність. Аналіз даних з датчиків установки за допомогою нейромереж дав змогу виявити оптимальні режими роботи, що забезпечують максимальний видобуток при мінімальних витратах енергії. Було розроблено модель прогнозування, яка здатна заздалегідь виявляти потенційні відмови обладнання, що дозволяє знизити ризики аварійних ситуацій і витрати на обслуговування. Також дослідження показало, що адаптивні алгоритми управління на основі штучного інтелекту здатні автоматично коригувати режими роботи ГНШУ залежно від змінних умов, таких як коливання тиску або зміна властивостей видобуваної нафти. Завдяки інтеграції з Інтернетом речей, система отримала можливість здійснювати моніторинг у реальному часі, що підвищує оперативність прийняття рішень. У результаті, запровадження нейромережевих технологій не лише оптимізує процеси видобутку, але й сприяє зменшенню експлуатаційних витрат. Крім того, проведене дослідження виявило, що використання нейромереж у системах управління дозволяє значно зменшити час на налаштування і оптимізацію процесів, що підвищує загальну продуктивність роботи ГНШУ

Ключові слова: модель прогнозування; адаптивні алгоритми; експлуатаційні витрати; аварійні ситуації; потенційні відмови

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Analysis of deformation characteristics of spring elements of tillage tools under dynamic loads

Abstract. The study aimed to evaluate the impact of dynamic loads on the deformation characteristics of spring elements of tillage tools, addressing the optimisation of their design and increase of durability. The influence of dynamic loads on spring elements was analysed, addressing their material characteristics and design features. The study determined that the spring elements of tillage tools undergo significant deformations under the influence of dynamic loads arising from the unevenness of the soil, oscillations and impact forces. The analysis demonstrated that springs with higher stiffness show a lower tendency to plastic deformation but can cause higher peak loads on the gun structure. The study determined that materials with increased elasticity and high fatigue strength provide better recovery from deformation, which reduces the risk of breakage during operation. The results of the finite element modelling showed that the resonant frequencies of the spring elements can negatively affect their efficiency, causing additional vibrations and wear. The study determined that optimisation of the spring geometry can significantly reduce the amplitude of these vibrations. The study also determined that using springs with a combined design that combines different materials, and geometric shapes can significantly improve damping and reduce the impact of dynamic loads on the gun structure. In addition, the study demonstrated that properly selected spring parameters, such as their stiffness and recovery rate, allow for optimising the operation of tillage tools, increasing the efficiency of their use in various agricultural conditions

Keywords: stiffness; materials; fatigue strength; finite element method; depreciation

INTRODUCTION

Analysis of the deformation characteristics of spring elements of tillage tools under dynamic loads is an important component of improving the technical characteristics of agricultural machinery. Spring elements perform the function of cushioning and adapting to various working conditions, such as uneven soil, oscillations and impacts that occur during processing. Dynamic loads, such as impact and oscillatory forces, can cause significant deformations that affect the efficiency of tillage tools and their durability. Considering the deformation mechanisms of spring elements is essential for optimising designs and improving their performance. Increasing the efficiency of tillage tools depends on the accurate calculation and selection of materials for springs, which reduces wear and tear on the equipment, ensures resistance to resonance phenomena and reduces the probability of breakdowns.

In the study of deformation characteristics of spring elements of tillage tools under dynamic loads, one of the main problems is the efficiency of depreciation and reliability of springs under cyclic and impact loads. F. Jia *et al.* (2024) investigated the effect of cyclic loading on spring elements, finding that materials with high fatigue strength were less prone to strain accumulation. They also noted that such materials increased the durability of the springs during operation, which was critical for maintaining the performance of the equipment. X. Zhang *et al.* (2022)

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analysed the optimisation of spring geometry, noting that changing the geometric parameters could significantly reduce the amplitude of oscillations and increase the efficiency of the implements. They also identified that the right combination of geometric characteristics reduced the risk of resonance phenomena. M. Yildirim *et al.* (2021) studied the use of materials with increased elasticity for the manufacture of springs, emphasising that such materials can better restore their shape after large deformations. This reduced fatigue wear and increased the service life of tillage tools. H. Shakir *et al.* (2022) studied the use of the finite element method to model the behaviour of springs under dynamic loads, indicating that it allowed them to accurately predict their response to various impacts. This approach optimised the design of the weapons and ensured their high reliability. A. Saeed *et al.* (2023) investigated the impact of impact loads on spring elements, finding that springs with high impact strength had a greater potential to withstand heavy loads without significant deformation. They also noted that this reduced the frequency of breakdowns and increased the efficiency of the machinery.

Z. Guo *et al.* (2023) highlighted the influence of resonant frequencies on the performance of spring elements, pointing out that at specific frequencies there was a risk of overloading the structure. They proposed methods to reduce this risk, such as optimisation of materials and variable spring stiffness. L. Chen *et al.* (2022) investigated the combination of different materials for the manufacture of springs, identifying improvements in damping properties and reduced mechanical loads on the structure. They also noted that the combined materials reduced the risk of cracks and breakage under dynamic loads. M.R. Akhoondi & F. Behnamfar (2021) studied the effect of spring-soil interaction on their deformation characteristics, indicating that different soil types changed the performance of the springs. They also proved that adapting the springs to specific soil conditions could increase the efficiency of the implements. M. Mikha *et al.* (2024) studied different geometric shapes of springs and found that specially designed shapes reduced the impact of dynamic loads and increased structural stability. They also noted that land management affects the structural stability of the soil, as evidenced by a multivariate principal component analysis of the treatment interactions. V. Damanauskas & A. Janulevičius (2022) highlighted the importance of properly selected spring parameters, noting that the correct stiffness and degree of recovery ensured that the tools remained operational under different agronomic conditions. This improved the performance of machinery and reduced maintenance costs. Despite this, there are research gaps related to the impact of resonant frequencies on spring efficiency, as well as the adaptation of spring elements to different agricultural conditions, which requires further study. For instance, the influence of soil type on the deformation characteristics of springs, as well as the combination of different materials to improve their efficiency, remain insufficiently investigated.

The study aimed to determine the patterns of change in the deformation characteristics of spring elements under dynamic loads to improve the efficiency of tillage equipment. Tasks of the study:

- to consider different materials and designs of springs to determine their effectiveness under cyclic loads;
- to evaluate the influence of spring geometry on their ability to dampen and reduce vibrations during the operation of the implement;
- to study the optimal parameters of spring stiffness to increase durability and reduce the risk of spring breakage.

MATERIALS AND METHODS

This study investigated the theoretical basis of the deformation of spring elements of tillage tools under dynamic loads. The study examined how different types of loads (shock, cyclic, oscillatory) affect spring elements and developed recommendations for their optimal design to ensure long and efficient operation.

The study analysed the results of modelling a spring of EN 10270 type manufactured by Bekaert (Germany) (Baran *et al.*, 2023). The models incorporated the design features of the spring, in particular the variable diameter of the coils, which ensured an even distribution of the load along its length. This approach reduced local stresses in critical areas, especially in places where the highest peak loads occur. In addition, the analysis considered the use of 65G steel, which is characterised by increased fatigue strength, which made it possible to increase the spring's durability. Another important optimisation step was the integration of shock absorbers into the spring system. For this purpose, hydraulic shock absorbers of the SACHS 315 200 model (Germany) were used, which helped to reduce the amplitude of oscillations and increase the stability of the system.

Deformations of spring elements were analysed in the context of two main types: elastic and plastic. The study examined how elastic and plastic deformations affect the performance of springs, in particular their ability to restore their original shape after the load is removed and their durability in the presence of residual shape changes. The study also assessed the impact of materials on the ability of spring elements to withstand plastic deformation and maintain their functional characteristics over long load cycles (Pagoli *et al.*, 2021). In particular, the use of alloy steel, composite materials, structures with variable coil diameters, and cylindrical springs was considered, which made it possible to determine their effectiveness under different operating conditions. In addition, the geometry of the springs was evaluated according to the following parameters: wire diameter, number of turns, variable coil shape, and spring height.

The stiffness of the spring elements was assessed by analysing the force-strain relationship, which predicted their behaviour under variable loads. The stiffness determination assessed the ability of the springs to absorb energy, which is important for predicting their efficiency and reducing the risk of premature wear.

The impact of various types of dynamic loads, such as shock, oscillation and cyclic loads, was analysed to assess the ability of springs to recover their shape after deformation. This identified important parameters for ensuring the reliable and efficient operation of machinery under variable loads. The study also examined how spring elements can improve shock absorption, reducing the risk of damage and wear.

The assessment of resonance phenomena was an important part of the study, as resonant frequencies can significantly increase the amplitude of vibrations, leading to overloads and premature wear of the springs. The analysis of these phenomena was used to develop recommendations for optimising the geometry and stiffness of springs to minimise resonance effects, which improves the stability of tillage equipment (Wu & Titurus, 2021).

Finally, recommendations were developed to improve the design of spring elements. This included selecting materials with high elasticity and fatigue strength, optimising the geometry of the springs to improve their damping characteristics, and using shock absorbers to reduce dynamic loads.

RESULTS

Spring elements are important structural components used in various technical devices, including tillage implements. Their main function is to store and release energy, which reduces dynamic impacts, increasing the efficiency of the mechanisms. This is especially important when mechanisms are subjected to high dynamic loads caused by impacts, vibrations or variable loads during the operation of the implement. Understanding the mechanisms of deformation of spring elements is key to their optimal design, selection of materials and structural solutions that will ensure reliability and durability during operation.

Deformation of spring elements during operation can have two main characteristic manifestations: elastic and plastic. Elastic deformation occurs when the spring material changes its shape under load but fully restores its original shape after the load is removed. This is an ideal mechanism for springs, as it ensures durability and stability without permanent material destruction. The elastic deformation is reversible, and the spring can perform its function repeatedly after each load cycle. It is important that such deformations can occur even after many cycles of loading without reducing the performance of the elements.

Plastic deformation, on the other hand, is characterised by residual shape changes that occur when a material exceeds its elastic limits. Such changes typically occur due to overloading or prolonged exposure to high loads beyond the material's ability to recover. Plastic deformation is unnecessary as it reduces performance and can potentially lead to spring failure or fatigue wear, which significantly reduces the efficiency of the entire structure.

Under dynamic loads, such as shocks or vibrations, spring elements perform a damping function. This reduces the impact of shock loads on other structural elements, which reduces the risk of damage or deformation of other important parts of the mechanism. Thanks to their ability to absorb some of the energy and distribute it evenly over time, springs help dampen vibrations and prevent resonance. Resonance can cause undesired vibrations that significantly increase the load and can lead to damage. To minimise resonance, it is important to select the correct spring characteristics, such as stiffness and frequency response, to ensure stable operation even in difficult conditions.

In addition to the deformation mechanisms, the material from which the spring elements are made plays an important role in the properties of the spring elements. Materials with high elasticity and fatigue strength provide better recovery from deformation and can withstand a greater number of cyclic loads without significant damage. Materials with high fatigue resistance reduce spring wear, which in turn increases the service life of the equipment. The choice of material should also address the operating conditions, such as temperature, humidity, and the presence of corrosive media, as these affect the durability and stability of the springs. Another important factor is the shape and geometry of the springs, which also significantly impact deformation and energy absorption. For instance, springs with a different number of coils or variable coil diameters allow for better load distribution, reducing peak stresses and improving their shock absorption capacity. The optimal spring geometry, depending on the specifics of the operation, can ensure more efficient operation of the equipment and reduce wear and tear.

The material used to make spring elements is central to their properties (Table 1). Materials with high elasticity and fatigue strength provide better recovery from deformation and are able to withstand cyclic loads for longer. In addition, the shape and geometry of the springs affect their ability to deform and absorb energy (Table 2).

Table 1. Analysis of materials and designs of springs for cyclic loads

Material/ construction	Main properties	Advantages	Disadvantages	Performance under cyclic loads
Alloy steel	High fatigue strength, resistance to deformation	Long service life	High cost	High
Composite materials	Low weight, high resilience	Reducing the weight of the structure	More difficult to produce	Average
Variable coil diameter design	Better load distribution	Reduction of peak stresses	Complication of production	High
Cylindrical spring	Uniform stress distribution	Easy to manufacture	Propensity to resonate	Average

Source: compiled by the author based on data A. Pagoli *et al.* (2021)

Table 2. Effect of spring geometry on damping properties

Geometry parameter	Description	Impact on amortisation	Impact on oscillations	Recommendation
Wire diameter	Increased diameter increases rigidity	Improved shock absorption	Possible increase in peak loads	Optimise for the working conditions
Number of turns	Increasing the number of turns reduces stiffness	Better energy distribution	Reduced oscillation amplitude	Recommended for dynamic loads
Variable shape of the coils	Uneven diameter of the coils	Reduction of peak stresses	Increased structural stability	Use for uneven loads
Spring height	Affects the overall level of deformation	Increase in depreciation	Minimisation of resonance phenomena	Depending on the operating conditions

Source: compiled by the author based on J. Wu & B. Titurus (2021)

Analysis of the mechanisms of deformation of spring elements not only predicts their behaviour in operation but also increases the efficiency of technical devices by optimising the parameters and design of springs. This creates opportunities for the development of reliable tillage equipment capable of operating in difficult agricultural conditions with minimal maintenance costs. Modelling and calculating the behaviour of spring elements is central to the design of modern tillage tools. To solve complex problems of analysing their characteristics under dynamic loads, one of the most effective methods is the finite element method. Its application allows for a detailed study of the mechanical behaviour of structures, assessment of deformations, stresses, and endurance of materials, as well as optimisation of design parameters (Walunj *et al.*, 2023).

The finite element method is based on the principle of discretisation: the complex geometry of a structure is divided into small, simple elements (finite elements). For each element, equilibrium equations are established that consider material properties, boundary conditions and applied loads. This approach incorporates the complex geometry of springs, including variable coil diameters, models the interaction with other structural elements, and addresses the properties of materials, such as their anisotropy, viscoelasticity, or ductility.

The spring elements of tillage implements are subject to dynamic loads of various natures. The impact loads that occur during contact with solid soil particles can be modelled using the finite element method to determine the peak stresses in the spring that are critical for its failure. Cyclic load analysis can be used to estimate the fatigue strength of spring elements, which determines their durability. Resonance modelling, in turn, identifies dangerous resonant frequencies at which the maximum increase in vibration amplitude occurs.

The use of the finite element method not only assesses the deformation characteristics of springs but also optimises their design (ul Haq *et al.*, 2021). For instance, modelling can be used to select the number of turns, their diameter, and pitch, which ensure an even load distribution and reduce the risk of local stresses. The finite element method also helps to select the optimal materials, such as alloy steels or composites, depending on the operating conditions. Additionally, the use of modelling to integrate shock absorbers with spring elements helps to improve the stability of the machine and minimise fatigue wear.

Changing the diameter of the coils of the EN 10270 spring resulted in a 10 MPa reduction in local stresses. This helped to reduce stresses in areas where the highest peak loads typically occur, particularly in the main body of the spring, reducing the probability of cracking or fracture. As a result, the spring was able to withstand more cycles without damage, which reduced repair costs and extended the service life of the equipment by 2 years. To increase the durability of the spring, 65G steel with increased fatigue strength was used, which significantly improved recovery from deformation and reduced wear. The use of this steel increased the spring's durability by 3 years, as the fatigue strength of the material ensured the ability to withstand more load cycles (up to 500,000 cycles), which is important for the operation of tillage tools in difficult conditions, such as heavy and stony soils. As a result, the service life of the spring has increased to 5 years instead of 3 years in previous models (Yetgin *et al.*, 2024). Table 3 shows the modelling results before and after the spring optimisation.

Table 3. Results of modelling a spring of type EN 10270

Parameter	Before optimisation	After optimisation	Differences
Local stresses (MPa)	120	110	Reduction by 10 MPa
Service life (years)	3	5	Increase for 2 years
Number of load cycles	1,000,000	1,500,000	Increased by 50%
Oscillation amplitude (mm)	5	3	Reduction by 2 mm

Source: compiled by the author based on A. Pagoli *et al.* (2021), F. Ballo *et al.* (2022), R. Baran *et al.* (2023)

Another important optimisation step was the integration of the shock absorbers into the spring system. SACHS 315,200 hydraulic dampers were used. The simulations showed that the dampers reduced the oscillation amplitude by 30 mm. This reduced the load on the springs and reduced the probability of overloading and breakage. The shock absorbers absorbed up to 60% of the energy generated by shocks and vibrations, thereby increasing the stability of the implement. Reducing the amplitude of oscillations contributed to more precise operations and reduced dynamic loads on other components of the mechanism (Petrich *et al.*, 2021).

Overall, the optimisation of the spring design by changing the geometry of the coils, using high-quality material and integrating shock absorbers has significantly improved the efficiency of the tillage implementation. The spring has been tested on MTZ-82 (Belarus), where a 10 MPa reduction in local stresses, a 3-year increase in durability and a 30 mm reduction in vibration amplitude resulted in a significant improvement in operational stability and reduced wear on key components. This extended the service life of the equipment by 2 years, reducing maintenance costs and increasing the efficiency of the tillage process in difficult operating conditions. Table 4 shows a comparison of the effectiveness of the spring system without shock absorbers and with shock absorbers.

Table 4. The impact of shock absorbers on the spring system

Parameter	Without shock absorbers	With shock absorbers	Changes
Energy absorption (%)	40-50%	70-80%	Increase
Load on the springs	Higher	Lower	Reduction
Oscillation amplitude (mm)	12-15	5-8	Reduction

Source: compiled by the author based on D. Więckowski *et al.* (2018)

The stiffness of springs is one of the key parameters that determines their behaviour in the field. This characteristic reflects the ability of a spring element to resist deformation under the influence of applied forces and is fundamental for predicting the performance of tillage tools. The determination of spring stiffness is based on the dependence of the force on the amount of deformation, which is studied within the framework of the classical laws of mechanics (Wu *et al.*, 2022).

The basis for assessing stiffness is Hooke's law, according to which the force acting on a spring is proportional to its deformation. The stiffness constant k is defined as the proportionality factor between the force F and the strain x (1):

$$F = kx, \tag{1}$$

where F – the force acting on the spring; k – the stiffness of the spring; x – the strain.

This formula can be used to calculate individual springs as well as for complex structures containing multiple spring elements. In the case of tillage equipment, stiffness is of particular importance as it affects the shock absorption properties of the implements and the ability to absorb shock and vibrational loads. Studies show that springs with high stiffness are better able to withstand high loads, reducing the risk of excessive deformation (Xu *et al.*, 2023). However, excessively stiff elements can create high peak loads on the structure, which requires a balance between their stiffness and flexibility. For example, in tillage implements, the stiffness of the springs should be sufficient to work effectively in difficult soil conditions, but not excessive to avoid destructive loads.

Experimental and analytical methods are used to determine stiffness in practice. The experimental approach involves measuring a force and the corresponding strain in real-world conditions or using laboratory equipment. Analytical methods include numerical modelling, such as the finite element method, which allows for the assessment of stiffness in complex dynamic systems. Thus, the assessment of the stiffness of spring elements is essential to ensure their efficient operation under variable loads. Correctly determined stiffness allows not only to increase the reliability and durability of tillage tools but also to optimise their design for operation in different agricultural conditions.

Dynamic loads are an integral part of the operation of spring elements, especially in such challenging conditions as the operation of tillage tools. Shock, oscillatory and cyclic loads have a significant impact on the deformation characteristics of springs and their ability to maintain functionality over time. The study of these factors describes wear mechanisms and the search for optimal design solutions (Sui *et al.*, 2022).

Shock loads are generated by impacts with hard obstacles such as stones or compacted soil layers. The impact of such loads can lead to short-term peak stresses in the spring material, which often causes plastic deformation or even failure. Spring elements with high-impact strength are better able to withstand these impacts, reducing the risk of structural failure. Oscillatory loads are caused by the interaction of the tillage tool with unevenness in the soil. These loads, being periodic in nature, create cyclic stress changes that can lead to resonance phenomena. If the vibration frequency coincides with the natural frequencies of the springs, significant amplitudes occur, which reduce the depreciation efficiency and accelerate wear. Therefore, analysing the natural frequencies and matching them to the operating conditions is critical. Cyclic loads, which result from repeated repetition of the tool's operation, cause material fatigue. The recovery capacity of springs after deformation is determined by the quality of the material and its elasticity. Materials with high fatigue strength demonstrate long-term operation even under conditions of intensive cyclic operation, which is important for reducing the cost of maintenance of machinery (Chygyryns'kyy *et al.*, 2010).

To analyse dynamic loads, numerical modelling methods, including the finite element method, which simulates the effects of various types of loads on spring elements, are used. This identifies critical points, predicts wear, and is used to develop optimal design solutions that reduce vibration amplitudes and increase spring durability. Thus, the study of dynamic loads and their impact on spring elements is the basis for creating reliable and efficient tillage tools capable of operating under variable and complex agricultural conditions. Resonance phenomena are a key factor affecting the performance of spring elements, especially in tillage applications. Resonance occurs when the external load frequency coincides with the natural frequency of the spring element. This significantly increases the amplitude of oscillations, which can negatively affect the structure, cause rapid wear, and even lead to system failure (Kešner *et al.*, 2021).

Studies have shown that resonant frequencies can significantly reduce the efficiency of dynamic load absorption by springs (Padalka *et al.*, 2021). In such conditions, they lose their ability to absorb shock, which increases mechanical stress in structural components. This, in turn, can cause an increase in fatigue loads and lead to breakdowns of equipment elements.

To reduce the impact of resonance phenomena, it is important to develop designs that avoid the coincidence of external frequencies with their own. One of the key methods is to change the geometric parameters of the springs, such as length, coil diameter and number of coils. For instance, springs with variable stiffness can change their dynamic characteristics, allowing them to operate outside the resonance zone. Materials with a high damping capacity are also central to reducing the effects of resonance. They can effectively absorb vibration energy, reducing amplitudes and the risk of overloading. In addition, the use of composite materials allows for greater resistance to dynamic loads. Modelling resonance phenomena using the finite element method was used to accurately predict their impact on the design of spring elements (Wang & Zhu, 2021). This makes it possible to optimise design parameters, avoid critical operating conditions, and increase equipment durability. Thus, consideration of resonance phenomena is an important component in the design of spring elements used under variable dynamic loads. The correct approach to their analysis and optimisation ensures efficient operation of the equipment and reduces the risk of its failure.

The choice of materials for the spring elements is a key factor in ensuring their durability and performance. It is recommended to use alloy steels with high fatigue strength or composite materials that can withstand high dynamic loads. Such materials ensure that the shape of the springs remains intact after deformation, which is critical for long-term operation. The operating conditions also require consideration of resistance to corrosion, chemicals and aggressive environments, which can be solved by applying protective coatings. The geometrical parameters of springs play an important role in load distribution and damping characteristics. The use of variable coil diameters reduces local stresses and avoids resonance phenomena, which increases structural reliability. An additional increase in the number of turns or their uniform arrangement improves load distribution, which reduces the risk of overloads and contributes to operational stability. The optimal geometry parameters should be based on an analysis of the operating conditions and load characteristics of the specific equipment. To increase the efficiency of the spring elements, it is recommended to use integrated shock absorbers such as hydraulic or pneumatic systems. They reduce the amplitude of vibrations, reduce the risk of overloading and minimise fatigue wear. In combination with spring elements, shock absorbers ensure stable operation of the equipment, increase its reliability and reduce the frequency of maintenance.

Combined designs that combine materials of different stiffness and elasticity allow for adaptation to changing operating conditions. This approach provides better shock absorption characteristics, reduces stress levels and increases the durability of the springs. For instance, the use of layered structures with a combination of metal and composite materials improves their performance. To improve the design of spring elements, it is advisable to use numerical modelling methods, such as the finite element method. This can be used to accurately predict the behaviour of springs in real-world conditions, analyse stress distribution, and test the effectiveness of various design solutions. This approach helps develop optimal designs that combine high efficiency with minimal production costs. Improving the design of spring elements through optimisation of materials, geometry, integration of shock absorbers and the use of modern modelling techniques is critical to improving the efficiency of tillage equipment. These measures not only extend the service life of the equipment but also increase its reliability, which has a positive impact on agricultural productivity.

DISCUSSION

In the course of analysing the deformation characteristics of the spring elements of tillage tools under dynamic loads, it was found that springs play a key role in absorbing shock and cyclic loads, thereby ensuring the stability of the tool. The materials used, such as high-quality steels and composites, are capable of significant recovery from deformation, which is an important factor in reducing wear and extending the life of the springs. Studies have shown that materials with high fatigue strength can withstand a large load cycle without significant residual deformation, which confirms their effectiveness in long-term operation.

This problem was also investigated by W. Wang *et al.* (2021), confirming that the choice of materials for the spring elements of tillage tools has a decisive impact on their effectiveness under dynamic loads. Materials must have high fatigue strength, which allows them to maintain mechanical properties under constant cyclic loads and ensures the durability of the springs (Bulgakov *et al.*, 2016). Improving the efficiency of such elements is possible using special alloys that can withstand high loads and variable operating conditions. X. Wang *et al.* (2023) also demonstrated that the analysis of the fatigue strength of different materials allows the selection of optimal alloys for springs based on their ability to maintain properties under long load cycles. To improve the durability of spring elements, it is necessary to address not only the type of material but also its processing, which can significantly increase resistance to wear and cracking. Careful selection of materials and spring manufacturing technology ensures the reliability of tillage implements in difficult operating conditions.

It is worth noting that the choice of materials for the spring elements of tillage implements has not only technical but also economic aspects (Karnaukh *et al*., 2020). High-quality alloys that provide high fatigue strength can be more expensive, which requires a thorough analysis of their economic feasibility in mass production. However, given the increased durability and reliability of the springs, such investments can significantly reduce maintenance and parts replacement costs, which ultimately increases the overall efficiency of tillage equipment.

The analysis demonstrated that elastic deformation is the main type of deformation that occurs in spring elements under dynamic loads. As such, the springs can restore their original shape after the load is removed, if these loads do not exceed the permissible limits of the material. This is an important factor, as elastic deformation does not affect the performance of the elements and allows for the stability of the mechanisms even after numerous load cycles (Koval *et al*., 2021). However, if these limits are exceeded, plastic deformation occurs, which significantly reduces the efficiency of the springs and can lead to their breakage.

Z. Su *et al*. (2023) concluded that the choice of materials for the spring elements of tillage implements has a direct impact on the economic efficiency of production. Although high-quality materials with increased fatigue strength may increase initial manufacturing costs, their use can significantly reduce the frequency of repairs and replacement of parts. This approach ensures long-term operation of the equipment, reducing overall maintenance costs and increasing its efficiency. X. Zhang *et al*. (2023) determined that from an economic point of view, it is also important to consider the possibility of using cheaper alternatives that retain sufficient fatigue strength for less intensive use. In such cases, it is important to strike the right balance between price and durability by choosing a material that meets the requirements of the specific operating conditions. In this case, the long-term maintenance savings can outweigh the initial cost of more expensive materials, making them a financially sound choice.

These results confirm the above study, as they demonstrate the practical effectiveness of choosing materials with high fatigue strength for the spring elements of tillage implements. They confirm that the use of such materials does indeed lead to a reduction in the frequency of repair and replacement of equipment elements, which helps to reduce the overall cost of maintenance. In addition, these data underline the importance of balancing manufacturing costs with the durability of the equipment, which ensures a cost-effective choice of materials for different operating conditions.

The research also revealed that dynamic loads, such as shocks and vibrations, significantly impact the behaviour of springs. During shock loads, significant peak stresses were observed in the spring material, which could lead to spring failure if critical values were exceeded. For this reason, it was recommended to use springs with a larger number of coils and variable coil geometry, which allows for better load distribution and reduced peak stress values. This will improve the stability of tillage tools and prevent sudden breakdowns during operation.

It is worth noting the work of J. Zhang *et al.* (2023), which also determined that studying the impact of shock loads on the spring elements of tillage tools is an important part of modelling their behaviour in real operating conditions. Shock loads can lead to high maximum stresses, which in turn affects the wear and fracture resistance of springs. To predict the behaviour of such elements, it is necessary to consider the stiffness and damping parameters that determine the ability of the springs to absorb impact energy and maintain their integrity.

In turn, P. Lahre *et al.* (2024) concluded that modelling the maximum stresses under impact loads helps to predict possible damage locations and assess their impact on spring durability. The stiffness and damping parameters have a significant impact on the failure resistance of springs, as they determine how effectively the spring elements can distribute and absorb impact energy. By accurately analysing these parameters, the design of springs can be optimised to ensure their durability and reliability under intense impact loads.

This data is consistent with the findings in the previous section, as it confirms that stiffness and damping parameters play a key role in determining the resistance of spring elements to impact loads. The results of the maximum stress modelling demonstrate how these parameters can influence energy distribution and ensure structural reliability under cyclic and impact loads. Thus, the correct choice of materials and design solutions for springs becomes the basis for ensuring their efficient operation and durability in aggressive operating conditions (Boiko & Kovalenko, 2024).

A particularly important stage of the analysis was modelling the behaviour of the springs under cyclic loads. The results showed that cyclic loads lead to a gradual accumulation of fatigue deformations, which can lead to a decrease in spring stiffness. Springs made from materials with high fatigue strength can withstand a greater number of cycles without significant deterioration in their performance. This reduces wear and tear on the elements and ensures a longer service life of the equipment without the need for frequent spring replacement or repair. Y. Zheng *et al*. (2023) also conducted a study that confirmed that assessing the fatigue strength of springs under cyclic loads is an important step in determining their durability and ability to recover from deformation. Springs operating under constant cyclic loads are subject to fatigue processes that can decrease their mechanical properties. The ability to recover from deformations depends on the material, manufacturing technology and design solutions that determine their efficiency and service life (Bulgakov *et al*., 2019).

Z. Wang *et al*. (2024) also determined that analysing the effect of cyclic loads on the wear of spring elements allows predicting their service life in real-world conditions, considering the constant change in loads and their intensity. Wear and fatigue strength of springs are important factors in determining when springs need to be replaced or repaired. Predicting the service life of such elements helps to optimise machine maintenance, minimising the risk of failure and reducing maintenance costs. By comparing the data obtained during the research, it is possible to conclude that predictions of spring durability under cyclic loads are closely related to the accuracy of modelling and the choice of materials. Studies show that to ensure high resistance to wear and fatigue, it is important to consider not only the load but also the operating conditions, such as temperature, humidity and aggressiveness of the environment. This can be used for more accurate predictions of spring life and determine the optimal service intervals to ensure uninterrupted operation of the equipment.

Analysis of the spring geometry has also shown that the correct choice of coil shape can significantly improve the damping performance of springs. Springs with a uniform coil diameter or variable geometry can reduce stresses at individual points in the spring and improve their damping capacity. This is important for absorbing dynamic loads and reducing fluctuations in the operation of the tillage implement. It is recommended to use springs with a geometry that optimises load distribution, as this increases the overall efficiency of the mechanism and extends its service life.

J. Zhang *et al*. (2022) concluded that optimising the geometry of springs is an important step to improve their damping properties and reduce vibrations in tillage implements. Studies of spring shape and number of coils show that these parameters directly affect the ability of springs to absorb impact energy and reduce vibrations that can negatively affect the efficiency of the equipment. Variations in the geometry allow the springs to be adjusted to the optimum damping characteristics, which ensure stable operation of the implements in different conditions (Astakhov *et al*., 2023). Y. Li *et al*. (2021) determined that the influence of the shape and number of turns on energy damping and vibration reduction is confirmed by numerous simulations showing a correlation between these parameters and the performance of spring elements. Changing the shape of the springs can improve their ability to dampen vibrations, which is important for reducing mechanical loads on other components of the tillage implement. On the other hand, varying the number of turns can be used to adjust the damping force, which increases the reliability and durability of the equipment during intensive operation.

The analysis of the results of the study demonstrated that optimisation of the geometry of the springs is important to achieve better-damping characteristics and reduce vibrations in tillage implements. Changes in the number of coils and the shape of the springs have a significant impact on their ability to absorb shock loads and reduce vibrations (Marchuk & Nishchota, 2018). This reduces mechanical stress on other components of the equipment, which in turn increases its efficiency and durability.

In general, the analysis demonstrated that the efficiency of the spring elements of tillage implements largely depends on the choice of materials, spring geometry and the ability to absorb dynamic loads. The identified patterns were used to develop recommendations for improving the design of springs, in particular, the use of high-quality materials and optimisation of their geometry to reduce wear and improve shock absorption characteristics.

CONCLUSIONS

The material used to make springs is central in ensuring that they can withstand cyclic loads without significant deformation. The high fatigue characteristics of alloy steels provide springs with greater durability and the ability to recover from deformation. This helps to reduce the risk of wear and tear and maintain the stability of mechanisms over time. Analysis of the spring geometry confirmed the importance of the correct coil shape for optimal load distribution. Springs with variable coil diameters demonstrated better energy absorption capability, which reduces peak stresses that can lead to material failure. Increasing the number of coils or their even spacing also improved damping properties, which reduces the impact of dynamic loads on other structural components.

Furthermore, the study confirmed that the optimal choice of spring stiffness is critical to the spring's durability. Springs with the right stiffness have been shown to effectively absorb shock and cyclic loads while reducing the risk of overloads and breakage. This helps to reduce wear and extend the life of the spring elements. At the same time, the study determined that resonance phenomena can seriously affect the efficiency of springs. Modelling has shown that under resonance conditions, the amplitude of oscillations can reach values that lead to damage or destruction of the springs. To prevent such phenomena, it is important to ensure the correct choice of spring geometry, as well as to include shock absorbers or other additional elements that reduce the amplitude of vibrations.

Thus, the results confirmed the importance of an integrated approach to the development of spring elements, which includes the correct choice of material, geometry and stiffness. Optimisation of these parameters not only improves the efficiency of tillage tools, but also significantly increases their durability. In addition, the use of modern modelling methods, such as the finite element method, can accurately predict the behaviour of springs under dynamic loads, which is an important step in developing reliable designs. A limitation of the study is the lack of real experimental data on the behaviour of spring elements under extreme operating conditions, such as high temperatures or aggressive environments. To further improve the calculation models, it is necessary to study the effect of variable temperature conditions and corrosion on the durability of spring elements in tillage tools.

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CONFLICT OF INTEREST

None.

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Аналіз деформаційних характеристик пружинних елементів ґрунтообробних знарядь під дією динамічних навантажень

Анотація. Дослідження проведено з метою оцінки впливу динамічних навантажень на деформаційні характеристики пружинних елементів ґрунтообробних знарядь з урахуванням оптимізації їх конструкції та підвищення довговічності. Здійснено аналіз впливу динамічних навантажень на пружинні елементи з урахуванням їх матеріальних характеристик і конструктивних особливостей. У ході дослідження було встановлено, що пружинні елементи ґрунтообробних знарядь зазнають значних деформацій під дією динамічних навантажень, що виникають через нерівності ґрунту, коливання та ударні сили. Аналіз показав, що пружини з більшою жорсткістю демонструють меншу схильність до пластичних деформацій, але при цьому можуть спричиняти більш високі пікові навантаження на конструкцію знаряддя. Визначено, що матеріали з підвищеною пружністю та високим рівнем втомної міцності забезпечують кращу здатність до відновлення після деформацій, що зменшує ризик поломок у процесі експлуатації. Результати моделювання за допомогою методу кінцевих елементів показали, що резонансні частоти пружинних елементів можуть негативно впливати на їхню ефективність, спричиняючи додаткові коливання й знос. Встановлено, що оптимізація геометрії пружин дозволяє значно зменшити амплітуду цих коливань. Також було виявлено, що використання пружин з комбінованою конструкцією, що поєднує різні матеріали та геометричні форми, дозволяє значно покращити амортизацію і зменшити вплив динамічних навантажень на конструкцію знаряддя. Крім того, дослідження показало, що правильно підібрані параметри пружин, такі як їхня жорсткість і ступінь відновлення, дозволяють оптимізувати роботу ґрунтообробних знарядь, збільшуючи ефективність їх застосування в різних агротехнічних умовах

Ключові слова: жорсткість; матеріали; втомна міцність; метод кінцевих елементів; амортизація

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Automated devices for quantitative phenotyping of sunflower seeds

Abstract. To develop new sunflower varieties, it is important to accurately assess phenotypic traits that influence yield, disease resistance, and stress tolerance. Automation allows for systematic data collection and more informed decision-making in the breeding process. The goal of the work was to enhance the efficiency of selecting and predicting the development of sunflower genotypes through the development of new methods, hardware, and software tools for quantitative phenotypic characterisation of seeds. The methods for determining phenotypic characteristics of sunflower seeds, including geometric dimensions, mass, colour, rheological properties, and seed surface properties, have been presented and improved. A module for determining the morphological properties of seeds (geometric dimensions, mass, surface colour, etc.) was developed. This module was configured for high precision in the individual measurement of the geometric dimensions of sunflower seeds, with the determination of their shape and colour. It ensured low labour intensity and high technological efficiency in the implementation of the phenotyping procedure (determination, identification, and separation) of seeds. The methodology for analysing the rheological properties of seeds was refined, and a method for their automatic determination, along with a corresponding module, was substantiated. The proposed module maintains the accuracy of individual measurement of the rheological properties of seeds, consistent with modern measurement tools, while ensuring low labour intensity and high technological efficiency. Additionally, the module significantly reduced the influence of the human factor on the accuracy of measuring the rheological properties of seeds. The proposed module for determining seed surface properties ensured the accuracy of individual measurements of the coefficients of static and sliding friction of seeds, aligning with modern measurement tools, while also ensuring low labour intensity and high technological efficiency. This also significantly minimised the influence of the human factor on the accuracy of these measurements. The use of automated devices in practical conditions can help optimise the selection of seeds with the best characteristics

Keywords: module; software; geometric dimensions; surface colour; rheological properties; frictional properties

INTRODUCTION

Plant phenotyping involves a comprehensive evaluation of complex traits such as growth, development, resilience, architecture, physiology, ecology, and yield, along with basic measurements of individual quantitative parameters that contribute to these traits. The plant phenotype includes these complex characteristics, with measurable parameters such as root morphology, biomass, leaf traits, fruit (seed) characteristics, yield-related factors, photosynthetic

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efficiency, and responses to biotic and abiotic stress. With the rapid advancement of high-throughput genotyping in plant breeding and genomics, there is an increasing demand for more efficient and reliable phenotyping data to support modern crop genetics.

To accomplish this objective, phenotyping integrates knowledge from biology, computer science, mathematics, and engineering. C. Costa *et al.* (2019) and Y. Jiang & C. Li (2020) highlighted that quantitative measurement greatly benefits from advanced imaging technologies, but also depends on standardised experimental protocols, including sensor calibration and accurate data processing methods, which are essential for best practices in plant phenotyping.

Modern imaging methods offer high resolution and allow for the visualisation of multidimensional and multiparametric data. These methods are used to quantitatively assess complex plant traits during their growth in both controlled environmental systems and field conditions. According to M. Deb *et al.* (2024) and B. Daviet *et al.* (2022) image analysis algorithms are the primary drivers advancing image-based research that requires quantitative phenotyping of plant parts such as roots, stems, leaves, seeds, flowers, etc. Phenotyping of seeds was not possible without the use of modern equipment. One of the first such automatic phenotyping devices that addressed the complex issue was phenoSeeder, mentioned in the article by S. Jahnke *et al.* (2016).

The study by S. Yang *et al.* (2021) introduced a novel phenotyping method based on image processing of soybean seeds using neural networks and Mask R-CNN training. The primary advantages of this method include automatic image segmentation and pre-defined model weight coefficients. However, the method has some drawbacks: the phenotyping analysis of soybean seeds was based on two-dimensional images; the computational costs for training the instance segmentation model are relatively high; and the method for generating and augmenting synthetic images is limited to a single object class for image segmentation.

Researchers at the Earlham Institute, J. Colmer *et al.* (2020), introduced the SeedGerm system, which integrates affordable hardware with open-source software to conduct seed germination experiments, automate seed imaging, and apply machine learning for phenotypic analysis. A significant advantage of this system is its ability to process multiple image series simultaneously while providing accurate analysis of traits associated with seed germination and viability.

Additionally, the study by Y. Nehoshtan *et al.* (2021) introduced the SeedNet technology and system for studying the germination of vegetable crop seeds, which is based on deep learning and RGB image data. The proposed technology's advantage is its ability to be used for industrial seed sorting based on germination rates across various crops. However, the SeedGerm and SeedNet systems are primarily designed for assessing seed germination dynamics.

In the work by K. Tu *et al.* (2023), new software called AIseed was developed, which automatically captures and analyses morphological traits such as shape, colour, and texture features of individual seeds. The AIseed software is based on machine vision technology and provides high-throughput processing and phenotyping of seeds of various sizes. The advantage of this system is its high efficiency in detecting phenotypic traits of seeds. However, the system is not open for general access.

Therefore, the goal of this work was to improve the efficiency of selecting and predicting the development of sunflower genotypes by developing new methods, hardware, and software tools for the quantitative phenotypic characterisation of seeds.

MATERIALS AND METHODS

The primary phenotypic characteristics of sunflower seeds were shape, geometric dimensions, mass, colour, rheological, and frictional properties (Pieruschka & Schurr, 2019). The shape and geometric dimensions of the seeds were determined using an image processing methodology. The developed algorithm for determining the shape and geometric dimensions of seeds was based on a new image analysis method. This method reduced the time required for seed preparation and image acquisition. The contours of the seeds were automatically detected on digital images, and several shape parameters were calculated. These parameters included seed length (*L*), width (*W*) or thickness (*T*), area (*S*), and perimeter length (*P*). The algorithm and corresponding software, based on Visual Studio C++ (USA) and the OpenCV library (USA), analysed all the images obtained from the camera. After analysis, the seeds were automatically identified by taking successive points along the seed perimeter and maximising or minimising values in the following sequence of stages.

The process involved loading the image and converting it to a 1-bit format (black seeds on a white background). Morphological analysis was conducted to remove noise and gaps. Contours were detected, all seeds on the image were labelled, and the length (*L*), width (*W*) or thickness (*T*), area (*S*), and perimeter (*P*) of the seeds were calculated.

Image processing consisted of three stages. The first stage was converting the image of the selected rectangular region of the seed material from 24-bit (full-colour) to 1-bit (black and white) using a segmentation method. This isolated the black seeds on a white background. This method was stable even with changes in lighting levels. The second stage involved removing any noise or gaps. For this purpose, the software used OpenCV (Kumar *et al.*, 2023) functions Erode and Dilate, based on morphological operations. The third stage was the automatic detection of each seed's contour in the 1-bit image using the Canny edge detector and Hough transform via the OpenCV FindContour function. This process yielded a set of coordinates for each seed contour. To measure the length *L*, the algorithm found the maximum distance between points along the perimeter by calculating all possible distances between points in the segment $l_{i,j}$ located on the contour boundary (Fig. 1):

$$l_{i,j} = \sqrt{\left(x_{li} - x_{lj}\right)^2 + \left(y_{li} - y_{lj}\right)^2}, \quad (1)$$

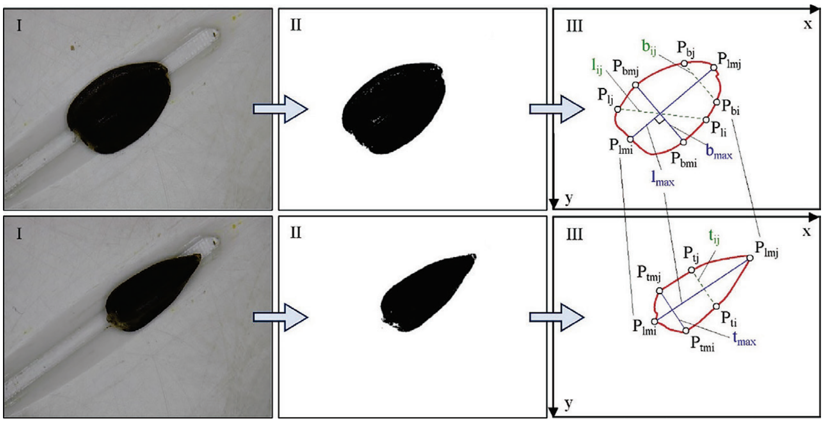

Figure 1. Stages of determining the geometric dimensions of seeds from photographic images
Note: *x, y* – coordinates, mm; l_{max} – length of the seed, mm; b_{max} – width of the seed, mm; t_{max} – thickness of the seed, mm; $l_{i,j}$, $b_{i,j}$, $t_{i,j}$ – distances between points of the segment, mm; P_{lj}, P_{bmj}, P_{bj}, P_{lmj}, P_{bi}, P_{li}, P_{bmi}, P_{lmi}, P_{tmj}, P_{tj}, P_{ti}, P_{tmi} – points on the seed contour; *I, II, III* – stages of determining geometric dimensions
Source: compiled by the authors

The determination of the largest segment *L* was carried out using the following method:

$$L = l\max_{i,j}\left(l_{i,j}\right)_{lmi}\left(x_{lmi}, y_{lmi}\right)_{lmj}\left(x_{lmj}, y_{lmj}\right)_{max}. \tag{2}$$

To measure the width *W* or thickness *T*, the algorithm found the largest segment that was perpendicular to the length *L* (Fig. 1):

$$w_{i,j} = \sqrt{\left(x_{wi} - x_{wj}\right)^2 + \left(y_{wi} - y_{wj}\right)^2} \quad \left(if\ \frac{(y_{lmi} - y_{lmj})}{(x_{lmi} - x_{lmj})}\frac{(y_{wi} - y_{wj})}{(x_{wi} - x_{wj})} = -1\right), \tag{3}$$

$$W = w\max_{i,j}\left(w_{i,j}\right)_{wmi}\left(x_{wmi}, y_{wmi}\right)_{wmj}\left(x_{wmj}, y_{wmj}\right)_{max}, \tag{4}$$

$$t_{i,j} = \sqrt{\left(x_{ti} - x_{tj}\right)^2 + \left(y_{ti} - y_{tj}\right)^2} \quad \left(if\ \frac{(y_{lmi} - y_{lmj})}{(x_{lmi} - x_{lmj})}\frac{(y_{ti} - y_{tj})}{(x_{ti} - x_{tj})} = -1\right), \tag{5}$$

$$T = t\max_{i,j}\left(t_{i,j}\right)_{tmi}\left(x_{tmi}, y_{tmi}\right)_{tmj}\left(x_{tmj}, y_{tmj}\right)_{max}. \tag{6}$$

The seed mass *M* was measured using a load cell with strain gauges, an HX711 module (China), and an Arduino control board (USA). The strain gauges and HX711 module were connected in a bridge configuration. The HX711 module, produced by Avia Semiconductors, was an analog-to-digital converter (ADC) with a 24-bit sampling frequency and an integrated operational amplifier.

The seed colour was determined using image processing techniques on images obtained under different lighting conditions. The seed was placed in a chamber beneath the camera, where controlled lighting was isolated from external light. RGB LEDs (*R* – red (465-470 nm), *G* – green (515-520 nm), *B* – blue (620-625 nm)) were used to provide light of specific colours, and the camera captured images of the seed either stationary or in motion, which were then transmitted to a personal computer.

The software algorithm consisted of the following stages:

1. Image Acquisition: capturing images from the video camera.
2. Colour Space Conversion: translating the image from RGB colour space to HSV (*H* – Hue, *S* – Saturation, *V* – Value).
3. Colour Filtering: setting the colour mask for filtering.
4. Morphological Transformations: applying basic morphological transformations such as dilation and erosion.
5. Contour Detection and Labeling: finding the contours of the detected object and drawing labels.

The advantages of this algorithm included: colour ranges were selected using *H*, *S*, and *V* scales, resulting in an immediate formation of a three-dimensional region in the colour space.

The algorithm was implemented using the OpenCV library. Various seeds of different colours, sizes, and shapes were tested. As noted, each seed required a specifically tuned colour mask. To isolate the desired colour, the *H* component boundaries had to be adjusted. The *S* parameter controlled colour saturation, while V determined colour brightness. A shaded object would have a low *V* value. From the obtained images, for each seed, a corresponding colour data matrix was determined under three types of illumination:

$$\begin{pmatrix} H_R & H_G & H_B \\ S_R & S_G & S_B \\ V_R & V_G & V_B \end{pmatrix}, \tag{7}$$

where *H* represented the hue; *S* denoted the colour saturation; and *V* indicated the amount of light. The indices *R*, *G*, and *B* corresponded to the wavelength of electromagnetic radiation (lighting) affecting the area under the camera. When the software for automated seed phenotyping was launched, five windows appeared (see (Fig. 2):

1. Camera Window: displayed the original image from the camera under white lighting (with all LEDs turned on),

highlighting the contours of the seeds and their geometric dimensions.

2. Filter Window: showed the image from the camera after converting the colour image from the HSV colour space to a black-and-white mask. In this mask, pixels falling within the specified range turned white, while others turned black.

3. HSV Window: featured sliders for adjusting the HSV colour mask.

4. RGB Bar Chart Window: displayed histograms of colour distribution in the RGB colour space.

5. CMD Window: provided an input and output interface for messages and data.

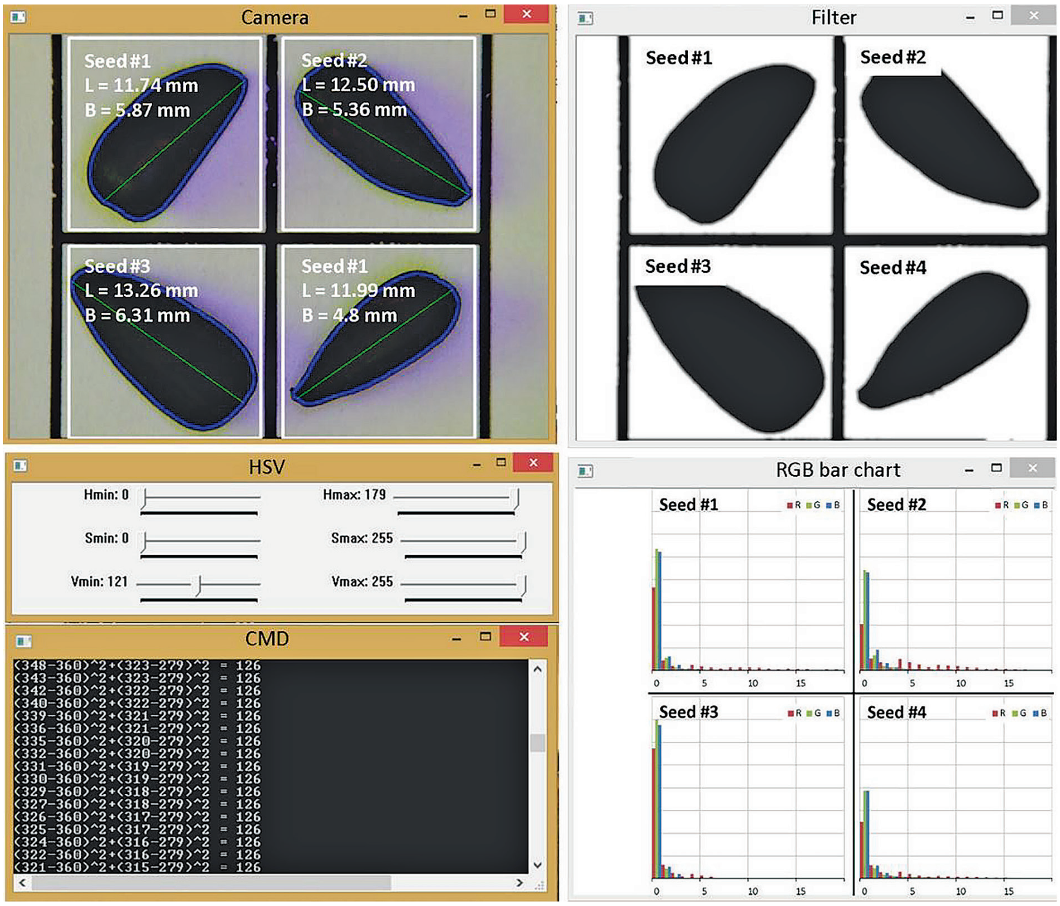

Figure 2. Software for automated phenotyping of sunflower seed material

Note: *L* – length of the seed, mm; *B* – width of the seed, mm; H_{min}, H_{max} – minimum and maximum value of hue; S_{min}, S_{max} – minimum and maximum value of saturation; V_{min}, V_{max} – minimum and maximum value of value; *R, G, B* – red, green, blue

Source: compiled by the authors

Determining the rheological properties of seeds involves the following stages:

1. *Stage one*. The seeds were placed in the required position on a flat horizontal surface of the working table in the area under a cylindrical indenter (diameter – 20 mm) mounted on a load cell that moved in the vertical plane. The load cell with the attached indenter had to be calibrated, and in its resting state, it had to correspond to a force of 0 N.

2. *Stage two*. The indenter started descending from the top point at a uniform, straight-line speed of 10 mm/s. Upon reaching the seed, the force on the load cell began to increase from 0 N. This moment was recorded as the start of the measurement process. Subsequently, the geometric size of the seed X was determined, with the working table set to the coordinate origin of 0 mm.

3. *Stage three*. During the measurement process, the time *t*, absolute deformation ΔX, and compression force *F* were determined. After the absolute deformation reached 10% of the seed size, the value of the force $F_{0.1}$ was recorded, and the seed stiffness coefficient k was calculated:

$$k = \frac{F_{0.1}}{0.1X_{max}}, \tag{8}$$

when the force *F* started to decrease, the maximum strength of the seed coat F_{max} was recorded.

The surface properties of seeds were primarily determined by roughness and/or the coefficient of friction (Fig. 3c). To determine the coefficient of friction of the seeds on the surface, a traditional method was used, which involved moving a load-bearing mass *M* of seeds (with mass M_s) across the working surface.

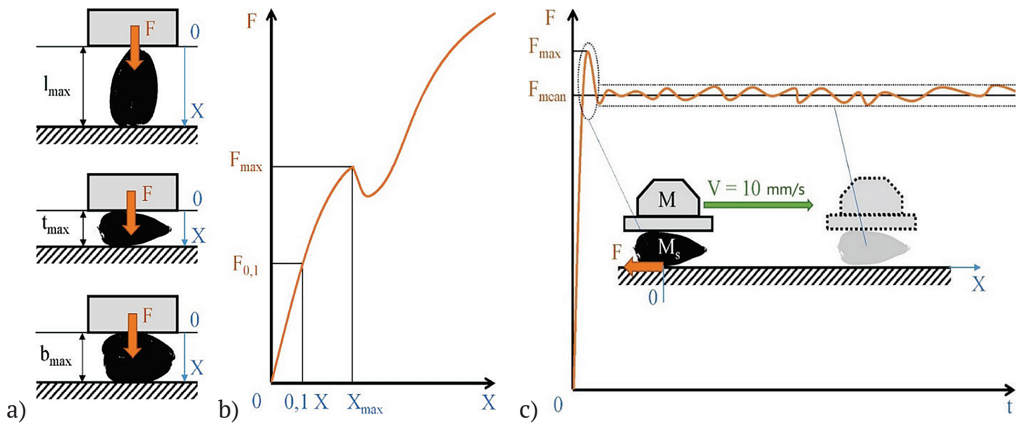

Figure 3. Process of determining rheological properties (a, b) and surface properties (c) of seeds

Note: *a* – seed placement options under the indenter; *b* – graph of the force *F* versus deformation *X* during seed compression; *c* – graph of the force *F* versus time during seed movement on the working surface; l_{max} – length of the seed, mm; b_{max} – width of the seed, mm; t_{max} – thickness of the seed, mm; F_{max} – the maximum strength of the seed coat, N; $F_{0,1}$ – force at 10% deformation, N; F_{mean} – the average force, N; *V* – speed of movement, mm/s; *M* – mass of the load, g; M_s – mass of the seeds, g; *t* – time, s; X_{max} – the maximum of the seed deformation, mm

Source: compiled by the authors

The change in the opposing force $F(t)$ during the movement was measured dynamically using a resistive load cell. The coefficient of static friction μ_r was calculated as the ratio of the maximum force at the initial moment F_{max} to the total mass of the seeds M_s and the load M, multiplied by the acceleration due to gravity g. The coefficient of sliding friction μ_s was determined as the ratio of the average force F_{mean} to the total mass M_s of the seeds and the load M, multiplied by the acceleration due to gravity g.

RESULTS

According to the accepted methodologies for determining phenotypic characteristics of seeds, experimental samples of three modules were developed and manufactured: a module for determining the morphological properties of seeds (shape, geometric dimensions, mass, surface coloration), a module for determining the rheological properties of seeds (seed stiffness coefficient, seed coat strength), and a module for determining the surface properties of seeds (static and sliding friction coefficients). The design and technological scheme, overall appearance, and electrical diagram of the module for determining the morphological characteristics of seeds were shown in Figure 4. The principle of operation of the seed morphological properties determination module was as follows. Seeds for examination were placed in the seed feeder tray. The desired seed feed rate was set on the conveyor belt using an adjustable gate.

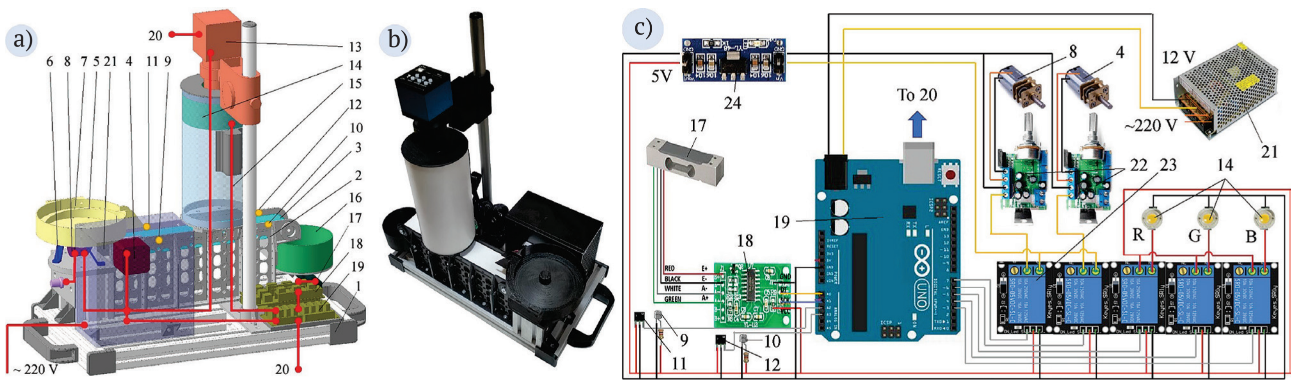

Figure 4. Structural-technological diagram (a), general view (b), and electrical schematic (c) of the seed morphological property determination module

Note: 1 – frame; 2 – belt conveyor; 3 – belt; 4 – electric motor; 5 – seed feeding tray; 6 – shock absorbers; 7 – gate; 8 – vibration motor; 9, 10 – infrared LEDs; 11, 12 – photoreceivers; 13 – camera (Eakins Video Microscope Camera (China)); 14 – RGB LEDs; 15 – lightproof tube; 16 – strain gauge; 17 – load cell; 18 – amplifier (weight sensor HX711); 19 – control unit (Arduino Uno ATmega328P-PU); 20 – personal computer; 21 – power supply; 22 – PWM controllers; 23 – relay block; 24 – voltage converter; *R, G, B* – red, green, blue

Source: compiled by the authors

The operator started the software on the personal computer, which was based on the OpenCV computer vision algorithms library. The personal computer sent a start signal to the control unit, which activated the vibration motor and the electric motor. The vibration motor generated vibrations in the seed feeder tray, causing the seeds to fall onto the belt, which moved due to the electric motor. The seeds passed between an infrared LED and a photodetector, generating a signal that was transmitted to the personal computer via the control unit. The personal computer activated the camera and sent a signal to the control unit to sequentially turn on the RGB LEDs. Images of the seeds under three different lighting conditions were stored in the personal computer's database. The seeds then passed between the infrared LED and the photodetector again, generating a signal that was sent to the personal computer through the control unit. After the conveyor belt movement was complete, the seeds fell into the collection tray. The signal from the load cell was transmitted through the amplifier and control unit to the personal computer, where the seed mass value was recorded in the database. The seed images were processed by the personal computer. During this process, the colour of each seed was determined under each activation of the RGB LEDs in red (*R*), green (*G*), and blue (*B*) spectra in the HSV colour space. Additionally, the personal computer determined the shape and geometric dimensions of each seed under examination based on the obtained images. All collected information was stored in the database and displayed on the personal computer's screen for the operator's review.

The design and technological scheme, general appearance, and electrical schematic of the seed rheological properties determination module were shown in Figure 5.

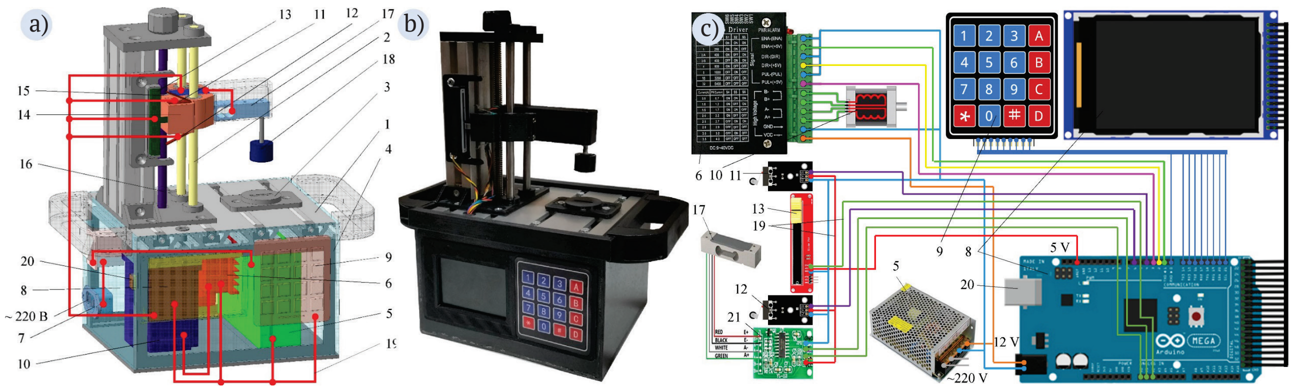

Figure 5. Structural-technological diagram (a), general view (b), and electrical schematic (c) of the seed morphological property determination module

Note: 1 – base; 2 – guide rail; 3 – worktable; 4 – housing; 5 – power supply; 6 – stepper motor controller (TB6600); 7 – socket with switch; 8 – control unit with LCD display (Arduino MEGA 2560 + 3.5 Inch TFT Color Display 320x480 Screen (China)); 9 – keyboard; 10 – stepper motor; 11 – upper limit switch; 12 – lower limit switch; 13 – variable resistor; 14 – carriage; 15 – nut; 16 – screw; 17 – load cell; 18 – indenter; 19 – electrical wires; 20 – USB output for connection to personal computer; 21 – amplifier (weight sensor HX711)

Source: compiled by the authors

The principle of operation of the seed rheological properties determination module was as follows. The operator placed the seeds on the working surface of the table and started the measurement process. The control unit with an LCD display sent a signal to the stepper motor controller, activating the stepper motor. The stepper motor shaft drove a screw, which rotated in the direction opposite to the thread of the screw. This caused the nut to unscrew, lifting the carriage along with the load cell and indenter along the guide. When the free wiper of the linear variable resistor reached the upper limit switch, the signal from the switch was sent to the control unit with the LCD display. The control unit with the LCD display sent a signal to the stepper motor controller, which stopped the stepper motor, and the indenter reached the topmost position.

The next step was the control unit sending a signal to the stepper motor controller, which activated the stepper motor. The stepper motor shaft started rotating the screw in the direction opposite to the screw thread direction. This caused the nut to start unscrewing, leading to the descent of the carriage along with the load cell and indenter along the guide. The indenter's movement speed remained constant at 10 mm/s. During the carriage movement, data from the load cell and linear variable resistor were sent to the control unit with the LCD display.

Starting from the zero value measured by the load cell, the force on the seed increased from 0 N as it was pressed. This moment was registered by the control unit with the LCD display as the beginning of the measurement. The thickness of the seed *X* was then determined via the linear variable resistor, assuming the working table corresponded to the initial coordinate of 0 mm. During the measurement process, the time *t* from the internal clock of the control unit, the absolute deformation ΔX from the linear variable resistor, and the compression force *F* from the load cell were recorded. After reaching the maximum force value or the lower limit switch of the linear variable resistor, the control unit sent a signal to the stepper motor controller, which turned off the stepper motor, stopping the indenter's movement. The control unit then returned the carriage to the topmost position.

All obtained data was stored in the database of the control unit with the LCD display and transferred via USB to the personal computer. Subsequently, the rheological properties of the seeds were calculated based on the obtained data. The design and technological scheme, general appearance, and electrical schematic of the seed surface properties determination module were shown in Figure 6.

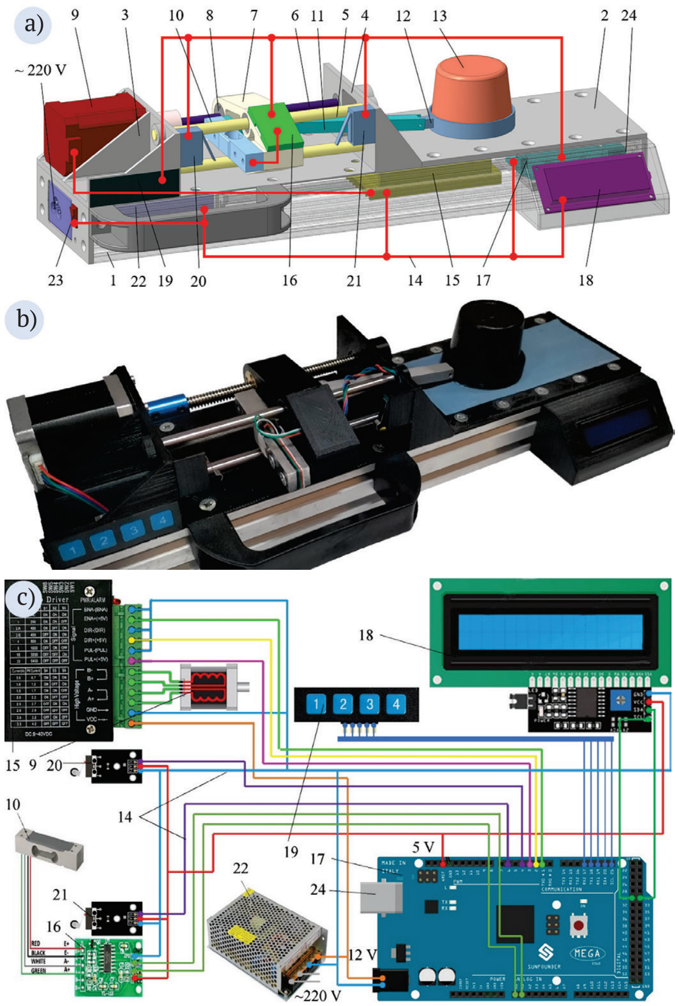

Figure 6. Design and technological scheme (a), general view (b), and electrical schematic (c) of the seed surface properties determination module

Note: 1 – base; 2 – working table; 3, 4 – left and right mounts; 5 – two guides; 6 – screw; 7 – carriage; 8 – nut; 9 – stepper motor; 10 – load cell; 11 – rigid connection; 12 – cup; 13 – weight; 14 – electrical wires; 15 – stepper motor controller; 16 – amplifier (weight sensor HX711); 17 – control unit (Arduino MEGA 2560); 18 – display (LCD 1602 I2C (China)); 19 – keyboard; 20, 21 – left and right limit switches; 22 – power supply; 23 – power button; 24 – USB port for connection to a personal computer

Source: compiled by the authors

The principle of operation of the seed surface properties determination module was as follows. The operator placed the seed on the working table surface and started the measurement process. The control unit sent a signal to the stepper motor controller, which in turn activated the stepper motor. The stepper motor drove the screw, which rotated in the direction opposite to the thread's winding direction. This caused the nut to unscrew, moving the carriage to the right along the guides. Once the carriage reached the right limit switch, a signal from the switch was transmitted to the control unit via electrical wires. The control unit sent a signal to the stepper motor controller, which stopped the stepper motor, placing the cup with the weight in the far-right position.

Next, the control unit sent a signal to the stepper motor controller, which activated the stepper motor again.

The stepper motor drove the screw, which rotated in the direction of the thread's winding. This caused the nut to screw back on, moving the carriage with the load cell, rigid connection, cup, and weight to the left. The speed of the carriage movement remained uniform and was set to 10 mm/s. During the movement, data from the load cell was transmitted to the control unit.

The control unit calculated the data and determined the coefficients of static and rolling friction. The obtained data was displayed on the screen. When the carriage reached the left limit switch, a signal from the switch was sent to the control unit. The control unit, via electrical wires, sent a signal to the stepper motor controller, which stopped the stepper motor, placing the cup with the weight in the far-left position. All obtained data was stored in the control unit's database and could be transmitted via the USB port to a personal computer.

DISCUSSION

As noted, the inspiration for creating an automatic phenotyping system that could be financially accessible to all breeders and geneticists came from the phenoSeeder systems (Jahnke *et al.*, 2016) and SeedGerm (Colmer *et al.*, 2020). The specialisation of the presented modules for automatic seed phenotyping is still limited and is currently applied only to sunflower seeds. However, all the specific characteristics of sunflower seeds have been considered, which allows for confident claims regarding the accuracy of the obtained results.

There are many methods for determining seed sizes, as used in the works of T. Tanabata *et al.* (2012) and F. Liu *et al.* (2022). In summary, these methods included forming a seed sample, scanning it, and processing the image to determine the actual sizes of the sample components. The image processing is performed using a computer program that automatically recognises the object and divides it into a predefined grid, determining the maximum, minimum, and average sizes in millimeters in two mutually perpendicular two-dimensional planes. To implement the proposed method, the body of the device has a shelf for the object under investigation. Two digital cameras are placed at a 90º angle to each other in specific slots. To improve the quality of images of seeds placed in the same direction on the shelf, they are illuminated by a lamp. The digital cameras are connected to a computer. The drawbacks of this method include the complexity of forming a row of seeds that must fall under the camera lenses. Another disadvantage is that this method allows the identification of seeds based on only two morphological characteristics – size and shape. There is no possibility of determining mass and colour. The proposed method and device for automatic seed phenotyping address these issues.

The known device for automatic seed phenotyping, described in the previous works of E. Aliiev (2020; 2023), contains a frame, a base, a matrix, a camera, and a personal computer. On the top of the frame, on the base, around the camera, and in the centre of the matrix, multi-coloured lamps of three electromagnetic radiation spectra (red (R), green (G), and blue (B)) are installed, which are controlled via a control unit connected to the personal computer. The matrix has square holes formed by movable horizontal and vertical plates, with springs on one side and pulling electromagnets (solenoids) on the other side, activated by the control unit via the personal computer. The new seed morphological property determination module addresses identified shortcomings, specifically the need to manually place seeds in the square holes of the matrix, which increases the labour intensity of determining the morphological properties of seeds. Additionally, previous devices lacked the ability to determine seed mass and conduct measurements in field conditions.

In the study by S. Wang *et al.* (2022), the physical characteristics of sunflower seeds were determined using physical tests, which were applied during simulation. To determine the rheological properties, the TMS-Pro physical property analyser (United Kingdom) with a sensor range of 0-2.5 kN was used. This equipment operates in accordance with the ASAE S368.4 DEC 2000 (R2017) standard. As part of the presented studies, the seed morphological property determination module was developed, which not only matches the accuracy of the known methods but also has several additional automated functions. However, compliance with the ASAE S368.4 DEC 2000 (R2017) standard has not been tested yet, which will be done soon.

Devices for determining the coefficient of friction, used in the works of S. Wang *et al.* (2022) and S. Bai *et al.* (2022), consist of a body, a sample, and a counter-sample with flat working surfaces, a counter-sample holder designed as a platform mounted on an axis, which can change its angle relative to the body, and a means for measuring the tilt angle of the counter-sample holder. The device also includes an intermediate platform that can rotate relative to the body and is fixed to the same axis as the counter-sample holder. Moreover, the device is equipped with a small displacement drive, for example, thermodynamic or spring-force, installed between the intermediate platform and the counter-sample holder. The disadvantages of such devices include low measurement accuracy, difficulty in processing information, and the inability to conduct research in field conditions. These drawbacks have been addressed in the newly developed seed surface properties determination module.

The known device for determining the coefficient of friction of agricultural materials, the FPT-H1 (United Kingdom), used in the research of E. Jotautiene *et al.* (2024), consisted of a frame, a chute, a carriage, and a drive. An analogous device is the ST-MXZ-1 (China), used in the work of M. Hu *et al.* (2022). The devices are equipped with a DC motor and an electronic dynamometer, capable of recording the final force. The drive system features spring-loaded rollers. The devices are equipped with a level and adjustable supports. These devices determine the average coefficient of friction of agricultural materials. Since seeds of agricultural crops, particularly sunflower, exhibit different adhesion to the working surfaces of agricultural machinery depending on the direction of movement due to the anisotropy of their surface, the disadvantage of these devices is the inability to determine the corresponding dependence of the coefficient of friction on the direction of seed movement along the working surface. The seed surface properties determination module developed in the article solves this problem.

The results presented in the works of S. Yang *et al*. (2021) and X. Jin *et al*. (2022) on seed image processing methods using neural networks and learning enable further development of research. This allows automating the seed image analysis process, reducing the likelihood of errors that may occur during manual classification. Moreover, modern machine learning methods enable the processing of large datasets, contributing to increased accuracy in predicting seed characteristics and accelerating breeding programs. The integration of such technologies into scientific research significantly expands the possibilities for developing new plant varieties with specific properties. The classification of seeds by their images and a complex of physico-mechanical properties will make it possible to create a complete workstation for breeders and plant geneticists.

CONCLUSIONS

The methods for determining the phenotypic characteristics of sunflower seeds were presented and improved, specifically geometric dimensions, mass, coloration, rheological properties, and surface properties of the seeds.

A module for determining the morphological properties of seeds (geometric dimensions, mass, surface coloration, etc.) was developed. The module was designed for high precision in individual measurement of sunflower seed dimensions, including shape and coloration, and ensured low labour intensity and high technological efficiency in the phenotyping procedure (identification, classification, and separation) of seeds. The methodology for analysing the rheological properties of seeds was improved, and a method for their automatic determination along with a module for this purpose was substantiated. The proposed module maintained accuracy in individual measurement of seed rheological properties, which met current measurement standards, and ensured low labour intensity and high technological efficiency. Furthermore, the proposed module enabled the determination of elasticity strength, elastic modulus, and static hysteresis indicators, which could not be measured directly. This significantly improved the overall productivity of the research and greatly reduced the influence of human error on the accuracy of measuring seed rheological properties.

The proposed module for determining the surface properties of seeds allowed for the maintenance of accuracy in individual measurement of static and sliding friction coefficients of seeds, meeting current measurement standards, and ensured low labor intensity and high technological efficiency. It also significantly minimised the impact of human error on measurement accuracy.

The prospects for further research include integrating the presented modules into a unified system for automatic sunflower seed phenotyping. Additionally, there is a need to refine the image processing software using neural networks and machine learning. Overall, the proposed improvements will enable the use of the automatic phenotyping system as a universal workstation for plant breeders and geneticists.

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CONFLICT OF INTEREST

None.

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Автоматизовані пристрої для кількісного фенотипування насіння соняшнику

Анотація. Для створення нових сортів соняшнику важливо точно оцінити фенотипові ознаки, які впливають на врожайність, стійкість до хвороб і стресостійкість. Автоматизація дозволяє систематично збирати дані та приймати більш обґрунтовані рішення в процесі селекції. Метою роботи було підвищення ефективності добору та прогнозування розвитку генотипів соняшнику шляхом розробки нових методів, апаратних і програмних інструментів для кількісної фенотипової характеристики насіння. Представлено і удосконалено методи визначення фенотипових характеристик насіння соняшнику, а саме геометричних розмірів, маси, забарвлення, реологічних властивостей і властивостей поверхні насіння. Розроблено модуль визначення морфологічних властивостей насіння (геометричні розміри, маса, забарвлення поверхні тощо). Модуль налаштовано на високу точність індивідуального вимірювання геометричних розмірів насіння соняшнику із визначенням їх форми і забарвлення та забезпечують низьку трудомісткість і високу технологічність реалізації процедури фенотипування (визначення, ідентифікації і сепарації) насіння. Удосконалено методику аналізу реологічних властивостей насіння й обґрунтовано спосіб їх автоматичного визначення і модуль для цього. Запропонований модуль зберігав точність індивідуального вимірювання реологічних властивостей насіння, що відповідає сучасним вимірювальним засобам, та забезпечував низьку трудомісткість і високу технологічність. При цьому також значною мірою зник вплив людського фактору на точність вимірювання реологічних властивостей насіння. Запропонований модуль для визначення властивостей поверхні насіння дозволив зберегти точність індивідуального вимірювання коефіцієнтів тертя спокою і ковзання насіння, що відповідає сучасним вимірювальним засобам та забезпечує низьку трудомісткість і високу технологічність. При цьому також значною мірою виключався вплив людського фактору на точність вимірювання. Використання автоматизованих пристроїв у практичних умовах може допомогти оптимізувати відбір насіння з найкращими характеристиками

Ключові слова: модуль; програмне забезпечення; геометричні розміри; колір поверхні; реологічні властивості; фрикційні властивості

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Optimisation of structural parameters of rotary tillage units to increase the stability of operation under the influence of variable loads

Abstract. The study was conducted to increase the stability of rotary tillage units by optimising their structural parameters considering variable loads. It was revealed that the stability of rotary tillage units under the influence of variable loads depends on such design parameters as the geometry and material of working bodies, the introduction of vibration-proof elements. It was determined that the optimal angle of attack (from 20 to 30 degrees) of the working bodies reduces the resistance of the ground, which, in turn, contributes to an even distribution of loads on the working elements of the unit. Changing the radius of curvature of the working elements reduces the stress concentration, which increases the durability of the working elements and reduces their wear during operation. Analysis of the mechanical properties of materials has shown that the use of special alloy steels containing chromium and manganese increases the wear resistance of the working bodies of units, reduces the frequency of maintenance, and extends the service life. The introduction of rubber shock absorbers in the design of attachment points helped to reduce the amplitude of vibrations and thus improve the stability of the unit during tillage. Analysis of the operation of the upgraded units showed an increase in productivity and a reduction in fuel consumption. Improving the quality of tillage was achieved by evenly distributing the depth of cultivation and reducing the level of soil compaction, which has a positive effect on the growing conditions of agricultural crops. Therefore,

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optimisation of the design parameters of rotary tillage units will increase their resistance to variable loads, reduce operating costs, increase operational efficiency, and ensure long-term and energy-efficient operation in complex geological processes

Keywords: blade geometry; alloy steels; wear resistance; damping elements; shock absorbers

INTRODUCTION

Dynamic loads that occur during the operation of tillage tools are a key factor that affects the efficiency and durability of their operation. Variable loads are caused by a number of reasons related to the characteristics of the soil, operating conditions, and design features of the units. The main causes of such loads include uneven soil, differences in the speed of movement of units, changes in the depth of cultivation, vibrations, fluctuations in the resistance force, and obstacles that affect the stability of working bodies. For example, different soil densities and structures create variable resistance to working elements, and surface irregularities or inclusions such as rocks or roots lead to sudden peak loads. Differences in the speed of movement of the aggregate associated with uneven ground surface or changes in the trajectory cause additional dynamic effects. Similarly, adjusting the depth of cultivation or fluctuation due to changes in field conditions also changes the force required for the units to operate. In addition, vibrations that occur during the operation of the units can reach resonant frequencies, which significantly increase the load on structural elements. Obstacles, such as uneven contact of the working elements with the ground or wear of parts, add unevenness to the operation of the system, causing additional loads. Changes in environmental conditions, such as temperature and humidity, also affect the mechanical properties of working body materials and soil, which creates additional difficulties in operation. Identification and analysis of these factors is a necessary condition for optimising the operation of tillage equipment: increasing its productivity, reducing maintenance costs, and improving the quality of tillage.

The problem of optimising the design parameters of rotary tillage units, in particular, increasing their resistance to variable loads, is relevant for ensuring the efficiency of agricultural machinery. One of the key aspects of optimising the operation of rotary tillage units is the analysis of the mechanical characteristics of the soil and their impact on the quality of cultivation. As noted by A. Panfilova *et al.* (2019), the correct selection of technological parameters of soil cultivation contributes to the reduction of its compaction and increased efficiency of agricultural machinery. The results obtained can be used to adjust the parameters of the working bodies of rotary tillage units in order to reduce loads on structural elements and improve the durability of their operation. D. Pandey *et al.* (2021) indicated that optimisation of the design parameters of the rotary cultivator blade significantly reduced specific energy costs. They developed a model of the blade and analysed the static force and fatigue of the material, which provided an improvement in its performance. As noted in the study by A. Dykha *et al.* (2020), the wear process depends on the mechanical properties of the materials and operating conditions, which confirms the feasibility of using alloy steels containing chromium and manganese to increase the durability of working elements.

Y. Zhang *et al.* (2024a) investigated the use of alloy steels with a high content of chromium and manganese for a guide shoe made of steel that supports the direction of movement of a coal combine and railway transport. They stressed the importance of choosing materials that can withstand high mechanical loads during intensive operation, which helped to increase wear resistance and reduce the frequency of maintenance of equipment. The wear resistance of the working parts of rotary tillage machines is an important factor determining their durability and operational efficiency. As shown in the study by O. Dubovoy *et al.* (2021), the use of electric arc spraying of cermet coatings can significantly increase resistance to abrasive wear. The study of materials based on 65G-TiC steel confirmed their high hardness and wear resistance, which makes such coatings promising for use in tillage machines operating under difficult conditions of variable load.

V. Budak *et al.* (2017) investigated the effect of changing the thickness of shells on the natural frequencies and modes of vibrations of non-cylindrical structures. This study can be useful for calculating and optimising the geometric parameters of rotating units operating under complex loading conditions. S. Mandal *et al.* (2021) investigated the optimisation of the blade design of rotary cutters to increase their service life. They focused on reducing the wear of the blades, which can withstand shock loads and high friction forces when interacting with the ground, which reduces unbalanced forces on the entire rotary cutter and ensures the durability of components. O. Grigorenko *et al.* (2021) investigate models of free vibrations of plate structures, which may be useful for the development of vibration-protective elements in the mounting nodes of rotary mechanisms. The introduction of such elements allows to reduce the amplitude of vibrations, which contributes to the uniform distribution of the load on the working bodies and increases the overall efficiency of soil cultivation.

A. Kumari & H. Raheman (2023) proposed a solution for operating the tractor and rotator at optimal speed, which reduces overall energy requirements and increases fuel efficiency. They examined the effects of throttle and transmission selection on energy requirements and power efficiency in various soil conditions. One of the important aspects of optimising the design parameters of rotary tillage units is to increase the reliability of rotor assemblies that are subjected to significant variable loads during operation. A. Panchenko *et al.* (2019) investigated the design features of orbital hydraulic motor rotors that are subjected to extreme loads and proposed methods for increasing their stability. The results obtained can be used to improve the rotary working bodies of tillage units, which will help reduce mechanical deformations and increase their durability. P. Zhao *et al*. (2024) proposed a fundamentally new soil treatment device with a wide seedbed, which includes a front pipe for applying fertilisers and an optimised design of rotary processing blades. For this purpose, a simulation model was developed and experiments were conducted to analyse the efficiency of straw cleaning, soil flushing, and energy consumption under different operating conditions.

J. Zhang *et al*. (2024b) proposed a cooperative control method for unmanned hybrid tractors to improve trajectory tracking accuracy and improve energy efficiency during their operation. This allowed reducing energy losses and improving the overall efficiency of tractors. S. Zhang *et al*. (2025) focused on the dynamic characteristics of rotary blades and their behaviour under variable loads. This helped to improve the accuracy of setting up equipment and ensure a more uniform load on the working elements. Optimisation of the design parameters of the working bodies of rotary units has a direct impact on the quality of soil cultivation and the productivity of agrotechnical processes. X. Zhang *et al*. (2024c) investigated the prediction of energy consumption based on cutting parameters in rotary units, applying a modelling method to determine optimal operating parameters. Their study showed that optimising these parameters leads to a reduction in energy consumption, which contributes to energy savings during rotary tillage. I. Torotwa *et al*. (2023) investigated the torque and power of the rotating blades of a milling cutter designed according to the spalax claw geometry. As a result of field experiments, they proved that biomimetic rotary blades are energy efficient and can improve soil structure. X. Zhang *et al*. (2023) modelled the movement of soil under the action of rotary blades, examining the interaction between soil and working bodies, which helped to accurately estimate changes in energy, cutting resistance, and movement of soil particles at different depths. This allowed optimising the design and ensuring its durability. One of the promising areas for increasing the wear resistance of working parts of rotary tillage units is the use of wear-resistant coatings. As noted by D. Marchenko & V. Kurepin (2021), electric spark treatment contributes to the formation of wear-resistant layers on steel surfaces, which can significantly increase the service life of parts in difficult operating conditions. Thus, although some aspects of optimisation of rotary tillage units have already been studied, there are gaps in the aspects of integrating new materials, technologies, and improving mechanisms for increasing resistance to variable loads, in particular, in the context of the deformation characteristics of spring elements, which requires further study.

The purpose of the study was to determine the optimal values of the design parameters of rotary tillage units, which would ensure their maximum resistance to variable loads. Research objectives:

- to explore different geometry options for working bodies to reduce ground resistance and improve work efficiency;
- to evaluate the impact of working body materials on their wear resistance and durability;
- to analyse methods for reducing vibrations and dynamic loads to improve the stability of the units.

MATERIALS AND METHODS

The main design parameters of rotary tillage units, in particular, types of rotors, shapes, and angles of knife installation, mounting options for working bodies and damping systems, were studied to improve their stability under variable loads. The geometry of disks and blades, their shapes, materials and location were analysed, which contributed to effective contact with the soil. Attention was paid to mounting systems and transmission mechanisms to achieve maximum rigidity and minimise vibrations that can negatively affect the operation of the unit.

At the beginning of the study, static and dynamic loads acting on the working bodies of the units were analysed. The variability of soil resistance was also considered, depending on such factors as the depth of cultivation, humidity, and soil density, which provided a more accurate picture of the impact of these loads on the working bodies of units in variable operation. Further, the geometry of the working bodies of the units was analysed, since changing its parameters can significantly affect the stability of the unit, minimise ground resistance, reduce stress concentration, and improve the uniformity of force distribution. Optimisation of the geometry of the working bodies allows achieving better energy efficiency and reducing component wear.

Materials for manufacturing blades with high wear resistance and impact strength were studied. This helped to ensure the reliability and durability of working bodies in conditions of variable loads that occur during tillage. To adapt to different working conditions, medium-strength alloy steels (AISI 52100, AISI 4130, 20CrMnTi), composites (TiC-VC-WC/nanoWC-NiCr) and carbide-coated materials such as medium-strength stainless steel (AISI 5040), medium-strength high-carbon steel (AISI 1080) and ceramic composites (ZrB_2) were investigated.

The John Deere 8370R tractor (manufacturer: John Deere, USA), complete with a rotary cutter Kuhn EL 402 R (manufacturer: Kuhn, France), which can work in sandy loam-clay soil conditions at a humidity of 11 ± 0.89% was studied. The working bodies in this milling cutter used standard rotary blades, but they can be replaced with the version developed by the authors in the study (Xu *et al*., 2024). These blades had geometry of a spalax claw that was created using biomimetic principles. This solution helped to significantly reduce the torque on the rotary shaft and increase the overall efficiency of tillage. The use of these blades can also help to reduce the energy consumption of the unit, especially on heavy soils or in conditions of intensive use.

Various types of springs were considered in the study, in particular, compression, tension, conical, serpentine, torsion, and leaf springs. Each of these types of springs performs specific functions in the design of rotary tillage machines. These springs were used to dampen loads, maintain precise adjustment of working bodies, and ensure the stability and durability of rotary tillage units.

RESULTS

Analysis of structural elements and selection of materials

Optimisation of working bodies, attachment systems and transmission mechanisms are key to improving the efficiency and reliability of rotary tillage units. The geometry and material of the working bodies (disks, blades, ploughshares) has a decisive influence on the quality of tillage. Blades with curved profiles reduce the resistance of the ground and facilitate penetration into it, which reduces the load on the unit and increases work efficiency. High-alloy steels or carbide coatings significantly increase wear resistance, which allows extending the operational life of these elements. The optimal arrangement of blades and angles of attack contribute to uniform tillage, reduce vibration, which contributes to stable operation of the unit.

The system of fixing the working bodies is an important element that ensures the rigidity of the unit structure and minimises the level of vibrations during its operation. It includes not only the choice of materials, but also the optimal arrangement of fasteners, such as bolts, nuts, welded joints, which ensure the reliability, and stability of the structure. The use of high-strength materials in these joints, such as AISI 52100 alloy steel, which has high hardness and wear resistance, significantly improves the performance of the units. In addition, composite materials such as Tic-VC-WC (titanium, vanadium, and tungsten carbide) and nanoWC-NiCr (nanostructured tungsten carbide and nickel-chromium alloy) are often used to increase strength under high loads, which provide resistance to wear and shock loads. Based on the correct choice and design solutions, the mounting system allows ensuring stable operation of the units, reducing the likelihood of damage and wear during operation.

Transmission mechanisms play an important role in transmitting torque from the engine to the working parts of the unit. Optimisation of the gear ratio, in particular, the choice of the correct gears, allows reducing the energy costs of the unit. The choice of gears includes not only determining the gear ratio, but also considering the material of the teeth, design features (in particular, the elasticity of the teeth, the accuracy of their manufacture), and the type of gears. For example, the use of alloy steels (AISI 4130, 20CrMnTi) for teeth increases their wear resistance and ability to withstand high loads, which is especially important for tillage equipment where torque transmission occurs under high mechanical loads. In addition, the correct choice of gear type (cast iron, steel, hypoid or spiral-cylindrical) depends on the requirements for working efficiency and wear resistance. The use of gears with hypoid or spiral-cylindrical teeth reduces energy loss, as they reduce friction and noise during operation. Production technologies such as heat treatment and carburisation also affect the strength and durability of gears, which is an important factor in reducing maintenance costs and increasing the service life of units.

AISI 5040 alloy structural steel is corrosion-resistant, making it ideal for use in aggressive environments. High-carbon non-alloy steel AISI 1080, in particular, provides high compressive strength and wear resistance when processing hard soils. ZrB_2-based ceramic composites are characterised by high heat resistance and wear resistance, which makes them ideal for use in conditions of high temperatures and abrasive wear. Given that vibrations are the main source of wear and damage, the use of shock-absorbing systems, in particular, rubber or spring shock absorbers, is an important element for reducing dynamic loads. This reduces the impact of vibrations on the working elements and components of the unit, extending their service life by 20-30%, which helps to reduce the frequency of repair and replacement of blades (Stavinskiy *et al.*, 2024).

Thus, optimisation of the structural elements of rotary tillage units allows increasing productivity, reducing energy costs, and extending the service life of equipment. The correct choice of materials, improvement of the shape of working bodies, and improvement of the fastening system and transmission mechanisms are necessary to achieve optimal results in agricultural engineering.

Load modelling and optimisation of working body geometry

Modelling loads on the working bodies of rotary tillage units is an important stage in the development and improvement of equipment. This allows optimising the design of the unit, reducing the risk of breakdowns and increasing its efficiency and durability. Given the complexity of the operating conditions, it is necessary to analyse both static and dynamic loads for different types of soil. In the design of the John Deere 8370R tractor complete with the Kuhn EL 402 R rotary cutter, static and dynamic loads play a key role in determining the efficiency of the unit and the durability of its components. Static loads occur when the tractor and milling cutter operate in stable conditions, without sudden changes in speed or irregularities on the ground surface. These loads include the weight pressure of the cutter transmitted through the attachment points to the tractor frame, and the uniform resistance of the soil to the working bodies during processing of a given depth. Dynamic loads, on the contrary, are variable in nature and occur due to uneven terrain, changes in the speed of the tractor, or when the working elements of the cutter come into contact with solid inclusions, such as stones. Such loads cause vibrations that are transmitted to the working elements and attachment system of the cutter, and pulse shocks that increase the risk of deformation or breakage. Given the complexity of the operating conditions, it is necessary to analyse both static and dynamic loads for different types of soil. Sandy soils with low resistance reduce horizontal loads, but can cause uneven vertical loads. Clay soils with high resistance increase horizontal and dynamic loads. Stony soils cause sudden shock loads (Sun *et al.*, 2022). Analysis of such variables allows optimising the design of aggregates and increase their efficiency. Virtual modelling of the working and structural parameters of a rotary cutter using Discrete Element Method (EDEM) software allows assessing the impact of various factors on its performance and durability. This approach makes it possible to analyse the interaction of the soil and the working elements of the cutter, considering such parameters as the angle of attack, knife geometry, rotation speed, and the physical and mechanical properties of the soil. Using virtual modelling tools, it is possible to determine the optimal parameters for reducing energy consumption, reducing wear on the working elements, and ensuring stable operation of the unit in various conditions. It also allows pre-testing new design solutions without the need to create physical prototypes, which significantly reduces development time and costs (Bossy, 2021).

Dynamic models are an important tool for analysing variable loads that occur during the operation of aggregates on different types of soils (Zhai *et al.*, 2022). They consider the physical and mechanical properties of the soil, such as its humidity, density and depth of cultivation, which directly affect the soil resistance and efficiency of the unit. Changes in soil moisture are one of the most significant factors affecting the operation of tillage units. Higher humidity can lead to increased soil resistance, which increases the load on the working elements. Dynamic models built with EDEM can anticipate these changes and optimise the machine's performance by adjusting the speed or rotation of the working members to avoid overloading. It also allows optimising fuel consumption, because energy savings can be achieved by reducing congestion. Considering variables such as soil density and structure helps to reduce the risk of premature wear of aggregates and ensure their stable operation under various conditions.

The efficient geometry of the working bodies of rotary tillage units is a key factor in ensuring their stable and long-term operation, reducing energy costs. Optimisation of geometric parameters allows reducing ground resistance, stresses in materials, and achieving an even distribution of forces during operation (Table 1).

Table 1. Influence of the geometry of the working bodies of rotary units on soil resistance and work efficiency

Working body geometry option	Angle of attack	Radius of curvature (mm)	Ground resistance level (N/m^2)	Productivity (ha/h)	Intended use
Direct disks	15°	50	2,000	1.2	Suitable for light soils or surface treatments with minimal energy costs
Curved discs	20°	70	1,800	1.5	Optimal for medium cultivation conditions, where an increase in soil resistance is required for better penetration into the deeper layers of the soil
Double angle blades	25°	60	1,700	1.8	They are used for heavy soils or to reduce fuel consumption by improving load distribution.
Combined disks (high radius)	30°	90	1,500	2	They are effective for working with heavy soils where maximum resistance reduction is required to achieve the highest productivity, especially for deep treatments.

Source: compiled by the author based on I. Shevchenko *et al.* (2024)

Optimisation of the geometry of the working bodies, including the shape of the blades (discs, claws, straight blades), is of great importance for the stable operation of rotary tillage units. Choosing the correct shape of the blades, along with the parameters of the angle of attack, the location of the blades, and the radius of curvature, helps to reduce ground resistance and reduce energy costs. Discs and claws provide different levels of soil penetration and processing efficiency, depending on their shape and angle of attack, which can reduce engine loads and increase productivity. The choice of working body geometry also affects the durability of the units, since reducing friction and optimal load distribution reduces the wear of the elements. Such changes help to reduce soil resistance and increase work efficiency. For example, if the soil resistance level is 2,000 N/m^2 the capacity is 1.2 ha/h, and when the resistance is reduced to 1,500 N/m^2 productivity increases to 2 ha/h. It also reduces stress in materials and promotes even load distribution during operation, which is important for efficient and economical tillage.

The angle of attack is one of the most important parameters for optimising the operation of working bodies. Correct adjustment of the angle of attack allows achieving an optimal balance between processing efficiency and energy costs. Too small an angle (less than 15°) leads to inefficient processing due to the sliding of the working body on the ground, which reduces the quality of processing. On the other hand, an excessively large angle increases the resistance of the soil, which leads to increased energy costs and overload of the unit. The ideal angle of attack usually varies from 20 to 30 degrees, depending on the type of soil and the depth of cultivation, which allows achieving an optimal level of productivity and reduce energy costs (Kalimullin *et al*., 2021).

In the case of using working bodies with a double angle of attack, the angle can vary depending on the processing area, which ensures more effective penetration into the soil. The double angle of attack combines two angles for different parts of the working body: one angle, which is sharper, provides deep penetration, and the second, which is less sharp, reduces resistance and increases the stability of the unit. This approach allows reducing soil resistance at different stages of processing and improving the quality of processing on different types of soils, while reducing energy costs. Similar solutions are used in blades and discs for heavy tillage equipment, where the efficiency of each stage of processing is critical. As for combined disks with a high radius, it is worth noting that a high radius means an increased diameter of the working body, which reduces soil resistance and improves processing efficiency. This allows evenly distributing the load over a large area and reducing energy loss during processing. This geometry is used for heavy soils, where conventional disks can create excessive resistance.

The uniform arrangement of the blades of the working bodies is also important for optimising loads and reducing vibrations. An asymmetric arrangement of the blades can occur in the event of improper installation or uneven wear of the elements, which leads to uneven distribution of forces. This causes additional vibrations that reduce the stability of the machine and can lead to rapid wear or even breakage of the blades. Damage to the blades can occur due to heavy use or insufficient maintenance, which is quite common in agricultural practice. On average, the blades break down after 300-400 hours of use without proper maintenance, which indicates the need for regular monitoring and maintenance to ensure efficient operation of the units (Acernese *et al*., 2021).

The optimal arrangement of the blades ensures constant contact with the soil, which contributes to uniform loosening and reduces energy costs. For example, for a rotary cutter, it is optimal to position the blades at a certain angle to the axis of rotation, which allows ensuring effective grinding of the soil without excessive resistance. In the case of a harrow, the blades must be positioned in such a way as to ensure an even load distribution over the entire width of the unit, which prevents uneven tillage and reduces wear on individual elements. This arrangement allows evenly distributing workloads, increasing the efficiency of the unit.

The radius of curvature of the working bodies plays a key role in reducing the stress concentration in the material (Havrylenko *et al*., 2021). Too small a radius of curvature (less than 50 mm) can lead to local overloads and cracks in the material, which reduces the service life of the working elements. Increasing the radius of curvature helps to reduce the stress concentration and the likelihood of cracks. The optimal radius of curvature is determined by mathematical modelling, considering the material of the working bodies and the operating conditions of the unit. This method allows analysing the mechanical properties of materials such as hardness, wear resistance and strength, and working conditions, including soil type, processing speed, and loads that occur during operation. Consideration of these parameters can significantly increase the durability of working elements and reduce the risk of their wear (Sanaei & Fatemi, 2021).

The choice of materials for the working bodies of rotary tillage units plays a crucial role in ensuring their durability, productivity, and resistance to variable loads. High-quality materials with high wear resistance and impact strength can ensure stable operation of the units even under difficult operating conditions (Table 2).

Table 2. Influence of materials on the wear resistance and durability of working bodies

Material	Steel/composite grade	Hardness (HRC)	Wear resistance (mm/h)	Durability (hours)
Alloy steel	AISI 52100	45	0.15	1,500
Composite materials	TiC-VC-WC/nanoWC-NiCr	55	0.10	1,800
Stainless steel	AISI 5040	50	0.12	1,700
High carbon steel	AISI 1080	60	0.08	2,000
Ceramic composites	ZrB_2	70	0.06	2,500

Source: compiled by the author based on Y. Wang *et al*. (2023)

The hardness of materials and their wear resistance significantly affect the durability of the working bodies of agricultural machinery. Alloy steel (AISI 52100) with a hardness of 45 HRC has a wear resistance of 0.15 mm/h and a durability of 1,500 hours, which is suitable for cultivator blades, gears, but the wear resistance is not the highest. Composite materials such as TiC-VC-WC/nanoWC-NiCr (hardness 55 HRC) have a wear resistance of 0.1 mm/h and a durability of 1,800 hours, making them effective for the manufacture of ploughs and ploughshares.

Stainless steel (AISI 5040) with a hardness of 50 HRC has a wear resistance of 0.12 mm/h and a durability of 1,700 hours, which is suitable for protective elements (equipment frames, protective covers). High-carbon steel (AISI 1080) with a hardness of 60 HRC is the most wear-resistant with an indicator of 0.08 mm/h and a durability of 2,000 hours, which makes it ideal for ploughshares, harrow discs. Zrb_2-based ceramic composites with a hardness of 70 HRC, have excellent wear resistance and durability of up to 2,500 hours, making them the best for use in plough heads, harrows. The choice of material depends on the operating conditions and the required characteristics of wear resistance and durability.

Wear resistance is the main criterion when choosing materials for working bodies, since constant contact with abrasive soil particles causes intense wear. Alloy steels 40X or 65G are often used in the construction of housings, shafts, and teeth of working bodies of tillage equipment, such as ploughs, cultivators, and harrows. These steels are high in carbon and alloying elements such as chromium, manganese, and silicon, which ensures their wear resistance. In addition, composite materials with carbide coatings can significantly increase the service life of working bodies, increasing their wear resistance to a level that is not achieved with conventional steels. Heat treatment technologies, in particular, quenching and carburisation, also significantly improve the wear resistance of steel, which reduces wear by 30-40% and increases the service life of working bodies by 50-60% (Tulaganova *et al.*, 2022). The choice of material depends on the type of soil that the unit works with and the required service life.

Impact strength is an important characteristic for materials exposed to dynamic loads, such as when handling uneven or dense soil. High impact strength (more than 50 J/cm^2) allows the material to absorb mechanical impacts without cracking or destroying elements, even under intense dynamic load. Materials enriched with nickel or molybdenum can withstand high shock loads without loss of strength, which is critical for stable operation of units in conditions of variable dynamic impacts, such as collisions with dense areas of soil or rocks. To ensure the reliability of materials, it is important to control technological processes, since the presence of defects, such as pores or microcracks, can significantly reduce the mechanical properties of the material. This requires the use of modern methods of monitoring the quality and processing of materials.

The combination of alloy steels (65-70%) and composite materials such as reinforced polymers (30-35%) provides an optimal balance between wear resistance and the ability to absorb shock loads. This is achieved through casting or mechanical integration of materials, in which steel components are connected to composite materials using welding, forging technologies or special adhesives that ensure a strong and long-lasting connection. Alloy steels give the structure high strength and durability, while composite materials help to effectively dampen vibrations and reduce shock load, which is especially important in conditions of intensive operation. The use of such materials allows achieving high indicators of durability and productivity of units, reducing the weight of working bodies by 20-25% and extending their service life by an average of 30-40% (Jaiswal & Barve, 2022). This has a positive effect on the energy efficiency of the units, since reducing the weight leads to a reduction in energy costs during operation. Material optimisation improves the performance of rotary tillage units by reducing wear, improving operational stability, and reducing overall maintenance and replacement costs. Thus, the correct choice of materials for working bodies is a key element for ensuring reliable and long-lasting operation of rotary tillage units, while maintaining high productivity and economy.

Springs in rotary tillage machines such as the John Deere 8370R tractor complete with the Kuhn EL 402 R rotary cutter are commonly used in parts of working bodies such as protective mechanisms and shock absorbers. They can be located in spring elements that provide repulsion of the working bodies when pressed or in contact with obstacles in the ground. Such springs help to protect the cutter teeth from overloads, reducing mechanical damage and extending the service life of the working parts of the unit. Spring elements can be installed directly in the system of fixing working bodies or in mechanisms that regulate the depth of cultivation, helping to adapt the equipment to different soil conditions (Fig. 1).

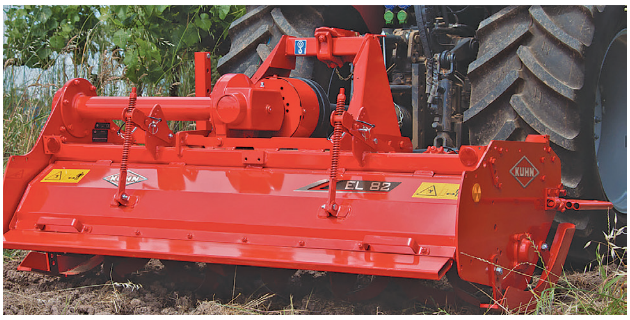

Figure 1. Rear hood with spring to optimise the seedbed where additional reinforcement and alignment is required
Source: Power Tillers EL Series (2023)

To increase durability and strength, the springs are made of alloy steels that have high strength and wear resistance, for example, steel with the addition of chromium, vanadium, or molybdenum. Alloy steels provide not only high elasticity, but also resistance to corrosion and high temperatures. This allows significantly extending the service life of the springs, even in harsh operating conditions, such as frequent collisions with rocks or dense areas of soil. The choice of spring material and design is important to ensure reliable operation of the units, since the correct selection of the spring helps to reduce the cost of repair and maintenance of equipment.

Compression springs are widely used to absorb vertical loads and impacts in various mechanisms of rotary tillage machines (Fig. 2). They can effectively reduce the impact of compressive loads and vibrations when working bodies come into contact with soil or obstacles. In rotary cutters, these springs are often placed in the suspension and shock absorber areas, where they protect the machine structure from damage when working on various types of soil. Such springs can also be used to control mechanical vibrations, reducing the level of vibrations and improving the stability of the unit.

Figure 2. Compression spring
Source: Types of spring (2022)

Stretching springs, on the other hand, are used in systems where it is necessary to maintain constant tension or stretching of elements (Fig. 3). They are used in tensioning mechanisms, such as dynamometers or belt tensioners, and for tensioning the working bodies of rotary tillage machines. Stretching springs ensure stable operation of the mechanisms and allow adapting the forces required to adjust the depth of tillage, which helps to increase the efficiency of the equipment.

Figure 3. Stretch spring
Source: Types of spring (2022)

Cone Springs with variable coil diameters are able to adapt stiffness at different stages of operation. They are often used in shock absorbers, where variable stiffness helps to more precisely adjust the operation of units for different conditions (Fig. 4). In rotary cutters, conical springs are used to reduce vibrations and shock loads, ensuring softer and more uniform operation of mechanisms under variable ground conditions.

Figure 4. Cone spring
Source: Types of spring (2022)

Serpentine springs, due to their ability to absorb vibrations, effectively reduce noise and vibrations in systems where flexibility is required (Fig. 5). They can be installed in various parts of rotary tillage machines, such as suspensions and shock absorbers. Their shape allows them to be used in such mechanisms where adaptation to variable loads is important.

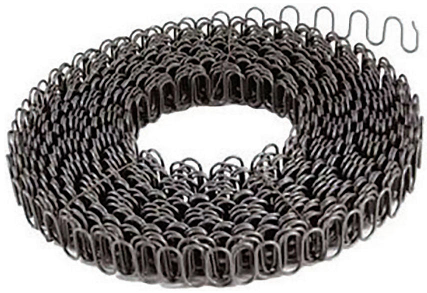

Figure 5. Serpentine spring
Source: Types of spring (2022)

Torsion springs are used to provide resistance to rotation in those mechanisms where protection against mechanical overloads or unpredictable rotational movements is required (Fig. 6). They are installed in the units responsible for the rotation of the working bodies or suspension mechanisms, helping to reduce the load on the machine structure when working on difficult and uneven areas.

Figure 6. Torsion spring
Source: Types of spring (2022)

The leaf type of springs is usually used to absorb heavy loads and ensure stable operation of mechanisms during intensive operation (Fig. 7). They are often installed in suspensions and other mechanisms of rotary tillage machines, where it is necessary to provide shock absorption and reduce vibration loads. The leaf type of springs allows reducing wear and improving the stability of equipment during operation.

Figure 7. Leaf type spring
Source: Types of spring (2022)

Poppet springs are used to create significant forces with minimal deformations (Fig. 8). In rotary cutters, they are used to precisely adjust the tension of the working bodies or adjust the pressure on the ground. This allows maintaining a stable processing depth and reducing the wear of mechanisms, improving work efficiency.

Figure 8. Poppet spring
Source: Types of spring (2022)

Machined springs made by mechanical processing allow creating complex shapes and precise mechanisms for rotary tillage machines (Fig. 9). These springs are used in systems where high accuracy and reliability are required, such as shock absorbers or suspensions. They can provide optimal vibration absorption and reduce noise during the operation of equipment, which increases operator comfort and reduces the need for maintenance.

Figure 9. Machined spring
Source: Types of spring (2022)

As a result of considering the different types of springs used in rotary tillage machines, it can be concluded that each type of spring has its own unique functions that ensure efficient and stable operation of equipment in difficult conditions. Compression, tension, conical, serpentine, torsion, and leaf springs perform a variety of tasks, from shock absorption of loads to maintaining precise adjustment of working bodies. The use of such springs reduces the wear of mechanisms, improves productivity, and increases the service life of machines, which is critical for efficient operation in the agricultural sector.

Damping elements and deformation characteristics of spring elements in tillage tools under the influence of dynamic loads

One of the most important ways to increase the stability of rotary tillage units is to use damping elements to reduce the negative impact of dynamic vibrations. Oscillations that occur during the operation of the units cause vibrations, increased wear of parts, and a decrease in the quality of tillage. The use of damping technologies can not only minimise these impacts, but also improve the performance and durability of equipment (Table 3).

Analysing the data in Table 3, conclusions can be drawn about the effectiveness of various methods of reducing vibrations and dynamic loads. The energy absorption indicated in Joules reflects the amount of energy that each element can absorb during operation. This indicator is key, as it determines the ability of the system to reduce vibrations and their negative impact on the stability of the unit. The more energy an element can absorb, the better it copes with reducing vibrations and shock loads. The effect on stability indicates the effectiveness of the elements in maintaining stable operation of the unit. For example, rubber shock absorbers and dynamic dampers show a high and very high level of stability, respectively, which makes them the most effective in reducing vibrations and protecting the structure from wear or breakage.

Table 3. Experimental data of the prototype sample of the SEMC

Vibration reduction method	Element type	Energy absorption (J)	Impact on stability
Rubber shock absorbers	Attachment points	5	High (ensure the stability of the unit as a whole)
Springs	Suspension system	7	Medium (reduce vibrations and contribute to the stability of the position of the working bodies)
Polymer inserts	Working bodies	4	Medium (absorb vibrations and ensure stability of the working body position)
Dynamic dampers	Unit chassis	6	Very high (effectively reduce vibrations and ensure the stability of the unit as a whole)

Source: compiled by the author based on R. Liu *et al.* (2022)

Among the considered methods, rubber shock absorbers absorb 5 Joules of energy and provide a high level of stability, which makes them a universal solution for complex vibration reduction in the unit. Springs that absorb 7 J have an average level of stability, but effectively compensate for dynamic loads that occur when working bodies interact with hard ground or stones. Polymer inserts absorb 4 J of energy and provide average stability, mainly used to reduce vibrations without significant mechanical load on the working elements. Dynamic dampers that absorb 6 J of energy have a very high impact on stability, which makes them ideal for providing effective vibration control and stable operation of the unit as a whole.

Optimal energy absorption depends on the operating conditions of the unit. It should be sufficient to reduce vibrations and dynamic loads, but without creating additional structural complications, such as being overweight. In this context, dynamic dampers and rubber shock absorbers are the most effective methods, as they provide a high level of stability of the unit, reduce wear on structural elements, and help to increase their service life. Rubber and rubber-metal vibration isolators are widely used vibration isolation systems in marine equipment and can withstand pulse loads, including from underwater explosions (Kluczyk *et al.*, 2022). In tillage equipment, rubber shock absorbers can absorb shocks and vibrations that occur in the attachment points. It is possible to use shock absorbers in disk units, where loads often have a pulsating character. They are resistant to soil moisture and abrasive particles, making them a practical choice for the field.

Polymer materials, in particular, polyurethane or high-strength plastic, are also widely used as damping elements. They combine high wear resistance with the ability to absorb shock loads. Polymer inserts can be integrated into attachment points or used as intermediate layers between metal parts. Their advantage is to reduce the weight of the structure and high resistance to chemical influences. The use of damping elements, in particular, shock absorbers and special rubber dampers on the joints, reduces vibrations and noise during operation of the units by 25-30% (Singh *et al.*, 2023). This not only extends the service life of individual components and the structure as a whole, but also provides more comfortable working conditions for equipment operators. In addition, reducing fluctuations contributes to the uniformity of tillage, which is an important factor for increasing yields. Thus, the introduction of damping elements is one of the key areas for improving rotary tillage units, which allows achieving better results due to stable operation and durability of equipment.

Variable loads are loads that change in their parameters (magnitude, direction, point of application) over time (Pylypaka *et al.*, 2024). In the context of the operation of rotary tillage machines, variable loads occur due to uneven soil, obstacles (stones, roots) and constant dynamic interaction of working bodies with the environment. Under these conditions, the key load characteristics are the modulus of force, the direction of the load vector, the point of application of force, and the arm of force, which determine the level of deformation and stress in the structural elements.

For example, during the operation of the Kuhn EL 402 R rotary cutter, the impact force modulus depends on the weight of the obstacle, the speed of the rotor, and the hardness of the ground. To determine the value of these parameters, dynamic models are used that consider the angular velocity of the rotor, the weight of the working body, and the interaction geometry. The force vector changes direction depending on the angle of interaction of the knife with the ground surface or obstacle, which creates complex combinations of loads, including vertical, horizontal and rotational components. The arm of force, which determines the load moment, is important for analysing the deformations of spring elements. For example, knife attachment mechanisms use torsion springs that respond to variable torques caused by shock loads. The deformation of such springs depends on the angular acceleration and moment of inertia of the working body, which provides protection against excessive load.

Cylindrical compression springs, which are installed in the suspension units, absorb vertical vibrations caused by the interaction of the rotor with the ground. Their work consists in changing the length under the influence of variable forces that occur during the movement of the machine. In such springs, it is important to ensure that elasticity is maintained after multiple deformation cycles. For this purpose, special materials with a high elastic limit are used, such as alloy steel.

Conical springs are often used to dampen vibrations with a gradual decrease in amplitude. Their design allows smoothly changing the stiffness depending on the applied load, which is useful for absorbing peak impacts. The operation of spring elements under the influence of variable loads also includes the study of oscillatory processes. For example, damping with polymer-metal shock absorbers allows absorbing both vertical and horizontal components of vibrations. The combination of rubber and metal in such elements reduces vibrations, which reduces noise and increases operator comfort.

Optimal values of design parameters of rotary tillage units

Optimal design parameters of rotary tillage units are key to ensuring efficient operation, high productivity and minimising wear. The overall dimensions of the unit determine its performance and manoeuvrability. For example, the working width usually varies from 1.5 to 4 metres for medium-sized machines, which allows processing large areas without excessive time spent. The length and height should be optimised for easy transport and stability in the field. Working elements, such as blades, must be made of high-strength materials that ensure wear resistance and long service life. Their number and location are selected in such a way as to ensure high-quality tillage, and the depth of tillage is regulated depending on the type of soil and agrotechnical requirements in the range of 10-30 cm. The speed of rotation of the rotor is a critical parameter. Optimal values are in the range of 200-350 rpm, which avoids excessive destruction of the soil structure. The rotor diameter, usually 50-80 cm, affects the energy consumption and quality of soil mixing (Du *et al.*, 2022).

Spring elements and dampers play an important role in reducing the impact of dynamic loads. The spring stiffness must be adjusted to compensate for peak loads without plastic deformation. For this purpose, high-strength steels such as AISI 52100, AISI 4130, 20CrMnTi are used. Polymer dampers provide vibration absorption, reduce noise and contribute to the durability of the unit. The weight of the aggregate should be sufficient to ensure stability, but not excessive to avoid compaction of the soil. For medium models, this parameter is about 800-1,500 kg. The working speed of the unit is usually 6-12 km/h, which provides an optimal balance between productivity and processing quality (Zhang *et al.*, 2022). The energy consumption of the unit depends on its design and working width. For example, vehicles with a width of 3 metres require a tractor with a capacity of 80-120 kW. All these parameters must be considered when designing and operating rotary tillage machines to ensure their efficiency, reliability, and durability.

DISCUSSION

The geometry and materials of the working bodies of the rotary tillage unit determined its resistance to variable loads. Determining the optimal angle of attack and radius of curvature of the elements contributed to a uniform distribution of stresses in the materials, which reduced the risk of premature wear and destruction. In addition, these parameters reduced dynamic loads, ensuring stable operation in difficult field conditions.

This issue was also investigated by K. Ravshanov *et al*. (2021). Their results confirmed that the geometry and relative position of the working bodies of rotary units reduce wear due to improved load uniformity and reduced friction. The use of optimal shapes, such as specially designed blades or discs, extends the service life of working bodies and increases the productivity of units, reducing energy costs. The most efficient design for non-dump tillage is a combination of a dumpless housing with flatteners, a battery with cut-out spherical disks, and a roller, which ensures high-quality processing with minimal energy costs.

Analysis of the results of the study indicates that the geometry of the working bodies of rotary units has a significant impact on reducing wear and improving the efficiency of tillage. Reducing the mechanical load on the working elements allows not only to extend their service life, but also to improve the productivity of equipment (Melnyk, 2024). In addition, the correct adjustment of parameters, such as the clamping force of the springs and the geometry of the working elements, reduces load fluctuations, which, in turn, reduces the risk of overload and damage to the components of the unit. Considering the type of soil and appropriate adjustment of the working bodies is important for achieving high efficiency and reliability of equipment in various operating conditions.

Y. Gao *et al*. (2024) also showed that the efficiency of rotary tillage largely depends on the interaction of the tractor, the three-point suspension mechanism, and the rotary mechanism. The study showed that as the speed of the unit increases, the vibration acceleration of all components increases, and the greatest changes were observed in the three-point suspension. To optimise the design of tractors and rotary cutters, it is important to consider resonant frequencies to minimise vibration, improve productivity, and reduce the negative impact on operator health.

Optimisation of the geometry of the working bodies of rotary units is a difficult task, since it requires considering not only technical characteristics, but also specific operating conditions (Bulgakov *et al*., 2019). Parameters such as the material of manufacture, shape and size of the working elements must be adapted to different types of soil and variable loads during operation. Incorrectly selected geometry can lead to rapid wear of the working elements and reduced productivity, which, in turn, increases maintenance costs and reduces the service life of the units.

It was found that structures with asymmetrically arranged working bodies often showed an increased tendency to vibrations, which negatively affected the overall performance of the units. Instead, the use of a uniform arrangement of the blades reduced vibrations and contributed to more efficient use of energy. It was found that optimisation of these parameters helped to reduce the energy costs of tillage compared to the basic structures, which are characterised by less efficient blade geometry, lack of vibration damping systems, and less adaptability to changing soil conditions.

B. Aramide *et al*. (2021) concluded that tools wear out quickly on arid agricultural land, which leads to high replacement costs and reduced operational efficiency. This wears out due to corrosion and tribocorrosion, which degrades the quality of tillage and increases fuel costs. To solve this problem, engineers are developing new technologies and materials to increase the durability of tools, which helps to reduce costs and increase productivity. The results obtained confirm the conclusions of B. Aramide *et al*. that optimisation of the geometry of the working bodies of rotary units significantly improves the efficiency of tillage. In particular, reducing friction and improving load uniformity leads to a reduction in the wear of working elements, which, in turn, helps to reduce energy costs and increase overall productivity. In addition, the results confirm that improving the design of aggregates, such as suspension mechanisms and clamping forces, also plays an important role in ensuring the stability of equipment and reducing negative environmental impacts.

The study by M. Askari *et al*. (2022) found that the energy efficiency of structures in optimising the distribution of loads on the working bodies of tillage units is a key factor, since the correct balance of loads can reduce fuel consumption and wear of working bodies. Improving this parameter is important not only to reduce operating costs, but also to reduce the negative impact on the environment (Shvedchykova *et al*., 2024). With this approach, geologists can achieve not only economic, but also environmental benefits. These findings of M. Askari *et al*. confirm the results of the study, as they demonstrate that the uniform arrangement of the blades of the working bodies significantly reduces the level of dynamic loads and vibrations affecting the unit. This allows not only improving the stability of the equipment, but also increasing its service life by reducing the wear of working bodies. In addition, an even distribution of loads helps to reduce energy costs, which also increases the overall efficiency of tillage.

The results also highlighted the importance of material selection. Alloy steels and composite materials with high wear resistance have ensured a longer service life of the working bodies. Heat treatment technologies, such as quenching and carburisation, increased the hardness of materials, which reduced their tendency to wear under the influence of an abrasive medium (Khlivnyi & Bazilo, 2023). This is especially true for the operation of aggregates on heavy soils, where abrasion is a significant factor.

This result is consistent with conclusions of I. Vidaković *et al*. (2021), who proved that the use of high-strength steels subjected to quenching and boron for the manufacture of working bodies of tillage units effectively increases their wear resistance. These machined steels have increased resistance to mechanical wear and corrosion, which reduces the frequency of replacement of parts and reduces maintenance costs. This is especially important for equipment operating in difficult environments, where durability and efficiency are key factors.

In turn, S. Locs *et al*. (2017) investigated tool steel reinforced with laser plating and concluded that heat treatment is an important process for reducing wear and extending the service life of tillage elements. It allows changing the internal structure of the metal, increasing its strength and resistance to wear. Based on the correct choice of temperature and processing time, an optimal balance between hardness and ductility can be achieved, which minimises the possibility of cracks or deformations during operation and reduces the frequency of repairs, improving the reliability of the equipment.

These data correspond to the theses given in the previous section, since they confirm that the use of high-strength alloy steels and heat treatment significantly increase the wear resistance and durability of the working bodies of tillage units. The high level of strength and resistance to external influences that tool steel provides reduces maintenance costs and the frequency of component replacement. However, given the higher cost of tool steel compared to carbon and alloy steels, there is a contradiction between its high performance characteristics and the economic feasibility of such use in agriculture (Adamchuk *et al*., 2016). Therefore, the use of such materials can be cost-effective only if the cost of their manufacture is reduced or due to significant savings on maintenance and repair of equipment in the long term.

The agreement between geometric parameters and materials showed a significant synergistic effect. The use of working elements with an optimal angle of attack in combination with high-carbon steel helped to significantly reduce local overloads, which often cause structural failure. This not only increased stability but also improved the quality of tillage. Y. Yang *et al*. (2021) developed biomimetic rotary tillage blades to reduce torque and power consumption based on the geometric characteristics of the spalax's five front claws. Their study considered the contour curves of the claw tips and the structural characteristics of the multi-claw combination. The optimal blade was chosen considering three factors: the ratio of the claw width to the lateral position, the angle of inclination of the multi-claw combination, and the speed of rotation, which was tested by testing with a ground hopper. The results of the study are consistent with the results of Y. Yang *et al*. in the fact that optimising the geometry of working bodies, in particular the shape and angle of attack, has a significant impact on reducing energy costs and improving the efficiency of tillage. The correct choice of materials and structural elements reduces wear and increases the durability of equipment, which is confirmed by positive test results and practical application of new technologies.

X. Zhao *et al*. (2025) also found that optimisation of the geometry of rotary blades of tillage units, in particular, in terms of specific strength and specific stiffness of structural efficiency, reduces local overloads, and lowers the risk of damage to machinery elements. They evaluated the developed model based on key performance indicators such as blade neck strength, maximum stress, fatigue life, and ultimate fracture stress. This optimisation ensures a more even distribution of forces, which reduces the concentration of loads on individual elements and increases the efficiency and reliability of equipment.

Comparing the data obtained in the course of the study, it can be concluded that optimisation of the geometry and materials of the working bodies of tillage units provides a significant increase in their reliability. It was revealed that the combination of an improved shape of working elements using high-strength materials allows not only reducing wear, but also increasing the resistance of units to mechanical damage under heavy loads. This helps to reduce the frequency of repairs and the overall operating costs.

However, further studies of variable loads that occur during the treatment of various types of soils, in particular static and dynamic loads, are necessary. Static loads usually occur due to the constant interaction of working bodies with the soil, while dynamic loads are associated with vibrations and shock impacts during the operation of aggregates. Understanding these loads will help to more accurately assess their impact on tool wear and durability. This is especially true for the development of universal structures that can adapt to different operating conditions. In particular, tests have shown that soil density significantly affects the efficiency of aggregates, so consideration of these factors in structural parameters is an important area of future research.

J. Shang *et al*. (2024) investigated the effect of the downforce of springs in seed drills on the stability of machinery during the treatment of various types of soils. They concluded that uneven loading can significantly reduce the efficiency of machinery, especially in conditions of heavy soils, such as clay or rocky. In such conditions, the units experience significant load fluctuations, which can lead to overload of the working bodies and their damage. To ensure stable operation, it is necessary to consider the type of soil and adjust the parameters of the units, in particular, the downforce of the springs, to reduce these vibrations. Conclusions of J. Shang *et al*. are consistent with the results of the study, as they confirm the need to adapt the structures of tillage equipment to the conditions of a particular soil. In particular, adjusting the pressure force of the springs is of great importance for ensuring stable operation of the units, especially in heavy soil conditions, where uneven loads can significantly reduce the efficiency of processing and accelerate the wear of working bodies. Consideration of these factors will not only reduce operating costs but also increase the durability of equipment and its productivity.

Z. Long *et al*. (2023) found that the development of universal designs that allow the tillage components of seed drills to adapt to different operating conditions is a key aspect for improving their efficiency and reliability. Such structures must be able to adapt to different types of soils, variable loads and atmospheric conditions, which allows maintaining the stability of the units in different conditions. Innovative solutions may include the use of replaceable working bodies or adaptive control systems that optimise the operation of equipment depending on external factors.

From the results of the study, it is clear that variable loads caused by different types of soils significantly affect the stability of tillage units. In particular, heavy soils, such as clay or stony ones, can lead to large load fluctuations, which increases the risk of overloading the working elements and their premature wear. This requires adapting the design of the units to ensure their stability and reliable operation in such conditions, which, in turn, confirms the need to improve the technologies and designs of tillage equipment. Optimisation of the design parameters of rotary tillage units not only increases their resistance to variable loads, but also reduces energy consumption and improves durability. This is of great importance for the development of energy-efficient and reliable agricultural machinery that can work stably even in difficult operating conditions.

CONCLUSIONS

The study confirmed the importance of choosing materials for working bodies with high wear resistance and impact strength. Medium-strength alloy steels, such as AISI 52100, AISI 4130, 20CrMnTi, and composite materials, in particular TiC-VC-WC/nanoWC-NiCr, demonstrate high efficiency in working with abrasive soils, reducing wear and increasing the overall durability of units. Carbide-coated materials such as medium-strength stainless steel (AISI 5040), high-carbon steel (AISI 1080), and ceramic composites (ZrB_2), showed excellent results in improving wear resistance. The use of heat treatment, in particular quenching and carburisation, allows achieving optimal material characteristics, which ensures reliability under dynamic loads.

To improve productivity and reduce energy costs, it is important to properly adjust the design of the units depending on the type of soil and working conditions. This allows ensuring stable operation and reduce the likelihood of overloading individual components of the units. Technical innovations aimed at improving these parameters can reduce the cost of operation and maintenance of equipment, which is an important factor in preparing the soil for further geological research or development of deposits.

Compression springs, tension springs, conical springs, coil springs, torsion springs, and leaf springs are all important in ensuring the reliable and efficient operation of rotary tillage machines. Each type of spring performs specific functions, including shock absorption of loads, maintaining precise adjustment of working bodies and reducing mechanical impacts on the design of equipment. Their use helps to improve productivity, reduce energy costs, and extend the service life of machines, which, in turn, ensures the efficiency of agricultural production.

Optimal parameters of rotary tillage units include a working width of 1.5 to 4 m, a processing depth of 10-30 cm, a rotor rotation speed of 200-350 rpm, and a diameter of 50-80 cm. The spring stiffness is selected using AISI 52100, AISI 4130, 20CrMnTi steels to compensate for peak loads. The weight of the unit is 800-1,500 kg, and the working speed is 6-12 km/h. The power of the tractor for a 3-metre-wide unit should be 80-120 kW, which ensures efficiency and reliability of operation. To further improve rotary tillage units, it is necessary to study the impact of the latest materials and technologies, such as nano-coating and alloying, on wear resistance and resistance to mechanical loads in long-term operation.

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CONFLICT OF INTEREST

None.

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Оптимізація конструкційних параметрів ротаційних ґрунтообробних агрегатів для підвищення стійкості роботи під дією змінних навантажень

Анотація. Дослідження проведено для підвищення стійкості ротаційних ґрунтообробних агрегатів шляхом оптимізації їх конструкційних параметрів з урахуванням змінних навантажень. Виявлено, що стійкість ротаційних ґрунтообробних агрегатів під дією змінних навантажень залежить від таких конструктивних параметрів, як геометрія та матеріал робочих органів, впровадження віброзахисних елементів. Визначено, що оптимальний кут атаки (від 20 до 30 градусів) робочих органів дозволяє знижувати опір ґрунту, що, своєю чергою, сприяє рівномірному розподілу навантажень по робочим елементам агрегату. Зміна радіусу кривизни робочих органів дозволяє знизити концентрацію напружень, що підвищує довговічність робочих елементів і зменшує їх зношення під час експлуатації. Аналіз механічних властивостей матеріалів показав, що використання спеціальних легованих сталей, що містять хром та марганець, підвищує зносостійкість робочих органів агрегатів, дозволяє зменшити частоту обслуговування, подовжити термін служби. Впровадження гумових амортизаторів у конструкцію вузлів кріплення допомогло зменшити амплітуду вібрацій і таким чином покращити стабільність роботи агрегату в процесі обробітку ґрунту. Аналіз роботи модернізованих агрегатів показав підвищення продуктивності та зменшення витрат пального. Покращення якості обробітку ґрунту досягнуто завдяки рівномірному розподілу глибини культивації та зменшенню рівня ущільнення ґрунту, що позитивно впливає на умови вирощування сільськогосподарських культур. Отже, оптимізація конструкційних параметрів ротаційних ґрунтообробних агрегатів дозволить підвищити їх стійкість до змінних навантажень, знизити експлуатаційні витрати, збільшити ефективність роботи та забезпечити довговічну й енергоефективну експлуатацію в умовах складних геологічних процесів

Ключові слова: геометрія лез; леговані сталі; зносостійкість; демпфуючі елементи; амортизатори

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Comparative research of 3D printer main control parameters and characteristics utilising Klipper firmware

Abstract. 3D printing is replacing traditional machine design methods, providing manufacturers with flexibility, ease of operation, and the ability to adjust process parameters in real-time. This study focused on determining the print speed to produce high-quality models in two scenarios: without Klipper firmware and using Klipper firmware for control parameters during printing. The 3D printer used in study used a Creality Ender 3 V3 SE printer with two sample 3D models. The authors conducted the testing process with three presets of print speed: medium speed, above-average speed, and maximum possible speed (maximum print speed 345 mm/s; above-average speed 180 mm/s; average 150 mm/s). As a result of the study, it was found that the most critical problem is that the stepper motor only sometimes has time to move the table by the required number of steps. The standard acceleration values were set at the level the original equipment manufacturer recommended, and the optimal printing speed was up to 120 mm/s. During the experiments, the standard acceleration values were increased, which showed positive changes and led to better print quality and stability of this process. It has been determined that it is best to keep the default settings and settings in the case of a standard (ready-to-pack) printer, as the printer will not be able to print faster due to its hardware limitations. In contrast, special hardware firmware can help dynamically adjust print parameters while maintaining maximum quality and optimising job performance. The study results can be used in industrial production to optimise 3D printing processes, improve product quality, and reduce manufacturing costs

Keywords: printing technologies; embedded systems; automated systems; iterative system evaluation; control systems

INTRODUCTION

Modern 3D printers increasingly rely on advanced hardware and firmware solutions to enhance performance and expand functionality. Contemporary hardware-software solutions offer a distributed architecture, high-speed command processing, and fine-tuned parameter adjustment capabilities in real time. These features enable precise motion control, higher printing speeds, and a reduction in the likelihood of defects, making them highly advantageous for various applications. Comparative analysis of such systems with traditional approaches is essential to identify optimal configurations for specific usage scenarios. This contributes to advancing 3D printing technology across industrial, scientific, educational, and other fields, ensuring more efficient and reliable printing processes.

Scientific study concerning 3D printers' print quality and speed is crucial, as it can significantly improve printer

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efficiency. H. Hemminger *et al.* (2022) emphasised the importance of effective system design for low-cost 3D printers, highlighting how stability, speed, and precision influence the printing process's output quality. The researchers examined key factors, including firmware, as essential components to enhance both speed and quality. Similarly, P. Geng *et al.* (2019) studied the effects of extrusion and printing speed on the stability of PEEK filaments. Their findings demonstrated that optimal parameter tuning significantly improves process consistency and output precision.

C. Arnold *et al.* (2019) explored strategies to achieve high accuracy and smooth surface quality in 3D-printed models, even when printing at elevated speeds. Their work provided insights into how specific adjustments to process parameters impact overall model quality. Expanding on this theme, A. Jandyal *et al.* (2022) presented a broader perspective, detailing the integration of 3D printing into Industry 4.0 frameworks. Their review highlighted sustainable practices and advanced technologies such as IoT and AI, showcasing their transformative potential for industrial applications.

Technical innovations in high-speed 3D printing, particularly with Fused Filament Fabrication (FFF) systems, have also been a focus of researchers. A.S. Suiker (2022) investigated the influence of small-scale parameters like raster angle and infill density, aiming to mitigate errors and enhance reliability in low-cost printers. Their work served as a foundation for improving mechanical properties and optimising speed. Similarly, R. Afshar *et al.* (2023) conducted a detailed analysis of the mechanical properties of PLA, utilising nonlinear modelling methods to determine the optimal infill density for maximising strength and minimising material usage.

Material optimisation remains another critical area of study. For example, M. Pivar *et al.* (2021) examined shape transformation capabilities in 3D-printed structures, emphasising the relationship between printing parameters and structural adaptability. Ş. Stănciulescu *et al.* (2015) addressed the issues of requirements to modify and adjust the open source firmware for embedded devices. In another study, M.R. Khosravani & T. Reinicke (2020) analysed the impact of raster orientation and printing speed on the strength of 3D-printed components, underscoring the importance of parameter optimisation for load-bearing applications.

Lastly, the exploration of material-specific settings has advanced 3D printing processes. J. Kentzer *et al.* (2011) focused on PLA, while others, like A. Jandyal *et al.* (2022), investigated nylon and composite materials, providing insights into durability and structural efficiency. R. Zucca *et al.* (2019) presented a case of modifying and adjusting 3D printer during set-up phase to fit a specific printing task. Collectively, these studies demonstrate that optimising parameters, material selection, and leveraging technological advancements are central to pushing the boundaries of 3D printing capabilities.

The research aimed to run an experiment using two identical printers, but one of them had been improved with the Creality Sonic Pad, which uses Klipper firmware to improve the processing of motor steps.

The tasks of the research included:

1. Analysing and comparing key parameters of 3D printers, such as printing accuracy, process stability, and job speed, focusing on their dependence on printing velocity.
2. Assessing the economic feasibility of upgrading printer firmware or implementing other modernisation measures by evaluating whether the potential improvements in printer performance justify the investment.

MATERIALS AND METHODS

This research was conducted in May 2024 at the research lab of the Department of Information Technologies, National University of Life and Environmental Sciences of Ukraine. Within the scope of the study, the printing speed of a conventional 3D printer and a printer with Klipper had been compared. Considering their technical features, the two printing options were carried out on the same printers. The main difference between the two printers was using the second printer of an additional controller called the Creality Sonic Pad, on which the Klipper is installed. In the course of the work, Creality Ender 3 V3 SE printers (Shenzhen Creality 3D Technology Co., Ltd., China) were used, which did not differ from each other, except for an additionally installed tablet with Klipper firmware (Fig. 1). It should be noted that the replacement of components that could affect their further operation was not carried out.

a) b) c)

Figure 1. 3D Printing equipment and materials
Note: a – Ender 3 V3 SE printer, b – Creality Sonic pad, c – sample yellow PLA material
Source: authors' photos

Critical to achieving high print quality was that the Ender 3 V3 SE has a sturdy aluminum frame that ensures high stability and accuracy when printing. The printer was designed to minimise vibrations, which was very convenient due to partial assembly before delivery; the setup process was greatly simplified, which lowered the entry threshold for different categories of users of this equipment.

The print area range of the Ender 3 V3 SE was quite wide and is 220×220×250 mm, which allowed one to create relatively large models without the need to divide them into parts. The heating platform of the device, which distributes heat quickly and evenly, allowed one to work with a wide range of different materials, such as PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), TPU (thermoplastic polyurethane), and others. This provided flexibility in the choice of materials and expanded the possibilities of using this printer. Note that the Bowden-type filament feeding system provides accurate and stable material feeding, which was essential for achieving high print quality even at high speeds. The use of high-precision threaded screws contributes to the accuracy of axis movement, which had a positive effect on the detail of printed models. The desktop of the Ender 3 V3 SE printer had a special coating that improves the adhesion of the first layer and makes it easier to remove finished models. This reduced the risk of deformation and damage to finished models when removed. An optional 32-bit control board provides smooth and precise control over the printing process, which was critical to achieving consistent, high-quality results. The equipment was equipped with an LCD (liquid-crystal display), which made it easy to adjust printing parameters and monitor the process. The detailed research hardware and set-up information is provided in Table 1.

Table 1. 3D printer characteristics and sample print model data

Type	Parameters	Description
Creality Sonic Pad	7' sensor display 1024x600 pixel res. ARM Cortex-A7 1.2 GHz.	USB, Wi-Fi та Ethernet G-code and STL – file support
Ender 3 V3 SE	220×220×250 mm. (printing range) 32-bit module	PLA, ABS, TPU – materials support
Klipper	Open source firmware Raspberry Pi	OctoPrint support
3D models	Calibration Cube 3D Benchy Model	3 axes calibration cube Complex 3D model of a ship

Source: developed by the authors

In the study, the Creality Sonic Pad were used, a high-tech accessory for 3D printers aimed at improving the control and optimisation of the printing process. It should be noted that the device was equipped with a 7-inch touchscreen with a resolution of 1024×600, which provides an intuitive interface for easy setup and monitoring of printing by users. The Sonic Pad supports USB, Wi-Fi, and Ethernet connectivity, providing a wide range of options for data transfer. This allowed users to easily upload files for printing directly from their computer or other devices. The device was compatible with G-code and STL file formats, allowing for the flexibility to use various 3D printing software.

An important characteristic of the Creality Sonic Pad was its ability to upgrade firmware, allowing users to integrate new features and improvements easily. This made the printer more adaptable to new technologies and user needs. The 1.2GHz ARM Cortex-A7 processor ensured fast data processing and stable operation even when printing complex models. The Sonic Pad also supported model previews and real-time tracking of print progress. Which in turn allowed the authors to control the printing process during the study and make the necessary adjustments promptly. In addition, the device has built-in capabilities for automatic platform calibration, which reduces setup time and increases print accuracy. Figure 2 and Table 2 outline the 3D model and printing details.

For comparison, the filament from the manufacturer Fainyi was selected with a type of plastic for printing – standard PLA. Such standard plastic required an operating temperature of 215-240 degrees at the nozzle outlet and a table heating temperature of 50-60. The following parameters were used during the work: nozzle temperature – 225°C and table heating temperature – 60°C. The recommended printing speed by the manufacturer of this equipment was 40-90 mm/s; these speeds result in sufficient print quality.

To conduct experimental research, a popular 3D model of the Benchy boat was picked, which had the necessary complexity and detail and contained a sufficient number of complex elements to check the print quality. This 3D model is often used as a base model for testing print quality. The basic and experimental printers needed a .gcode file that had been created using a slicer to print. For this, Creality Print, a slicer from the printer manufacturer, was used. During the experimental work, the following basic settings of the slicer were chosen: layer height of 0.20 mm, number of wall lines – 2, number of layers of the bottom and lid of 4, and Occupancy – 15%.

a) b)

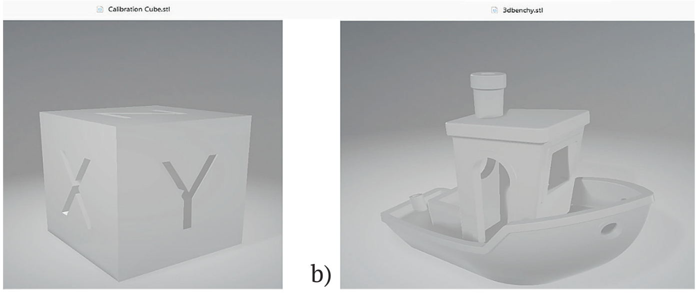


Figure 2. 3D print models

Note: a – calibration cube, b – sample research print 3D model

Source: developed by the authors

Table 2. Printing data

Components/Stage	Parameters	Description
3D printer filament *default*	PLA (Fainyi)	215 – 250C Nozzle output temperature 50-60C Print Bed temperature
3D printer filament *research set-up*	PLA (Fainyi)	225C Nozzle output temperature 60C Print Bed temperature
Printing Speed *recommended*		40-90 mm/s for optimal 3d printing model quality
3D models	3D Ship model (Fig. 2)	Designed in Benchy
3d printer slicer	1. printing tasks 2. ball height 3. number of wall lines 4. number of layers of the bottom and lid 5. occupancy	1. gcode code 2. 0.2 mm 3. 2 4. 4 5. 15%

Source: developed by the authors

In the study, Klipper, a powerful and flexible software for managing 3D printers, was used; it was necessary to improve the productivity and quality of printing. Such was an open-source firmware that leverages the computing capabilities of both the printer itself and an additional computer, usually with a single plateau such as a Raspberry Pi. The primary purpose of using the optional Klipper software was to streamline the printing process by reducing delays and improving motion control accuracy. During the work, Klipper ensured efficient task distribution: the basic calculations related to motion planning and command processing were performed on an additional computer. At the same time, the printer's microcontroller was used only for low-level tasks. This approach allowed us to achieve smoother and more precise motion control, which was especially useful when printing complex or high-speed models. With efficient motion planning and minimised latency, Klipper has made it possible to significantly improve print speeds without sacrificing quality. It was found that more precise control of the movement of the extruder and axes provides better positioning and detail of the printed models during the work.

RESULTS AND DISCUSSION

It has been found that during the operation phase, Klipper supported a wide range of functions, including the ability to control several extruders, which made it possible to print simultaneously from several materials and colors when performing work. Various printing settings, including acceleration, speed, and other characteristics, could be easily adjusted, which helped achieve optimal research results. Compatibility with popular 3D printer management software, such as OctoPrint, provided a user-friendly web interface for monitoring and managing the printing process.

As a result of the research, the equipment was utilised to its full capacity, including software and performance characteristics. After identifying the main features of different printers, it was possible to proceed to a practical comparison and test two different technologies (Klipper and standard firmware). During the work, the print quality was compared on two printers with the same technical component, but one was equipped with an additional device that should improve printing at high speeds. Therefore, during the study, the authors planned to study what speed indicators guarantee the printing quality and compare the work of two printers: the basic configuration and the improved version with Klipper retrofitting.

During the experiment, it the initial print speed settings were based on the previous experience and research reports. For the initial testing the default print speed had been set up, as expected the output model had been in high quality (Table 3). One of the research questions was to evaluate at what speed there would be a noticeable deterioration in print quality and how much worse the quality would be when using a basic printer. Accordingly, during the experiment, the following settings for the print speed in mm/s were set (Table 4).

Table 3. Print iterations velocity data

Iteration number	Perimeters, mm/s			Filling, mm/s			Bridge, mm/s	Fill-in gaps, mm/s	Press, mm/s	First layer speed, mm/s
	normal	small	external	normal	solid	top solid				
1	70	50	60	90	40	70	25	30	150	30
2	80	60	70	100	50	80	25	30	150	30
3	10	90	90	120	70	100	25	120	150	30

Source: developed by the authors

Table 4. First print iteration speed parameters (average speed)

Setting	Print speed	Top/Bottom layer speed	First layer movement speed	Acceleration of the top/bottom layer	Speeding up the printing of the first layer
Value	150 mm/s	75 mm/s	33 mm/s	2500 mm/s^2	500 mm/s^2

Source: developed by the authors

It should be noted that the other research models had already been printed using these printer settings, and the output print quality had been sufficient. There was no need to interfere with the print acceleration setting, and the print time on both printers was 1 hour and 28 minutes. The print output model is highlighted in Figure 3. The next phase of the research was to significantly increase the printing speed and adjust the acceleration parameters (Table 5).

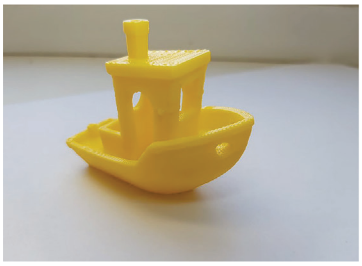
a)  b) 

Figure 3. Ship model result during the first iteration

Note: a – without using Klipper, b – with using Klipper

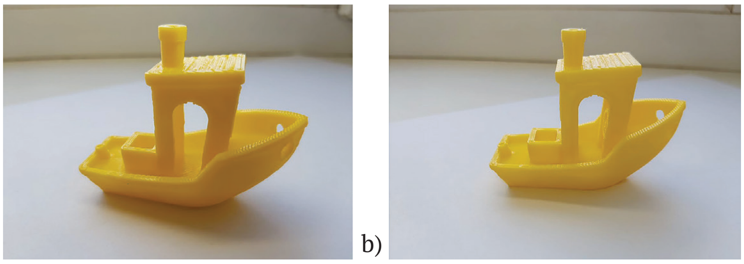
Source: developed by the authors

Table 5. Second print iteration speed parameters (higher speed)

Setting	Print speed	Top/Bottom layer speed	First layer movement speed	Acceleration of the top/bottom layer	Speeding up the printing of the first layer
Value	300 mm/s	250 mm/s	16.67 mm/s	3500 mm/s^2	1500 mm/s^2

Source: developed by the authors

There were no particular differences in print quality; both models had sufficient quality. With the increase in print speed and acceleration, the quality of both printers did not deteriorate, but certain work features were revealed. At this stage, there was already a noticeable difference in printing time between the two printers. A standard printer printed a part in 1 hour and 13 minutes, and a printer with a clipper in 51 minutes and 33 seconds. This result was unexpected and required determining its reason because the slicer displayed the approximate printing time as 48 minutes. Based on previous experience, the printing time using firmware was always less than the standard settings printing time by 3-5 minutes, which fits into the printing time of a printer with a clipper but is significantly different from a regular printer (Fig. 4). This could happen due to the insufficient processing power of a conventional printer, which does not have time to process each next step for a stepper motor. Accordingly, it led to the conclusion that the printer had certain architectural limitations that did not allow it to print at higher speed. The printer's printing speed with the Clipper was unexpected during the second attempt. It was clear, based on the printing process, that printing new layers becomes complex layers. The printer operated at a much higher volume than under normal conditions prior. At the same time, it should be noted that despite the mentioned issues, the printer continued its process, and the print speed was still significantly ahead of the competitor's. The main point of this experiment was to reduce the actual printing time. The goal was to reduce the printing time to at least 40 minutes. However, achieving such a goal took a great deal of effort. As a result, the final print time was reduced to 42 minutes. In order to achieve and maintain the speed, the layers' movement speed had been significantly increased. The printing time of the model was 1:13 on a regular printer, which was the limit for this printer, and 46:24 on a printer with a clipper.



a) b)

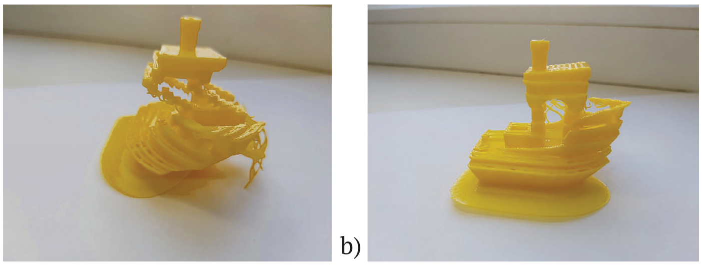
Figure 4. Ship model result on higher print speed
Note: a – without using Klipper, b – with using Klipper
Source: developed by the authors

Table 6. Third print iteration speed parameters (maximum speed)

Setting	Print speed	Top/bottom layer speed	First layer movement speed	Acceleration of the top/bottom layer	Speeding up the printing of the first layer
Value	345 mm/s	350 mm/s	45 mm/s	5000 mm/s^2	4000 mm/s^2

Source: developed by the authors

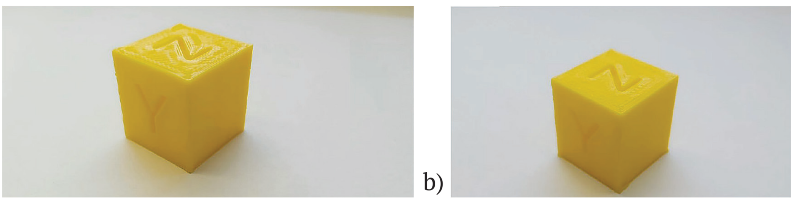
The numerical results showcased in the data table appear good (better than before); however, the original objective of the study was to evaluate the output model quality, which in this case could have been better (Fig. 5). The resulting model was of poor quality. It was now a minor flaw – the model of such quality can be used in practice under any application. It can only be used to highlight the results of scientific research. It was determined that the main reason for poor output quality was due to the printer engine. The engine did not have enough time to move the pin, and due to this fact, the engine skipped several preliminary steps altogether.



a) b)

Figure 5. Ship model result during third speed-test iteration
Note: a – first try, b – third try, both using Klipper
Source: developed by the authors

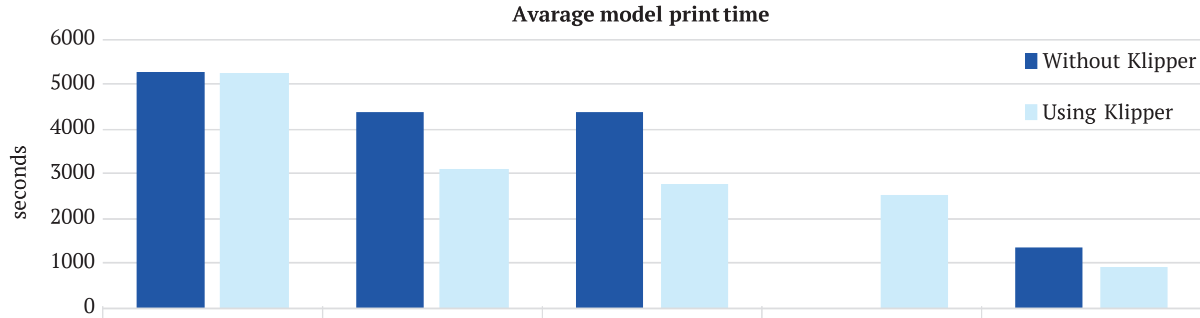
The next step of the research was to print the XYZ calibration cube (Fig. 6). It was decided to keep the print settings the same and determine if the printer could handle the model quality at high printing speed. The projected printing time was 14 minutes, but the printer with the Clipper coped with it in 15 minutes, and the regular printer in 23 minutes and 1 second. Surprisingly, judging by the print quality alone, a default settings printer had output a lower quality model than the Clipper. The model can be determined to be quite simple in terms of geometrical details and has few complex elements. At the same time, the printer with the Clipper produced a high-quality model, as it showed with more complex models in previous research iterations.



a) b)

Figure 6. XYZ calibration cube printing at highest speed
Note: a – without using Klipper, b – with using Klipper
Source: developed by the authors

After conducting a series of experimental studies and comparing the main parameters and characteristics of a conventional 3D printer and a printer retrofitted with Klipper, increasing printing speeds, it was found that the print quality is independent of the use of standard printer firmware or Klipper. In most cases, the study experiments had determined that in case when the equipment and its software parameters are set correctly, temperature and speed, acceleration values are selected correctly, the print quality does not change critically (not significantly) with an increase in print speed (Fig. 7). In some cases, degradation of the output printing model was detected. It should be noted that the changes were insignificant. However, if the parameters are set-up beyond the recommended print speeds, it could be stated that a printer with standard firmware does not have time to process the required steps for stepper motors and does not print faster, even if this was programmed in the slicer settings.



	Iteration 1	Iteration 2	Iteration 3	Max. speed (Fig. 5a)	XYZ cube (max. speed)
Without Klipper	5280	4380	4380		1381
Using Klipper	5280	3093	2784	2520	900

Figure 7. Iterations speed comparison charts – without and using Klipper firmware
Source: developed by the authors

The pursuit of high-speed 3D printing has become a focal point of research and development within additive manufacturing, driven by the need to improve productivity without compromising quality. This research compared experimental findings on the limitations of high-speed 3D printing with critical insights from scientific studies addressing the role of process parameters, hardware improvements, and material performance. Collectively, it was explored how advancements in print speed intersect with printer mechanics, material behavior, and industrial applicability. A critical speed ceiling for standard 3D printers was identified at approximately 180 mm/s, with most operations optimised around 150 mm/s. When augmented with systems like Klipper, speeds can reach up to 249 mm/s, but these enhancements expose significant mechanical and structural challenges. Chief among these issues is the stepper motors' inability to maintain precise control at high speeds, leading to printer vibrations, misalignment along the Y-axis, and, ultimately, print failure. The research results aligned with A. Kantaros & D. Piromalis's (2021) findings emphasised that low-cost desktop 3D printers struggle with maintaining accuracy at elevated speeds due to hardware constraints, particularly mass and inertia. The referred research focused on studying the moving parts, such as printer beds. Additionally, V.G. Gokhale *et al.* (2017) highlighted the impact of errors and degraded print quality at higher speeds for low-cost 3D printers, underscoring the importance of tuning acceleration values and optimising firmware settings.

There are many limitations related to low-cost 3D printers. Some researchers used different approaches to address and overcome such limitations – modifying slicer settings or adjusting acceleration, all efforts to improve model print quality. J. Wu (2018) showcased the post-effects of optimisation parameters, such as layer height, nozzle speed, and extrusion rates, to mitigate inaccuracies at higher printing speeds. At the same time, it should be noted that the experiment results showed that the effect of the mentioned modifications had to be balanced, adhering to the physical limitations of cartesian printers. This is all because the movement of heavy components poses inherent challenges. A. Lanzotti *et al.* (2015) found that hardware and parameter tuning had to be set up so that the joint parameters set up and material picked both lead to performance optimisation in the case of PLA parts for open-source printers.

High printing speed and movement acceleration introduced an additional layer of system complexity related to material properties, particularly in thermoplastics like PLA and nylon composites. The experimental results of the referenced scientists highlighted that the stress on printer structures and motors increases with increased print speed. It can sometimes lead to issues like uneven material deposition and reduced interlayer bonding. A. Kaman *et al.* (2023) proved this statement by the research findings, stating that nylon-based composites require careful calibration of temperature and speed to maintain structural integrity. It has been proven that at elevated speeds, the thermal environment around the nozzle and the cooling rate of the material become critical factors influencing print quality.

According to I. Christodoulou *et al.* (2023), the current trend of 3D printing innovations lies in achieving reliable high-speed 3D printing utilising the Fused Filament Fabrication (FFF) system. This work showcased the improvements in print head dynamics and the inertia reduction for the moving components. Using a fused filament system enabled significantly higher print speeds than standard printers. The highlighted approach addressed issues, such as the challenges of heavy-moving beds in Cartesian systems. K. Gomathi *et al.* (2021) explored advanced error characterisation and system optimisation for 3D printer systems, presenting firmware-level interventions to mitigate the impact of rapid movements on print accuracy. The presented findings can be summarised as the importance of balancing high-speed printing with adjustments tailored to specific applications and material requirements.

The experimental results of this work set the foundation for future research, such as firmware level code modifications, using complex 3D models, and expanding the range of tested printers. This path adheres to the broader trends in additive manufacturing research, where improving printer capabilities and expanding material compatibility are vital priorities. This research goal had been proven by the research conducted by A. Albar *et al.* (2019) and D. Chen *et al.* (2013). They strongly emphasised the importance of intelligent control systems and modular hardware integration. This leads to new system designs that support a broader range of industrial applications. Similarly, it has been noted that the precision and resolution of different 3D printing technologies at high printing speeds must be at the center of the resulting 3D printed model to meet industrial standards (Kluska, 2018). Examples of industrial applications where high-speed printing can be used include aerospace, automotive, and consumer goods sectors. Reducing model (part) production times is critical for the mentioned areas.

The comparison of experimental findings presented in this work with those conducted by renowned scientists highlights the complex nature of the high-speed printing field. Many more printed issues and challenges must be addressed apart from those mentioned in this research. Using Klipper firmware and fused filament fabrication systems has solved some of the high-speed printing challenges; optimisation of printing (filling) material usage and end-model mechanical endurance will be solved. The author plans to address the presented challenges by utilising printing and material process optimisation and creating a robust software framework for high-speed 3D printers to automatically adjust system parameters based on the printing industry and the end goal of the process. Besides, it can be beneficial to study and compare various 3D printer construction technologies in the future.

CONCLUSIONS

It had been established that the maximum print speed on a standard printer cannot exceed 180 mm/s; most often, it is about 150 mm/s. With additional equipment such as Klipper, the print speed can reach 249 mm/s, which is relatively high for printing, although it cannot be constant. At these print speeds, many properties could be improved, namely those that had to do with engine and layer functionality. In the study it was outlined that the most critical problem was the stepper motor only in some cases had time to move the table by the required number of steps. This was reflected in the appearance of a crackling sound in the printer and the vibrations of the equipment. In addition, the model was then offset along the Y-axis. After such an event, the printing process the could not continue print operations as the output model would had been damaged, and there was no point in reprinting it.

During the study, a newfound problem was identified. This issue arises when the print speed was increased – which resulted in a significant load on the engine. Due to which the structure and motors of the printer had been affected. Such loads were too significant for such classes of printers, namely those that utilise Cartesian mechanics. The main disadvantage was the movement of the table, which had a significant mass and took much energy to move. On average the printer only in a small number of cases had time to move then table. As the study showed, if one experienced a high print speed in a slicer, this would only in several occasions be considered when cutting the model because the slicer also considers the acceleration values, which are configured separately. Typically, the acceleration values were set to the OEM's recommended settings and did not require adjustments when set to optimal print speeds (up to 120 mm/s). During the experiment, the acceleration values were increased proportionally, which showed positive results.

If we take a case when the stock printer was used, like the research readings. In that case, one should refrain from interfering much with their standard parameters and settings because the printer could not print faster due to its hardware limitations. In the future, the authors plan to expand the presented research results, make manual code edits to the firmware, use more complex 3D models, and increase the variety of tested printers with a research focus on applications to several industrial applications.

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CONFLICT OF INTEREST

None.

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Порівняльне дослідження основних параметрів і характеристик системи управління параметрами 3D-принтера з використанням апаратного забезпечення типу Klipper

Анотація. 3D-друк активно замінює традиційні методи конструювання машин, забезпечуючи виробників гнучкістю, зручністю управління та можливістю реального часу налаштовувати параметри процесу. Дане дослідження було зосереджено на визначенні швидкості друку для отримання якісних моделей за двома сценаріями: без використання прошивки Klipper та з використанням мікропрограми Klipper для контрольних параметрів у процесі друку. 3D-принтером, який використовувався в дослідженні, був принтер Creality Ender 3 V3 SE з двома зразками 3D-моделей. Процес тестування проводився з трьома попередніми налаштуваннями швидкості друку: середня швидкість, вище-середнього швидкість та максимально можлива швидкість (максимальна швидкість друку 345 мм/с; вище-середнього швидкість 180 мм/с; середня – 150 мм/с). В результаті дослідження становлено, що найбільш критична проблема полягає в тому, що кроковий двигун не завжди встигає переміщати стіл на необхідну кількість кроків. Стандартні значення прискорення були встановлені на рівні рекомендованих виробником оригінального обладнання, а оптимальна швидкість друку становила до 120 мм/с. У ході проведення експериментів було збільшено стандартні значення прискорення, що показало позитивні зміни, та призвело до кращої якості друку і стабільності такого процесу. Було визначено, що у випадку зі стандартним (готовим з пакування до роботи) принтером найкраще зберегти стандартні параметри та налаштування, оскільки принтер не зможе друкувати швидше через свої апаратні обмеження, у той час як спеціальна апаратна прошивка може допомогти у виконанні завдання динамічного налаштування параметрів друку при цьому зберігаючи максимальну якість та оптимізуючи на виконання завдань. Результати дослідження можна використати в промисловому виробництві для оптимізації процесів 3D-друку, підвищення якості виробів та зменшення витрат на виготовлення

Ключові слова: 3D друк; апаратне програмне забезпечення; автоматизовані системи; контроль параметрів; ітераційна оцінка системи; системи управління

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Application of automated welding processes in the restoration of pipelines of power facilities

Abstract. The purpose of the study was to investigate the efficiency of automated welding processes in the restoration of pipelines of power facilities, with an emphasis on improving reliability and reducing repair time. The study used the analysis of technical literature, practical cases and the results of experimental implementation of automated welding technologies at power facilities. It was established that automated welding processes ensure high quality of welded joints in pipelines of power facilities, which significantly reduces the likelihood of defects. It was confirmed that the use of modern welding technologies helps to increase the corrosion resistance of joints and their ability to withstand high loads. Process automation has proven effective in ensuring stable welding performance, even under difficult operating conditions. It turned out that automated systems reduce the impact of the human factor, increasing the safety and reliability of work. The study also showed that automated technologies contribute to the rational use of energy resources during welding, minimise

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the cost of operating equipment, and ensure compliance of restored pipelines with modern technical and environmental standards. The introduction of these technologies helps to optimise repair work, reduce their duration and increase the durability of pipelines. This confirmed the feasibility of using automated welding processes to restore the infrastructure of energy facilities. It was determined that automated processes can ensure high welding accuracy, which is critical for the operation of pipelines under high pressure. The study showed that such technologies help to reduce material consumption by minimising the number of defects. In addition, the introduction of automation has proven to be an effective tool for improving the productivity of repair work and ensuring stable operation of energy systems in the long term

Keywords: corrosion resistance; high loads; human factor; safety; energy resources; environmental standard

INTRODUCTION

The use of automated welding processes in the restoration of pipelines of power facilities is important for improving the quality and efficiency of repair work. Pipelines of power facilities are operated in difficult conditions, which requires high requirements for the strength and tightness of connections. Automation of welding processes allows ensuring high accuracy and stability of welding, reducing the likelihood of defects due to the human factor.

Automated welding systems improve the corrosion resistance of welds and ensure their ability to withstand high loads, which is important for the durability of pipelines. They also allow achieving stable welding performance under variable operating conditions. The use of robotic systems significantly reduces repair time, reduces labour and material costs due to precise dosing. Welding automation also increases productivity and reduces the amount of material waste, which has a positive impact on economic and environmental performance (Naik *et al.*, 2024).

Based on these technologies, the frequency of pipeline repairs is reduced, which ensures uninterrupted operation of power facilities. Thus, automated welding processes are an effective tool for restoring pipelines, which helps to increase reliability and reduce the cost of their operation. The problem of ensuring the reliability and quality of welding connections of pipelines of power facilities in conditions of high operational loads has attracted the attention of many researchers. S.A. Sazonova *et al.* (2021) noted that automation of welding processes helps to improve welding accuracy, reducing the likelihood of defects. But their research focused on the need to improve technology, as some welding systems cannot operate in extreme conditions. M. Faccio *et al.* (2023) determined that robotic systems can minimise the human factor, but noted the high cost of such technologies, which limits their widespread adoption. A. Mehta & H. Vasudev (2024) examined the corrosion resistance of welds obtained using automated technologies and found that these joints have greater strength and resistance to destructive factors. However, their study showed the need to adapt processes to different types of materials, which requires additional research. C. Loukas *et al.* (2021) investigated the impact of automation on the cost-effectiveness of production, pointing to a reduction in material costs by minimising defects, but they noted that existing models for predicting costs have limited accuracy. M.A. Said *et al.* (2023) noted the importance of implementing automated welding systems in existing production processes, but the influence of external factors, in particular, humidity and temperature, was not considered.

M.A. Karim *et al.* (2023) investigated the influence of external factors on the quality of welding joints and found that temperature changes can lead to an increase in the likelihood of defects, which requires additional study for the stability of the results. T.-T. Nguyen *et al.* (2023) investigated the energy efficiency of automated welding technologies, finding that they provide energy savings, but stressed the need to improve energy control. J.E. Naranjo *et al.* (2022) analysed the operational durability of pipelines restored using automated welding technologies and found that such systems contribute to a significant reduction in repair time, providing significant resource savings. However, they did not consider the impact of different types of loads, which requires clarification. D. Mishra *et al.* (2021) analysed the quality of welded joints using automated technologies in industrial settings, finding that these technologies can significantly improve the stability of pipelines, but their application is limited by the lack of standards. R. Mahto & M. Rout (2024) investigated the impact of modern automated welding technologies on reducing maintenance costs, noting the rapid return on investment in these systems. Moreover, the need for additional research on the long-term effectiveness of such technologies in difficult operating conditions was emphasised.

These studies highlight advances in the automation of welding processes for pipelines of energy facilities, but point to existing gaps that require further study, in particular, in the adaptation of technologies to different materials, prediction accuracy and durability in difficult conditions. The purpose of the study was to determine the efficiency of automated welding processes in the restoration of pipelines of power facilities, focusing on improving reliability and reducing the duration of repair work. Research objectives:

- to investigate the effectiveness of using automated welding technologies for restoring pipelines of power facilities under high loads;
- to consider the impact of automation of welding processes on the quality of welded joints and reliability of pipelines of power facilities;
- to evaluate the cost-effectiveness of automated welding technologies compared to conventional methods

in power systems, considering the cost of materials, energy and labour, and the impact on the performance and quality of welded joints.

MATERIALS AND METHODS

The study evaluated the use of automated welding technologies for the restoration of pipelines of energy facilities, in particular, at thermal power plants (TPP), nuclear power plants (NPP), in hot water supply systems, and for fuel transportation and water supply. Welding methods were considered, which included both classical approaches and modern automated technologies that ensure high welding accuracy with minimal operator intervention. In particular, the methods of submerged arc welding, tungsten inert gas welding (TIG), plasma welding, and laser welding were analysed. The study also evaluated the economic efficiency of using automated welding technologies in comparison with conventional methods in the operating conditions of power systems. In particular, the cost of materials, the time required to perform welding operations, and the energy efficiency of various welding methods were compared. Automated systems showed significant savings both in material costs and in reducing the time required to perform repairs, which significantly reduced the overall maintenance costs of energy facilities and increased their operational efficiency (Alarcón *et al.*, 2021).

Numerous technical calculations were used to accurately control and optimise the welding process. One of the main aspects was the heat flow analysis, which determined the efficiency of the welding process using equation (1), which was used in the study:

$$Q = \frac{V \times I}{U}, \tag{1}$$

where Q – heat flow transmitted to the weld (W); V – volume of the material to be welded (m^3); I – strength of current (A); U – voltage across the electrodes (V). This parameter has a significant impact on the quality of the joint and the stability of the pipe connection.

The heat flow transmitted to the welding seam was calculated using equation (1). To optimise the welding parameters, the required heat flow was determined, considering the volume of welding material, current strength, and voltage at the electrodes. The efficiency of the welding process and the quality of the resulting joint depended on this, which is important for ensuring the tightness of pipelines, especially in conditions of high temperatures and pressures. The strength of the welded joint was calculated using equation (2):

$$\partial = \frac{F}{A}, \tag{2}$$

where ∂ – strength of the welded joint (Pa); F – load on the joint (H); A – cross-sectional area of the joint (m^2).

In equation (2), the strength of the welded joint was calculated, which is critical for determining the reliability of pipelines. A load on the connection that exceeds certain limits can cause damage to the pipelines. Assessment of the strength of the weld allowed predicting its durability and endurance during operation under high pressure and temperature, reducing the risk of accidents. The efficiency coefficient of the welding process was calculated using equation (3):

$$\mu = \frac{P_{out}}{P_{in}}, \tag{3}$$

where μ – coefficient of efficiency of the welding process; P_{out} – output power of welding process (W); P_{in} – input power of welding process (W).

A coefficient comparing the output and input power was used to evaluate the efficiency of the welding process. This helped to determine the energy costs of welding and evaluate the optimal use of energy. Technical features of submerged arc welding, TIG welding, plasma and laser welding were considered, with an emphasis on compliance with the requirements of energy facilities. Technical reports containing data on the efficiency of welded joints, material consumption, productivity and durability of structures were analysed (Kou, 2003; Mishra & Ma, 2005). The quality of joints, mechanical properties of materials, cost of welding materials, energy consumption, speed of work and durability of joints were evaluated.

Special attention was paid to comparing the economic efficiency of automated and conventional technologies. The use of automated systems helped to reduce the cost of materials and labour, decrease welding time, and reduce the number of defects, which confirmed the economic feasibility of their introduction in the energy industry.

RESULTS

Analysis of modern welding methods at power facilities

In modern energy production, where quality and safety requirements are extremely high, welding has become one of the main processes for connecting metal structures. The use of the latest welding methods, such as argon-arc, laser and electric arc welding, allows providing high-quality joints that can withstand significant mechanical loads and temperature fluctuations characteristic of energy facilities.

The process of reconstruction of heat exchangers and hot water pipelines at power facilities involved the use of automated welding systems to replace damaged or worn sections. In such operations, welding accuracy, temperature control, and ensuring minimal interference with the surrounding infrastructure remained critical. Automated systems equipped with modern robotic heads provided high-quality connections even in hard-to-reach places, which made it possible to avoid additional costs for dismantling equipment or expanding access to repair areas. Table 1 shows the main parameters used for various welding methods in power plants. The choice of welding method depends on the characteristics of each specific process and the requirements for the strength and tightness of the joints.

Table 1. Welding parameters for different methods

Welding method	Strength of current (A)	Voltage (V)	Welding temperature (°C)	Welding seam parameters
Submerged arc welding	150-250	22-32	2,000-2,500	High corrosion resistance
TIG welding	100-200	10-20	1,500-2,200	High accuracy
Plasma welding	100-300	20-40	2,000-3,000	Minimal deformations
Laser welding	50-150	5-15	2,500-3,000	High speed

Source: compiled by the authors based on B. Bagheri *et al*. (2021)

Automation of welding processes has a significant impact on improving productivity and reducing costs in energy enterprises. The use of robotic systems for welding operations ensures high accuracy, process stability, and reduces the risk of weld defects. This allows reducing the amount of waste and improving the quality of finished products, which is an important factor in a competitive environment. One of the key aspects of automated welding was to ensure proper thermal impact on the metal in the seam area. This parameter directly affected the quality, strength, and durability of the joint. Equation (1) was used to estimate the heat output that was released during welding. Automated systems allowed precisely adjusting the parameters V, I, and U, ensuring even heat distribution and preventing overheating or insufficient melting of the material. For example, in the case when V = 0.02 m/s, I = 200 × A, U = 24 × V, the heat output was calculated by equation (1):

$$Q = \frac{0.02 \times 200}{24} = 0.167.$$

Value Q determined the optimal welding mode in which the metal in the seam area melted enough to form a strong and stable joint. The use of automated systems also reduced the risk of defects such as pores, cracks, or uneven joints, which could reduce the reliability of the pipeline. Evaluation of the economic efficiency of using automated welding technologies in comparison with conventional methods in the operating conditions of power systems has shown significant advantages of automation. In particular, the introduction of automated welding systems has reduced the cost of welding operations. According to the calculations, the use of automated technologies reduces labour costs by 30-40%, since the need for numerous workers to perform welding operations decreases. This was made possible by reducing the time required to perform operations, which reduces the number of hours spent welding a single object (Bulganbayev *et al*., 2024). Analysis of technical reports showed that the quality of joints and mechanical properties of materials depend on the selected welding technology and process parameters. The speed of work and durability of joints can be improved by optimising the welding process (Mishra & Ma, 2005).

Material costs were also significantly reduced when using automated systems. Due to the accuracy and stability of welding processes, automated methods can reduce material waste by 15-20% compared to conventional methods, where a significant part of the materials goes to joints with defects. Automation also reduced energy consumption by 10-15%, as the systems optimise welding parameters and operate without constant operator intervention. In addition, automated welding technologies have shown higher productivity compared to conventional methods. Welding time was reduced by 25-30%, which allows increasing the number of completed works per unit of time. As a result, the total cost of performing welding operations was reduced by 20-25%, which makes the use of automated technologies economically feasible in the long term for energy enterprises (Curiel *et al*., 2023; Chukwunweike *et al*., 2024).

Automated welding technologies, such as submerged arc welding or tungsten inert gas (TIG) welding, have been widely used to restore heat exchangers. Submerged arc welding provided better protection against metal oxidation, while TIG welding allowed extremely precise seams, which is especially important in cases of working with thin-walled pipes. The use of automated welding systems in the reconstruction of heat exchangers helped only to improve the quality and durability of connections, but also to minimise the impact of the human factor on the process. This helped to reduce the time required for repairs, reduce operating costs, and ensure stable operation of hot water supply systems at power facilities.

Calculation and optimisation of thermal parameters of the welding process

One of the most important aspects of optimising the welding process is the calculation of thermal parameters. They depend on many factors, such as the type of welding machine, the material of the workpiece, and the welding mode. The correct choice of these parameters allows minimising thermal deformations and ensuring the necessary strength of joints with minimal energy costs.

TPP steam pipelines are key elements of the energy infrastructure, through which heat energy is transferred in the form of steam to turbines. The high pressures and extreme temperatures in which these systems operate create an increased load on materials, which requires periodic maintenance and repair to prevent accidents. In such conditions, modern automated welding technologies are of particular importance, which ensure high quality of connections and long-term operation of equipment. The use of these technologies allows not only extending the service life of steam pipelines, but also minimising downtime of power plants during repair work. Steam pipelines at thermal power plants are an important element of infrastructure that ensures the transportation of steam under high pressure and temperature to turbines. High temperature and mechanical loads create conditions in which metal joints can lose strength over time, which increases the risk of accidents. Therefore, the repair of steam pipelines is critical for ensuring the safety and efficiency of thermal power plants. Automated welding systems, in particular, submerged arc welding, allow creating high-quality seams with controlled properties. Submerged arc welding ensures uniform heating and melting of the metal, and also protects the welding area from oxygen and moisture, which significantly increases the strength and durability of joints.

During the repair of steam pipes, the strength of the weld is estimated by calculating the stress in the material using equation (2). For example, if a force F = 1,000 N is applied to the weld and the cross-sectional area of the joint is A = 0.005 m², the voltage is determined by the equation (2):

$$\partial = \frac{1.000}{0.005} = 200.$$

The obtained voltage value $\partial = 200$ MPa demonstrates that the weld can withstand significant mechanical loads characteristic of the operating conditions of steam pipelines. This ensures high structural reliability even when exposed to extreme temperatures and pressures. Advantages of automated welding systems:

1. High precision and quality. Automated systems ensure uniform heat distribution, which minimises the development of microcracks in the joints.

2. Reduced repair time. The use of automation significantly speeds up the welding process, which is important for reducing downtime of power plants.

3. Reduced human factor. Automated welding systems reduce the risk of errors caused by operator fatigue or inexperience.

4. Improved corrosion resistance. Submerged arc welding creates joints with high corrosion resistance, which is crucial for the operation of steam pipes in aggressive environments (Ren & Skilton, 2024).

The use of automated welding systems for the repair of steam pipelines at thermal power plants helps to increase operational reliability and extend the service life of equipment. Mathematical calculation confirmed that the welds made using modern technologies can withstand significant loads, ensuring uninterrupted operation of power plants in difficult conditions. Main pipelines designed to transport oil, gas, and other fuels required maximum tightness and strength of welded joints. Automated welding systems helped to minimise the human factor during operation, ensuring uniformity and high quality of seams. This was critical to preventing leaks that could lead to serious environmental disasters and economic losses.

The tightness of main pipelines was estimated using equation (3). This coefficient of efficiency of the welding process allowed assessing how effectively the pipeline retains pressure after welding. For example, if the inlet pressure was $P_{in} = 2.5$ MPa and output $P_{out} = 2.45 \times$ MPa, then:

$$\mu = \frac{2.45}{2.5} = \approx 0.98.$$

The value μ = 0.98 indicated that the pressure loss was minimal and the tightness of the weld met the standards required for fuel transportation. Modern automated welding systems used methods such as submerged arc welding, laser or plasma welding, which ensured the accuracy and constancy of the welding process parameters. In addition, before starting operation, the restored pipeline sections underwent additional leak tests using hydrostatic testing to confirm the reliability of the connections in real-world operating conditions. The introduction of automated technologies in the restoration of main pipelines has helped to improve environmental safety, reduce repair costs and the risk of accidents. This made such systems indispensable in the field of transportation of energy resources.

NPP cooling systems are among the most critical components that ensure the safety of reactors and other functions necessary for the normal operation of the plant. The main requirements for these systems are high tightness and strength of pipeline connections, which ensures efficient cooling of the reactor and prevents leaks of radioactive materials. Automated welding technologies, in particular laser welding, occupy a special place in the restoration of NPP cooling pipelines. Laser welding ensures high accuracy and cleanliness of the joints, which are necessary to ensure tightness. Based on the use of laser technologies, it is possible to avoid microcracks in welded joints, which can lead to leaks. In addition, laser welding allows performing high-precision welding, which is necessary for working in high-pressure and temperature conditions typical of nuclear power plant cooling systems.

These technologies minimise the risk of radiation leakage, as they reduce the likelihood of defects in welds that can cause radiation leaks. In addition, the use of laser welding guarantees high durability of the pipeline structure, which is important for the smooth and safe operation of nuclear power plants in the long term (Li *et al.*, 2023). Table 2 contains the key characteristics of welding technologies for different types of pipelines.

Table 2. Comparison of welding technologies for different types of pipelines

Pipeline type	Welding technology	Performance parameters	Notes
TPP steam lines	Submerged arc welding	High joint strength, resistance to temperatures up to 600°C	Provides high resistance to corrosion and thermal loads
Hot water heat exchangers and pipelines	TIG welding	Welding accuracy, minimal deformations	Used in confined spaces, minimises heat exposure
Main pipelines for fuel transportation	Submerged arc welding, laser welding	Tightness, joint strength, leak reduction	Tightness is important to avoid fuel leaks

Continued Table 2.

Pipeline type	Welding technology	Performance parameters	Notes
NPP cooling systems	Laser welding	No microcracks, high tightness requirements	Minimises radiation leaks, ensures durability of joints
Alternative energy pipelines	Robotic welding	Welding speed and accuracy, saving time	Used for rapid reconstruction of pipelines in bioenergy installations
Water supply pipelines for energy facilities	Manual welding, automated welding	Resistance to corrosion, water shocks	High strength to ensure uninterrupted water supply

Source: compiled by the authors based on M. Alarcón *et al*. (2021), S.M. Senthil *et al*. (2022)

A comparison of welding technologies used in various types of pipelines at power facilities was considered, and the efficiency of laser welding in the context of nuclear power plants was analysed.

Economic and technical advantages of implementing automation in welding production

Investing in automated welding systems offers significant technical and economic benefits. Firstly, automation allows reducing the time required to perform welding operations, which helps to increase the overall productivity of the enterprise. Secondly, automated technologies reduce the impact of the human factor, which minimises the number of errors and defects, thereby increasing the quality and reliability of products.

Welding technologies, such as laser welding, play a critical role in ensuring the safety and reliability of nuclear power plant cooling systems. They allow achieving high tightness of joints, minimise the risk of radiation leaks, and ensure the durability of structures. A comparison of welding technologies shows that laser welding is one of the most effective methods for restoring NPP pipelines, since it ensures the accuracy and cleanliness of welds, which is especially important in conditions of high temperatures and pressures. Laser welding technologies are also essential for improving the durability and reliability of all critical components of power systems.

The growing use of alternative energy sources, in particular biogas, poses new challenges for engineers to design and maintain efficient and safe pipelines for transporting these energy carriers (Iskandarov & Baghirov, 2022). Biogas, as one of the most promising sources of energy, plays an important role in the development of renewable energy systems, due to its accessibility, environmental cleanliness and the ability to reduce greenhouse gas emissions. However, although biogas has many advantages, its transportation requires particularly high standards of tightness and reliability of pipelines (Doroshenko *et al*., 2023). The main problem is the chemical composition of biogas, which contains methane (CH_4), carbon dioxide (CO_2), water vapour, and trace amounts of hydrogen sulphide (H_2S) and ammonia (NH_3). These components can have an aggressive effect on pipeline materials, causing them to corrode and reducing the durability of pipes. Special materials and state-of-the-art welding technologies, such as automated welding systems, are used to ensure proper tightness of pipelines, especially in high temperature and pressure conditions. These technologies ensure welding accuracy and high quality of joints, which is critical for preventing leaks and ensuring the reliability of pipelines during biogas transportation. The use of automated welding technologies can reduce the risks of the human factor, increase efficiency and ensure the stability of the quality of joints. In addition, such systems allow controlling welding processes, minimising the possibility of defects such as cracks or pores that can lead to biogas leaks (Berx *et al*., 2022).

A special feature of biogas pipelines is the increased requirements for their tightness, since even minor leaks can lead to dangerous situations, such as explosions or environmental pollution. The use of automated welding technologies is an important step in meeting these requirements. Robotic welding systems can significantly reduce the risk of human errors that can occur during manual welding, such as incomplete connection or uneven heating of the seam, which increases the likelihood of defects. The use of automated systems allows controlling the entire welding process, ensuring stable quality of welds, and also guarantees accurate heat dosing, which is necessary to create a uniform seam. An important aspect is the possibility of using such technologies in hard-to-reach places, which allows quickly reconstructing existing pipelines without the need for significant volumes of dismantling and replacement of pipes (Hicks *et al*., 2022). Reducing the impact of the human factor also has a positive impact on the economic aspects of projects, as it reduces the amount of labour costs, and reduces the likelihood of errors that may require expensive corrections in the future. Robotic welding in bioenergy can significantly reduce pipeline maintenance costs, which has a positive impact on the overall efficiency of projects in the energy sector. Automation of this process also increases the speed of pipeline repair and reconstruction, which is especially important for ensuring uninterrupted operation of bioenergy plants (Table 3).

Table 3. Parameters of automated welding processes in the reconstruction of pipelines of alternative energy sources

Parameter	Description
Welding type	Use of robotic welding systems to ensure high accuracy and repeatability of joints, which reduces the risk of defects
Advantages of automation	Reduction of the impact of the human factor, improvement of efficiency and accuracy, reduction of the time required to complete work, ensuring stable quality

Continued Table 3.

Parameter	Description
Pipeline materials	Application of special alloys and materials that are resistant to corrosion and mechanical loads, which increase the durability of pipelines
Key success factors	Welding quality control, seam accuracy, efficiency of technologies used, adaptation to specific operating conditions
Application	Transportation of biogas and other renewable energy sources through pipelines in bioenergy plants
Risks	High pressure and aggressive properties of biogas can lead to leaks; the need to ensure tightness and strength of compounds

Source: compiled by the authors based on L. Hart *et al*. (2023)

Modernisation of water supply pipelines at energy facilities is an important aspect for maintaining the stable operation of all systems of an energy enterprise. Water at such facilities is used not only for cooling equipment, but also for technological processes, sanitation, and other purposes. Due to the high requirements for the safety, reliability, and resistance of pipelines to external and internal loads, it is necessary to regularly modernise water supply systems (Hrytsanchuk *et al.*, 2023). Automated welding technologies play a key role in pipeline modernisation, as they provide high welding accuracy, which is crucial for ensuring strong and tight connections. One of the main advantages of automated welding is the ability to create seams that are free of defects such as pores, cracks or uneven material distributions, which reduces the risk of pipeline damage during operation (Liu *et al.*, 2022a).

Modernisation of water supply pipelines at power facilities includes the use of welding to replace old pipelines, and to create new connections. An important aspect is that when upgrading pipelines, it is necessary to consider the possibility of corrosion on the metal parts of structures. To ensure high resistance to corrosion, special materials and welding techniques are used to reduce the impact of aggressive media, such as water with a high content of chemical impurities. In addition, automated welding allows connecting pipelines, considering the optimal mechanical characteristics of the materials used for their manufacture. Welding performed by automated systems has high stability, which reduces the likelihood of mechanical damage to pipelines during operation. Calculations of the optimal mechanical characteristics of connections can ensure resistance to internal loads and increase the durability of water supply pipelines. Due to automated welding, the modernisation of water supply pipelines ensures high resistance of pipelines to corrosion, which is especially important for energy facilities, where any malfunctions of the water supply system can lead to serious consequences. The use of automated welding systems reduces the cost of maintenance and modernisation of pipelines, and increases their service life (Prodous *et al.*, 2024). The use of automated welding technologies for the reconstruction of pipelines of biogas and water supply systems at energy facilities is a key factor in ensuring the reliability and safety of these infrastructures. Robotic systems can reduce the impact of the human factor, which significantly improves welding accuracy and reduces the risk of defects. Modernisation of pipelines using automated welding technologies ensures high mechanical characteristics of joints, which increases their resistance to external influences, such as corrosion, and increases the durability of pipelines. Based on the use of these technologies, an efficient and cost-effective solution is provided for the modernisation of water supply systems and pipelines of alternative energy sources, which is important for the stable operation of energy facilities and reducing maintenance costs.

DISCUSSION

The use of automated welding processes in the restoration of pipelines of power facilities is an important step in ensuring the reliability and safety of power systems. Pipelines at facilities such as thermal and nuclear power plants, and alternative energy facilities, face high requirements for tightness, strength, and durability. Automation of welding processes ensures high accuracy of welding joints, which is especially important in conditions where even minor defects can lead to serious consequences, such as fuel leaks or radiation leaks.

One of the key advantages of automated welding systems is the reduction of the human factor. Manual welding can lead to significant errors due to operator fatigue or lack of proper control over the process parameters. At the same time, automated systems ensure the stability and accuracy of each weld. This is important for pipelines operating in high temperatures, pressures, or aggressive environments, such as nuclear power plant cooling systems or pipelines for transporting biogas in bioenergy plants (Ismayilov *et al.*, 2020; Valovoi *et al.*, 2022).

This problem was also investigated by X. Zhang *et al*. (2024), who confirmed that automation in welding production significantly improves the accuracy and stability of processes. The use of robotic systems and automated welding machines allows achieving high accuracy in controlling temperature, speed, and other important parameters that determine the quality of the weld. The use of sensor technologies and feedback systems helps to constantly monitor welding parameters in real time, reducing variability and ensuring constant high quality. This is especially important in industries where the accuracy and stability of welding processes are critical, such as in the aviation or automotive industries. The study by R. Chakradhar *et al.* (2022) also showed that reducing the human factor in welding processes also contributes to improving welding quality. The human factor can lead to errors in settings, inaccuracies in performing operations, or physical fatigue, which affects the final result. Automation eliminates these risks, as robots and automated systems are not subject to fatigue and do not allow errors due to subjective factors. This reduces the number of defects and increases the durability and reliability of welded joints, which is especially important in highly responsible industries where every defect can lead to serious consequences. It is worth noting that automation in welding production not only increases accuracy and stability, but also reduces the cost of materials and energy by optimising processes. Robotic systems can automatically adjust parameters in real time, ensuring welding with minimal waste and energy costs. This helps to reduce the cost of production, making processes more cost-effective and efficient for enterprises. On the other hand, it is worth noting that although automation significantly reduces the impact of the human factor, an important role is still played by qualified specialists who are responsible for setting up and monitoring automatic systems. Therefore, although automation significantly improves welding quality, the need for technical supervision and maintenance of robotic lines remains an important component to ensure the continuity and reliability of production processes.

M. Iqbal *et al*. (2023) concluded that the use of various welding methods in pipeline restoration ensures high quality and durability of joints, especially in aggressive environments. Innovative methods, such as welding under water or using high-temperature methods, allow repairing pipelines even in hard-to-reach places. Based on the use of the latest materials and technologies, such as laser welding and ultrasonic methods, it is possible to significantly reduce the likelihood of defects and ensure high resistance of welds to corrosion and mechanical damage. The study by S. Gbagba *et al*. (2023) found that in the field of energy facilities, specialised welding technologies play a key role in ensuring the reliability and safety of structures operating under high loads and temperatures. The use of welding methods such as TIG or metal inert gas (MIG) allows achieving precision and purity of joints, which is critical for power equipment. These methods ensure high strength of welds, which, in turn, reduces the likelihood of accidents and breakdowns, and also allows extending the service life of power facilities, reducing the cost of their maintenance and modernisation. These results support the above study, as they demonstrate the effectiveness of using innovative and specialised welding technologies to improve the quality of joints in difficult operating conditions. For example, the use of laser welding and ultrasonic technologies in pipeline restoration processes can significantly reduce the likelihood of defects, such as cracks or pores, which can affect the reliability and durability of connections. This confirms the importance of investing in modern welding technologies to ensure efficient and safe infrastructure operation. In addition, the results also confirm that specialised welding techniques used at power facilities are capable of providing high weld strength, which is critical for facilities exposed to high loads and temperatures. This helps to mitigate the risks of accidents and malfunctions and reduces maintenance costs, which is especially important for the long-term and economical operation of energy facilities.

It is necessary to emphasise the study by S. Schumacher *et al*. (2022), who also found that one of the main problems associated with the introduction of automated welding systems is their high cost and limited availability, especially for small and medium-sized enterprises. The cost of such systems includes not only the cost of purchasing the equipment itself, but also its installation, configuration and maintenance. In addition, regular investment in software and hardware support is necessary to ensure the proper efficiency of automated systems. This can be a financial barrier for many companies looking to modernise their welding processes. In turn, Q. Guo *et al*. (2024) concluded that the need for highly qualified personnel to work with new technologies is also an important challenge. Automation of welding processes requires employees not only knowledge in the field of welding, but also the ability to work with modern equipment, including working with robotic systems, setting parameters, and monitoring the operation of automated lines. Insufficient skills of employees can lead to a decrease in the efficiency of systems or to technical problems. Therefore, for the successful implementation of innovative welding technologies, it is necessary to create training and retraining programmes that will ensure proper operation of new equipment. These data are consistent with the theses given in the previous section, as they confirm the importance of investing in welding automation to improve their efficiency and quality. However, as practice shows, high costs for the implementation and maintenance of automated systems create barriers to their widespread use, especially for small and medium-sized enterprises, which restricts access to the latest technologies. This confirms the need to find optimal solutions to ensure the availability of such systems, for example, through government support or equipment rental. In addition, as noted in the previous section, successful implementation of automated technologies is impossible without appropriate personnel qualifications. The data confirming the importance of highly qualified specialists for working with new welding systems once again emphasise the need to develop training programmes and retrain employees in the field of automation and robotisation of welding processes. This will ensure not only efficient use of technologies, but also increase the safety and reliability of welding operations.

A.S. Buang *et al*. (2024) also conducted a study, the results of which confirmed that the future of welding automation in the energy industry looks extremely promising, as with the development of technology, the need to improve the accuracy and efficiency of welding processes at energy facilities increases. Given the high loads and safety requirements, automated welding systems can provide significantly higher accuracy than conventional methods, which is crucial for preventing defects and accidents. The use of robotic systems allows reducing the time required to perform welding operations, reduce the likelihood of human error, and ensure the continuity of production processes even in difficult conditions (Andrienko & Tsybulskiy, 2024). The introduction of the latest technologies, such as artificial intelligence for monitoring and analysing welding quality in real time, also opens up new opportunities for optimising and controlling processes. Q. Liu *et al*. (2022b) also found that one of the main areas of development of automated welding technologies is to improve their availability and efficiency. As the cost of components decreases and technical solutions improve, automation will become more accessible to more enterprises, which will contribute to the spread of these technologies in various industries, in particular in the energy sector. In particular, portable automated systems that allow welding operations to be carried out directly on the ground are subject to development, which significantly reduces the cost of transportation and storage of equipment. In the future, it is also expected to develop the integration of automated systems with other production processes, which will optimise the operation of enterprises, increase productivity, and reduce the risks associated with the human factor. The findings indicate that automation of welding processes not only improves quality and safety, but also opens up new opportunities for the development of the industry in the face of modern requirements. Comparing the data obtained in the course of research, it can be concluded that automation of welding processes significantly increases efficiency and safety at energy facilities. A comparison of the results of using conventional welding methods and robotic systems shows a significant reduction in the number of defects and an increase in the accuracy of connections. This confirms that automation can provide significantly higher process stability, which is especially important for ensuring the safety and reliability of power systems. However, despite the obvious benefits, the cost of implementing such technologies remains a significant barrier for many businesses. A comparison of data on the availability and efficiency of automated technologies also indicates a tendency to gradually reduce the cost of equipment due to technology development and mass production. This, in turn, opens up new prospects for the use of automated welding systems not only at large power facilities, but also at smaller enterprises. Given this trend, it can be expected that in the coming years automation will become more affordable for medium-sized enterprises, which will significantly increase the efficiency of production processes and reduce dependence on the human factor.

J. Kahnamouei & M. Moallem (2024) concluded that automation of welding processes has a significant impact on the efficiency of pipelines, since it can significantly improve the quality of welded joints, which is critical for the durability of pipelines. The use of automated systems ensures the stability of the welding process, minimising the likelihood of human errors that can lead to defects in the joints, such as cracks or pores. This is especially important for pipelines transporting energy or chemicals, where any defects can lead to accidents or leaks. Automation also allows achieving greater accuracy in the execution of welding seams, which guarantees their high strength and resistance to loads and corrosion, thereby increasing the service life of pipelines. H. Hrinchenko *et al*. (2023) found that ensuring the reliability and safety of energy facilities through welding automation is an important component of their operation. High accuracy and quality control of welding in automated systems ensure the strength of joints operating under high temperatures and pressures, which is especially important for power facilities such as thermal power plants or nuclear power plants (Ismayilov *et al*., 2021). Automated technologies allow constantly monitoring the welding process in real time, which allows quickly identifying and eliminating possible defects even before they cause serious problems. This significantly reduces the risk of accidents and increases the level of safety at facilities that require the highest standards of reliability and control. When analysing the results of the study, it is clear that automation of welding processes has a significant impact on improving the efficiency and safety of pipelines, which is especially important for energy facilities. Research data show that automated welding systems provide higher accuracy and stability of welding seams, which reduces the risk of defects and, accordingly, increases the reliability of pipelines in the long term. This is an important factor for ensuring the smooth operation of power facilities, in particular, those that are exposed to high loads and aggressive environments. The results also show that welding automation significantly improves the level of safety at power facilities, reducing the likelihood of accidents and unforeseen situations. Systems that automatically monitor the welding process in real time allow quickly detecting and correcting even minor deviations, thereby preventing possible catastrophic consequences. This confirms the importance of investing in innovative technologies to ensure safety and efficiency in the energy industry, especially in environments that require high standards of reliability and accuracy.

CONCLUSIONS

The use of automated welding processes in the restoration of pipelines of power facilities has demonstrated significant potential for improving the efficiency, quality and safety of repair and modernisation works. The analysis showed that welding automation ensures high accuracy of joints, minimises the likelihood of defects, and reduces the time of work, which is critical for the infrastructure of power facilities. It was established that specialised methods of automated welding are used for various types of pipelines, such as main oil and gas lines, NPP cooling systems, heat supply networks and pipelines of alternative energy sources.

Among the advantages of automation, a reduction in the influence of the human factor was noted, which helps to increase the stability of technological processes and reduce the risk of accidents. Automated systems also reduce the cost of operating pipelines in the long term by improving the reliability and durability of structures. The results highlight the importance of implementing automated welding processes to reduce environmental risks associated with leaks or accidents at energy facilities. This allows ensuring high quality of service for critical infrastructure elements and contributes to their compliance with modern standards of energy efficiency and environmental safety.

The results of the study confirmed the high efficiency of automated welding technologies for restoring pipelines of power facilities, especially under high temperature and mechanical loads. In the course of the study, the tasks set were achieved, which provided a number of important conclusions. A study of the use of automated systems has shown that such technologies provide high welding accuracy even in severe operating conditions. For NPP pipelines, laser welding has allowed achieving sealed and durable connections, which helps to increase the level of safety.

Process automation has significantly improved the quality of welded joints. The use of robotic systems reduces the likelihood of human error, which reduces the risk of defects such as microcracks or pores in the metal. The results showed that automated methods contribute to a longer service life of pipelines, reducing the frequency of accidents. Automated welding technologies have demonstrated high economic profitability compared to conventional methods. Reducing repair time and maintenance costs, and increasing pipeline durability help to optimise costs. The analysis confirmed that the introduction of such technologies is financially justified even for large-scale projects. Thus, the use of automated welding processes is a necessary condition for ensuring the reliability, quality, and efficiency of pipelines of power facilities. Further development and adaptation of these technologies to new conditions will contribute to their widespread use, which is important for improving the country's energy security.

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CONFLICT OF INTEREST

None.

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Застосування автоматизованих зварювальних процесів при відновленні трубопроводів енергетичних об'єктів

Анотація. Мета роботи дослідити ефективність автоматизованих зварювальних процесів у відновленні трубопроводів енергетичних об'єктів з акцентом на підвищення надійності та скорочення часу ремонту. У дослідженні було використано аналіз технічної літератури, практичних кейсів та результати експериментального впровадження автоматизованих зварювальних технологій на енергетичних об’єктах. Встановлено, що автоматизовані зварювальні процеси забезпечують високу якість зварних з'єднань у трубопроводах енергетичних об'єктів, що значно знижує ймовірність виникнення дефектів. Було підтверджено, що використання сучасних зварювальних технологій сприяє підвищенню корозійної стійкості швів та їх здатності витримувати високі навантаження. Автоматизація процесів виявилася ефективною для забезпечення стабільних характеристик зварювання, навіть за складних умов експлуатації. З'ясувалося, що автоматизовані системи зменшують вплив людського фактору, підвищуючи безпеку та надійність виконання робіт. Дослідження також показало, що автоматизовані технології сприяють раціональному використанню енергоресурсів під час зварювання, мінімізують витрати на експлуатацію обладнання та забезпечують відповідність відновлених трубопроводів сучасним технічним і екологічним стандартам. Впровадження цих технологій сприяє оптимізації ремонтних робіт, зменшенню їх тривалості та підвищенню довговічності трубопроводів. Це підтвердило доцільність використання автоматизованих зварювальних процесів для відновлення інфраструктури енергетичних об'єктів. Визначено, що автоматизовані процеси дозволяють забезпечити високу точність зварювання, що є критичним для роботи трубопроводів під високим тиском. Дослідження показало, що такі технології сприяють зменшенню витрат матеріалів за рахунок мінімізації кількості дефектів. Крім того, впровадження автоматизації виявилося ефективним інструментом для підвищення продуктивності ремонтних робіт та забезпечення стабільної роботи енергетичних систем у довгостроковій перспективі

Ключові слова: корозійна стійкість; високі навантаження; людський фактор; безпека; енергоресурси; екологічні стандарт

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Modelling the energy balances community under conditions increasing energy independence and reducing greenhouse gas emissions

Abstract. There is a need to develop effective technical and technological solutions to optimise the use of renewable energy in combined energy supply systems, which will solve the problems of uneven load and stochastic generation, ensuring energy independence of communities and minimising environmental impact. The aim of the work was to create a model of optimal loading of the installations of the technological structure of the combined energy supply of the community when covering the daily schedules of the electric and thermal load of the microenergy system. Its use made it possible to form the structure of annual monthly forecast balances of heat and electricity of an energy-independent community with minimisation of negative impact on the environment for further forecast analysis and determination of directions of innovative improvement of the community energy system in terms of climate change prevention and sustainable development of society. The results of model calculations of monthly annual balances of heat and electricity for the formed variants of the technological structure of the combined energy system of the Smila territorial community showed that an increase in the share of renewable energy capacities in its structure from 55% to 69% with a 30% limitation of electricity consumption (imports) from the external grid leads to a 3.5-fold reduction in greenhouse gas emissions (CO_{2eq}) from electricity production. The overall reduction in GHG emissions of the community's combined energy supply system amounted to 42%. The increase in the share of green generation in the technological structure of the community's combined energy supply caused a surplus of electricity in the local grid, the share of which in the total annual consumption

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of the community for the option with the largest volume of green generation was 2.5 The research results showed that ensuring the alignment of renewable energy generation with the variable load local grid required further consideration of the possibility using energy storage systems to transfer excess electricity or technologies for converting it into heat energy. This would allow for the replacement of equivalent amounts of heat generation from natural gas boilers, contributing to an increase in the community's energy independence and reducing greenhouse gas emissions

Keywords: mathematical programming model; daily load curve; technological structure; energy balance; combined energy supply system; energy independent community

INTRODUCTION

Widespread implementation objects of renewable energy soursys and the current state of development of the latest technical and technological solutions for the conversion of biofuels for combined production of electricity and heat created opportunities for managing the efficiency energy supply to territorial communities under the conditions of increasing their energy independence and environmental friendliness. The strategic goal of decarbonisation of Ukraine's energy sector by the middle of this century has been proclaimed at the state level (Order of the Cabinet of Ministers of Ukraine No. 373-p, 2023) requires a further increase in the share of energy from renewable energy sources (RES) in the balance of regional energy systems, which until now have traditionally relied on generation from fossil fuels. The National Action Plan on Renewable Energy until 2030 (Order of the Cabinet of Ministers of Ukraine, 2024) is a supplement to the National Energy and Climate Plan (NECP) (Order of the Cabinet of Ministers of Ukraine No. 587-p., 2024) and determines the trajectories of its development by sectors until 2030, taking into account the policies and measures identified by the NECP: share of RES in gross final energy consumption in Ukraine in 2030 will be 27%.There will be in in heat supply and cooling systems – 33%; in electricity production – 29%; in the transport sector – 17%.

Local micropower grids have opportunities for the integration RES, taking into account the peculiarities of their interaction in meeting the demand of end consumers and coordinating the using the external energy system. Support for the development of local energy in Ukraine is envisaged by the Strategy for the Development of Distributed Generation for the period until 2035 (Order of the Cabinet of Ministers of Ukraine No. 713-p, 2024). The Strategy defines highly maneuverable natural gas installations, as well as RES – wind and solar power plants and energy storage facilities – as expedient for the creation of distributed generation systems. Further substitution of natural gas as a fuel with renewable gases, in particular biomethane, at gas reciprocating and gas turbine plants, in cogeneration, will contribute to the overall decarbonisation of the energy system.

In the reasearch by G. Kostenko & A. Zaporozhets (2023) the role of micropower systems with RES in increasing the stability of the power system was analysed. It was determined that the concept of local networks with distributed generation, storage and management of energy can reduce dependence on the common power grid and centralised power supply, as well as its vulnerability, while increasing its overall and local resilience and significantly reduce recovery time.

In the paper by Y. Varetsky & Z. Hanzelka (2015) presented a model for evaluating different strategies for electricity dispatching in a hybrid system connected to the grid, which includes solar and wind installations, as well as a grid storage system, taking into account the load profile of the microgrid. To calculate the flow of electricity in the system, statistical indices of solar radiation and wind speed data were used. O. Hotra *et al.* (2023) proposed a mathematical model for studying the processes of frequency and power regulation in power systems with distributed generation, which integrates renewable energy sources (primarily wind and solar power plants – wind and solar power plants – wind farms and solar power plants) and energy storage systems according to the principles of their self-sufficiency, which means that all activities of such a combined energy system, including stabilisation of energy frequency and capacity, are carried out exclusively through the use of own energy of local origin.

The research by V. Babak & M. Kulyk (2023) was devoted the creating of a fundamentally new structure and foundations for the functioning of the electrothermal system that connects the unified energy system of Ukraine and the district heating system (DHS) through the electrification of DHS through using of energy from autonomous wind and solar power plants and the capacities of nuclear power plants, which ensures high manufacturability, efficiency, reliability and environmental friendliness of each of these components.

In the paper by V. Derii *et al.* (2023) the results of the assessment the impact of structural changes in the DHS on greenhouse gas emissions were presented. It was shown that the increase in the consumption of biomass and solar energy in the DHS with the simultaneous reduction of the consumption of fossil fuels – coal and natural gas – contributed a significant reduction in greenhouse gas emissions (GE).

The theoretical and applied foundations of structural implementations of combined energy systems (CES) for energy supply of territorial communities with heterogeneous sources, formulated in the work by V. Kaplun (2023). It was based on a resource-process analysis of the functioning of local networks by searching for the optimal using local biofuels and RES in the combined production of electricity and heat, taking into account their present value. The key feature of such CES were their ability to predictably change the structure of the energy balance by replacing the main component of energy consumption from external networks and, under certain conditions, switch to an isolated (island) mode of operation without reducing the quality of energy supply. Synchronisation with external grids provided operational flexibility when using distributed generation sources with stochastic parameters, primarily from solar power and wind plants, and allowed maneuvering distributed generation in a micropower system.

Compilation of monthly balances of production and consumption of electricity and heat usually consists in determining the monthly volumes of energy generation of CES technologies based on the coefficients of use of their rated capacity for the production of electric and thermal energy in the monthly cycle. However, the unevenness of the daily load schedules of the local energy system, their seasonal, monthly and daily differences, the stochasticity generation of solar power and wind plants and the discrepancy of their capacity profiles to the form the daily schedule of electric load without the ability to control the supply of their power to the grid requires an analytical and computational study of the corresponding energy balances in the daily context.

Optimal composition and utilisation of generating capacities of the local power grid of the community covering daily schedules of electrical loads (DSEL) determined using the model of mathematical programming with integer variables, which belongs to the class of mathematical models for solving the problem optimal dispatching of generating capacities the power system (Abdou & Tkiouat, 2018).

The reasearch was devoted a model of optimal loading of units the technological structure combined energy supply when covering the daily schedules of electrical and thermal load of the micropower system. The use of such a model made possiblity to form the structure of annual monthly forecast balances of heat and electricity a non-volatile community with minimisation of the negative impact on the environment for further forecast analysis and determination directions for innovative improvement of the community's energy system under the conditions of climate change prevention and sustainable development of society.

MATERIALS AND METHODS

The model optimal loading of agreggats the technological structure combined power supply micropower system was developed on the basis of the model optimisation of the loading the generating capacities of the power system. The optimisation criterion was the minimisation production costs in compliance with the requirements of balance sheet reliability, as in S. Shulzhenko *et al.* (2020), T. Nechaieva (2021). At the same time, coverage of daily schedules of electric and heat load was provided. The main factors taken into account in the simulation were:

- actual structure, physical, technical and technical and economic indicators of electric and heat energy generation installations local CES. Relevant forecast indicators of generating plants that can be implemented in the process of technological development and improvement of the power system. In particular, cogeneration plants and power generating plants based on piston engines, gas turbines and combined-cycle gas technologies using natural gas, biogas and synthetic gases;
- simultaneous observance of the hourly balance of production and consumption of electric and heat energy in the power system in accordance with the daily schedules of electric and heat loads local power grid throughout the calendar year;
- hourly profiles of electricity generation by wind and solar power plants throughout the calendar year.

The formation of the forecast annual monthly balance of heat and electricity of the energy-independant community consisted in optimising the simultaneous coverage of the daily schedules electric and heat load of consumers local community with the summation of the obtained daily indicators of production and consumption in monthly and annual terms.

The main limitations of the developed mathematical model were balances for each time period of the day between the volumes of consumption and production of electricity and heat by electricity, heat and cogeneration plant. They were considered in modelling using artificial variables of import and export from the external power grid to settle the imbalance of electricity and artificial variable closing technology of heat production to settle the imbalance of thermal energy.

The balance of electricity production and consumption of the local power grid of the community for each hour of the day was as follows:

$$P_t^{WPP} + P_t^{PV} + \sum_{k\in K^{TPP}} p_{kt}^{TPP} + z_t^I - z_t^E = D_t,\ \forall t \in T, \qquad (1)$$

where T – set of modelling time periods. Since the daily hourly schedule of electrical loads is simulated (SEG), the set T consisted of 24 (1...24) items, everyone corresponds to a certain time of day; P_t^{WPP}, P_t^{PV} – capacity of electricity supply of wind farms and solar power plants to the local power grid of the community within an hour t, MWh; K^{TPP} – set of heat power plants local network the community considered in modelling (gas pistons, gas turbine plants with a quick start on natural gas, biogas cogeneration plants, cogeneration plants on natural gas, local mini-CHPs); p_{kt}^{TPP} – a variable from a set of real numbers, corresponding to the total power generated by installations from the set K^{TPP} during an hour t, MWh; z_t^I – variable of the amount of electricity imported from the external network during the hour t, MWh.; z_t^E – variable of the volume of exported excess electricity from the local network of the community to the external network within an hour t, MWh.; D_t – electricity consumption (power) by the local community within an hour t, MWh.

The hourly generation capacities of WPP and SPP were input data of the model and set in accordance with the profiles of their generation for a certain location of their location and installed electrical capacity. Heat power plants were defined by their unit capacities, the number available for operation, the range of power change relative to the previous period, the duration continuous operation and the number of possible start-ups during the day (Shulzhenko *et al.*, 2020).

The balance of production and consumption of heat energy of the CES of the community for each hour of the day was as follows:

$$\sum_{k\in K^{HP}} p_{kt}^{H\_HP} + \sum_{k\in K^{CHP}} p_{kt}^{H\_CHP} + z_t^{HI} - z_t^{HE} = D_t^H, \forall t \in T, \quad (2)$$

where K^{HP} – a variety of technologies for the production of heat energy the local grid heating network of the community (fossil fuel boilers, biofuel boilers, etc.)); $p_{kt}^{H\_HP}$ – a variable set of real numbers, which corresponds to the total power of heat generation by heat production units from a set K^{HP} of the loca heating network of the community (fossil fuel boilers, biofuel boilers); K^{CHP} – multiple combined heat and power plants and cogeneration plants (biogas cogeneration plants, natural gas-piston cogeneration plants), $K^{CHP} \subset K^{TPP}$, which are integrated into the local heating grid of the community; $p_{kt}^{H\_CHP}$ – a variable from a set of real numbers, corresponding to the total power heat energy generation by installations from a set K^{CHP}; z_t^{HI} – "artificial" variable for regulating the imbalance of heat production and consumption with determination of the volume of power deficit during the hour *t*, MWh; z_t^{HE} – "artificial" variable to settle the imbalance of production and consumption of heat energy with the determination volume of power surplus in the hour *t*, MWh; D_t^H – heat consumption power in the local community's CES within an hour *t*, MWh.

The power of heat supply cogeneration plants and combined production depends on the technological ratio between electric and heat power:

$$p_{kt}^{H\_HP} \leqslant p_{kt}^{TPP} \kappa_k^{E2H}, \forall k \in K^{CHP}, \forall t \in T, \quad (3)$$

where κ_k^{E2H} – correlation between electrical and heat power of a combined power and heat unit *k*.

The energy independence of the community is ensured by a certain level of self-sufficiency in its own electricity generation with a reduction in electricity consumption (imports) from the general centralised electricity supply network, which is set in the model by the share of electricity consumption from the external network from the total electricity consumption local community k^1:

$$\sum_{t=1}^{T} z_t^I \leqslant k^I \sum_{t=1}^{T} D_t. \quad (4)$$

The conditions for the use of heat and power plants for DSEG coating are formulated using restrictions on the number of their start-ups, composition and permissible load modes, described in detail S.V. Shulzhenko *et al.* (2020). Conditions for the use of heat generation units to cover the daily heat load schedule (DSEG) is formulated using restrictions on the number of their start-ups, composition and permissible load modes, similar to the restrictions for heat and power plants to cover DSEG.

The criterion of the optimisation problem is to minimise the costs of supplying electric and heat energy during the day using the generating power involved in the coating DSEG та DSHG, the cost of electricity consumed from the external network and supplied to the external network, the cost of heat energy of the technology to settle the heat imbalancea:

$$\sum_{t=1}^{T} \Big(\sum_{k\in K^{TPP}} p_{kt}^{TPP} c_{kt}^{TPP} + z_t^I c_t^I + z_t^E c_t^E + \sum_{k\in K^{HP}} p_{kt}^{H\_HP} c_{kt}^{HP} + \sum_{k\in K^{CHP}} p_{kt}^{H\_CHP} c_{kt}^{HP} + z_t^{HI} c_t^{HI} + z_t^{HE} c_t^{HE}\Big) \to \min, \quad (5)$$

where c_{kt}^{TPP} – the cost of electricity supply by an installation of the type *k* during an hour *t*, USD/ MWh; c_t^I – the cost of electricity imported from the external network during an hour *t*, USD/ MWh; c_t^E – cost of electricity exported to the external grid within an hour *t*, USD/ MWh; c_{kt}^{HP} – cost of heat supply by heat generation and combined heat generation units during an hour *t*, USD/ MWh; c_t^{HI} – cost of "closing" heat production technology to settle the imbalance of heat energy in the event of a shortage of heat energy, USD/ MWh; c_t^{HE} – coefficient at an artificial variable of the export excess heat energy to settle the imbalance of heat energy in the event of a power surplus, which is much more important than the cost of other technologies, USD/ MWh.

The total monthly balance of electricity production and consumption of the CES of the local community consisted of the sum of the resulting indicators of daily optimisation calculations for the corresponding month of the year:

$$\sum_{d=1}^{N_m} \Big(E_d^{WPP} + E_d^{PV} + \sum_{k\in K^{TPP}} E_{kd}^{TPP} + E_d - I_d\Big) = D_m, \; m = 1 \div 12, \quad (6)$$

where N_m – number days of the month *m*, $m = 1 \div 12$; E_d^{WPP} – volume of released WPP electricity per day d, MWh; E_d^{PV} – volume of released SPP electricity per day d, MWh; E_{kd}^{TPP} – the volume of electricity supplied by heat power installation type *k* per day *d*, MWh; E_d – the volume of excess electricity supplied to the network per day d, MWh; I_d – the amount of electricity consumed from the grid per day *d*, MWh; D_m – electricity consumption in month m, MWh.

The annual balance of electricity production and consumption of the CES of the local community consisted of the sum of monthly balances:

$$\sum_{m=1}^{12} \sum_{d=1}^{N_m} \Big(E_d^{WPP} + E_d^{PV} + \sum_{k\in K^{TPP}} E_{kd}^{TPP} + E_d - I_d\Big) = \sum_{m=1}^{12} D_m, \quad (7)$$

The total monthly balance of heat energy production and consumption CES local community consisted of the sum resulting indicators of optimisation calculations each day corresponding month:

$$\sum_{m=1}^{12} \Big(\sum_{k\in K^{HP}} H_{kd}^{HP} + \sum_{k\in K^{CHP}} H_{kd}^{CHP} + H_d^I + H_d^E\Big) = DH_m, \; m = 1 \div 12, \quad (8)$$

where, H_{kd}^{HP}, H_{kd}^{CHP} – volumes of heat output by heat generation units and combined generation of electricity and heat type *k* per day *d*, MWh; H_d^I – the volume of heat energy deficit local heating system of the community per day d, MWh; H_d^E – the volume of excess heat energy in the local heating system of the community per day d, MWh; DH_m – consumption of heat energy in the local heating system of the community in the month m year, MWh.

The annual balance of heat production and consumption in the local heating system community consisted of the sum of monthly balances:

$$\sum_{m=1}^{12}\sum_{d=1}^{N_m}(\sum_{k\in K^{HP}}H_{kd}^{HP}+\sum_{k\in K^{CHP}}H_{kd}^{CHP}+H_d^I+H_d^E)=\sum_{m=1}^{12}D_m. \quad (9)$$

Data on energy consumption of the Smila Community Cherkasy region of Ukraine for 2021 were used modelling the optimal loading of the generating power of the micro-energy system with the formation monthly balances of production and consumption electric and heat energy (Smila city territorial community, n.d.), which covered both the population and legal entities. This year was the first after the lifting of quarantine restrictions caused by the pandemic COVID-19, and the last before the start of full-scale Russian aggression against Ukraine. Indicators of electricity and heat consumption for this period served as the basis for the formation forecasts the post-war energy recovery community.

Model calculations of the optimal utilisation of the power of the CES with the coating of DGEN and DGTN local network of the Smila Community with the formation of monthly balances electric and heat energy was carried out using a software and information complex for modelling multi-node integrated and autonomous electricity and heat supply systems, developed using a combination of standard software Microsoft Excel and plug-in SolverStudio.

RESULTS AND DISCUSSION

The projected transformation of the technological structure of the microgrid of the Smila Community is based on the use of SPP, WPP and combined energy production units on solid biofuels and biogas. The energy independence of the community is ensured by the restriction 30% the share of daily electricity consumption from the external network from the volume of daily consumption of the community. As a maneuverable technology to ensure the balance of production and consumption of electricity, cogeneration gas piston units (KGPU) on natural gas with a total installed electric power of 10 MW were adopted. Excess electricity production that may occur during periods of "failure" of the GEN and the presence of significant base generation can be exported to the external (centralised) power grid, sold to third parties or accumulated.

The introduction of cogeneration is possible both on the basis of gas turbines and gas piston agregats. Gas piston agregats have a higher electrical efficiency than open-cycle gas turbines. Such agregats work best at biogas plants and in municipal heat supply, where there is a possibility of introducing cogeneration and using energy for heating.

The advantages of equipping existing boiler houses centralised supply systems (CCS) in Ukrainian cities with cogeneration gas piston units are availability appropriating infrastructure at the industrial sites of existing boiler housesю These are connected power lines and existing transformer substations for supplying electricity to local distribution power grids, which does not require additional costs for their construction. Boiler CCS are consumers of electricity of the first and second categories, which makes it possible using two power lines (main and backup) at the same time to supply electric power to the distribution grid. Gas pipelines for the supply of natural gas have already been supplied to these boiler houses (Teslenko, 2024). KSPE have high energy efficiency due to the cogeneration of electrical and heat energy (short terms of delivery, installation and adjustment of equipment with the presence of highly professional personnel, easier permitting procedures and faster construction times). They are responsible the requirements for frequent rapid starts and stops, which are becoming more and more necessary as the share of wind and solar energy in the energy mix increases. The simplification of the procedure for connecting generating installations (gas turbine, gas piston, cogeneration, etc.) to electricity networks, introduced by the National Regulator in May 2024, will help reduce the time for connecting such installations to electrical networks with priority using the exister energy infrastructure.

There is a mini-thermal power plant (mini-CHP) on wood chips and agricultural waste on the territory of the Smila Community. CHP provides 20-31% Community's total electricity demand. The production of electric and heat energy is provided using two modernised biofuel boilers DKVR-10-39-44 (Ukraine). Part of the high-pressure steam from which is supplied to two turbine generators, with a capacity of 6 MW each. The rest in the form of heat energy and hot water is supplied through the district heating system to the municipal sector, social and industrial enterprises of the city of Smila. To produce heat during the peak periods of the heating season, the CHP uses a KVGM-20 (Ukraine) natural gas water heating boiler with a heat power of 20 Gcal/h (23.2 MW).

For calculations, the monthly supply of electricity and heat of the Smila CHPP in 2021 were used. In model calculations, it is assumed that the CHP operates in the basic mode during the day without changing the power.

Determination of generation profiles of wind and solar power plants located within the Smila Community was carried out using a system for modelling the generation RES System Advisor Model (SAM), developed by the National Renewable Energy Laboratory (NREL) (Nate *et al.,* 2018). The detailed model of the PV simulation system SAM (Gilman, 2015) calculates the electrical power of the grid-connected PV system according to the number and specification of the system's PV modules and inverters, taking into account the impact on the performance the modules, the temperature of the environment and the structural features of the station construction. The Wind Power model of the SAM simulation system is capable of simulating the generation of electrical energy from either a single wind turbine or a wind plant with multiple turbines (Freeman *et al.,* 2014).

To determine the generation power WPP and SPP meteorological data of the area of their location are necessary. For SPP, they can be downloaded from the national solar radiation database NREL (NSRDB) by coordinates of the location of the installations. For wind farms, SAM only supports meteorological data for the continental USA. From June 2024, it became possible to download data on wind speed and direction in Ukraine from the RE Data Explore information resourcer. This resource allows to obtain data on wind speed at different heights and directions both for a separate location and for a certain area, which are used as an information resource to determine the performance of wind plants in the Wind Power model of the SAM modelling system.

The received monthly volumes of electricity generation from WPP and SPP with a nominal power of 1 MW, which are installed within the Smila Community, are given in Figure 1.

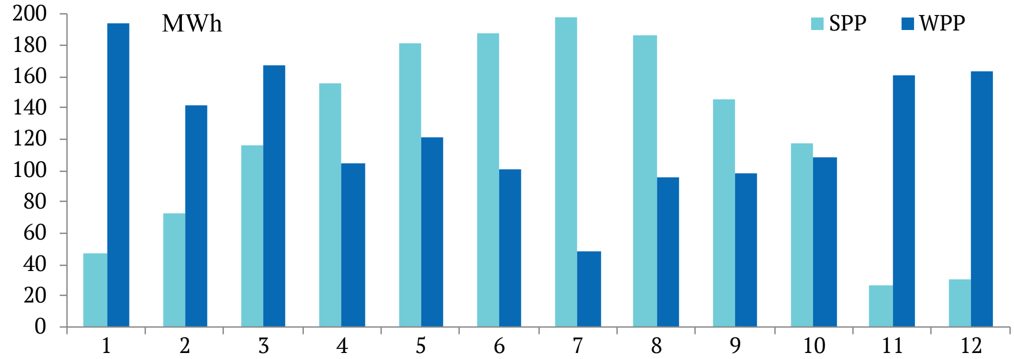

Figure 1. The monthly volumes of electricity generation from WPP and SPP with a nominal power of 1 MW within the Smila Community

Source: compiled by the authors

Model calculations of the optimal load power of the CES when covering the DGEN and DGTN of the local network Community were performed in forming variants of the technological structures of the power supply Smila Community (Table 1). During the simulation, it is assumed that the biogas gas compressor plant operates in the basic mode with a power change range of 10%. Natural gas KSPE is used as a highly maneuverable energy source with the possibility of frequent starts and stops. The heat load coverage takes into account the use of biomass CHP power, cogeneration plants, CHP hot water boiler and gas boiler houses CCS Community.

Table 1. Experimental data of the prototype sample of the SEMC

Technology	CSE structure options			
	1	2	3	4
CEC(PV)	1	2	3.5	4.5
BEC (WPP)	1.6	2.4	3.2	4.8
Biomass CHP plant	8.5	8.5	8.5	8.5
KSPE on biogas (BCGU)	1	2	3	4
KSPE on natural gas (NGCGU)	10	10	10	10

Source: compiled by the authors

The results forming monthly balances electricity for the corresponding variants of the technological structures CES Smila Community are shown in Figure 2.

As can be seen from the electricity balance coverage structures shown in Figure 2, the increase in the share of renewable generation in the structure CES leads increasing in excess electricity volumes for Community consumption. This is due to both the limited range of regulation of biomass and biogas installations, and the uncontrolled supply of energy from WPP and SPP to the grid, especially during night and day failures of DGEN. Figure 3 shows the structure of DGEN coverage for variant 4 of the technological structure CES for winter and summer days with the largest volumes of excess energy in these seasons.

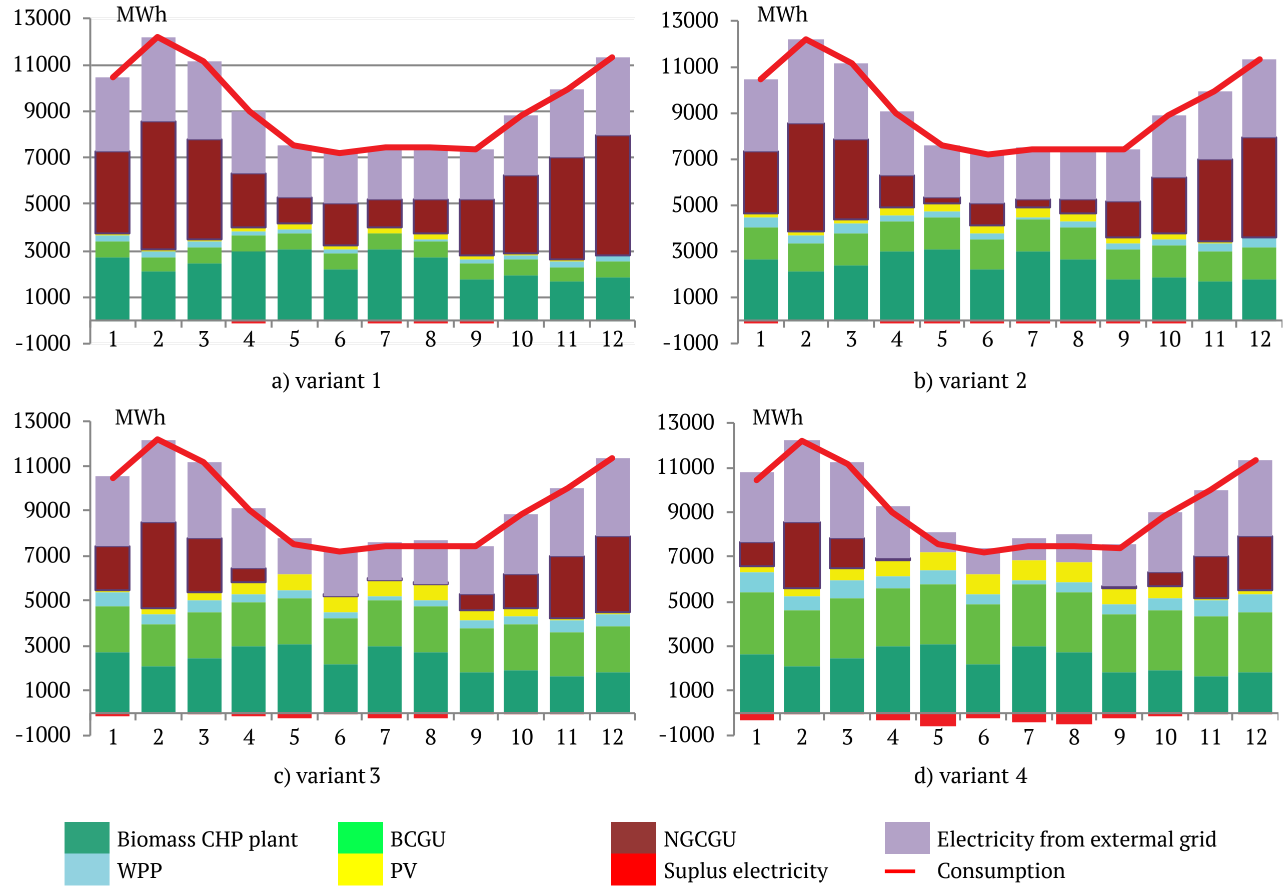

Figure 2. The monthly balances electricity for the corresponding variants of the technological structures CES Smila Community

Source: compiled by the authors

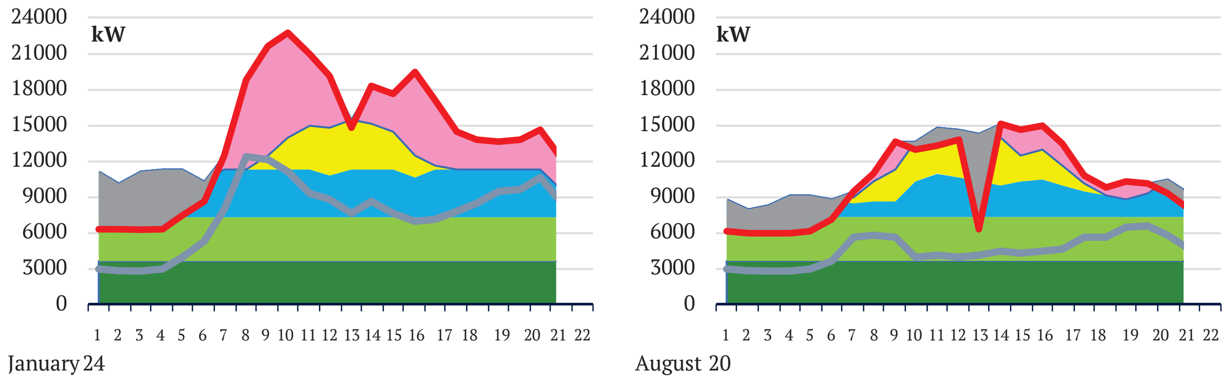

Figure 3. The load coverage schedules for variant 4 of the technological structure CES for summer and winter days with the largest amount of excess energy

Source: compiled by the authors

The analysis of outdoor temperature indicators showed that the minimum air temperatures in Smila Community were recorded on January 18, 2021 and reached -18.4°C (World weather, n.d.). For this day, the calculation method determined the hourly DHT, which was used in further studies as a base period for predicting and comparing the results obtained. The structure of coverage the schedules of electric and heat load of the day with the minimum air temperature according to the variants of the technological structure CES Smila Community is shown in Figure 4.

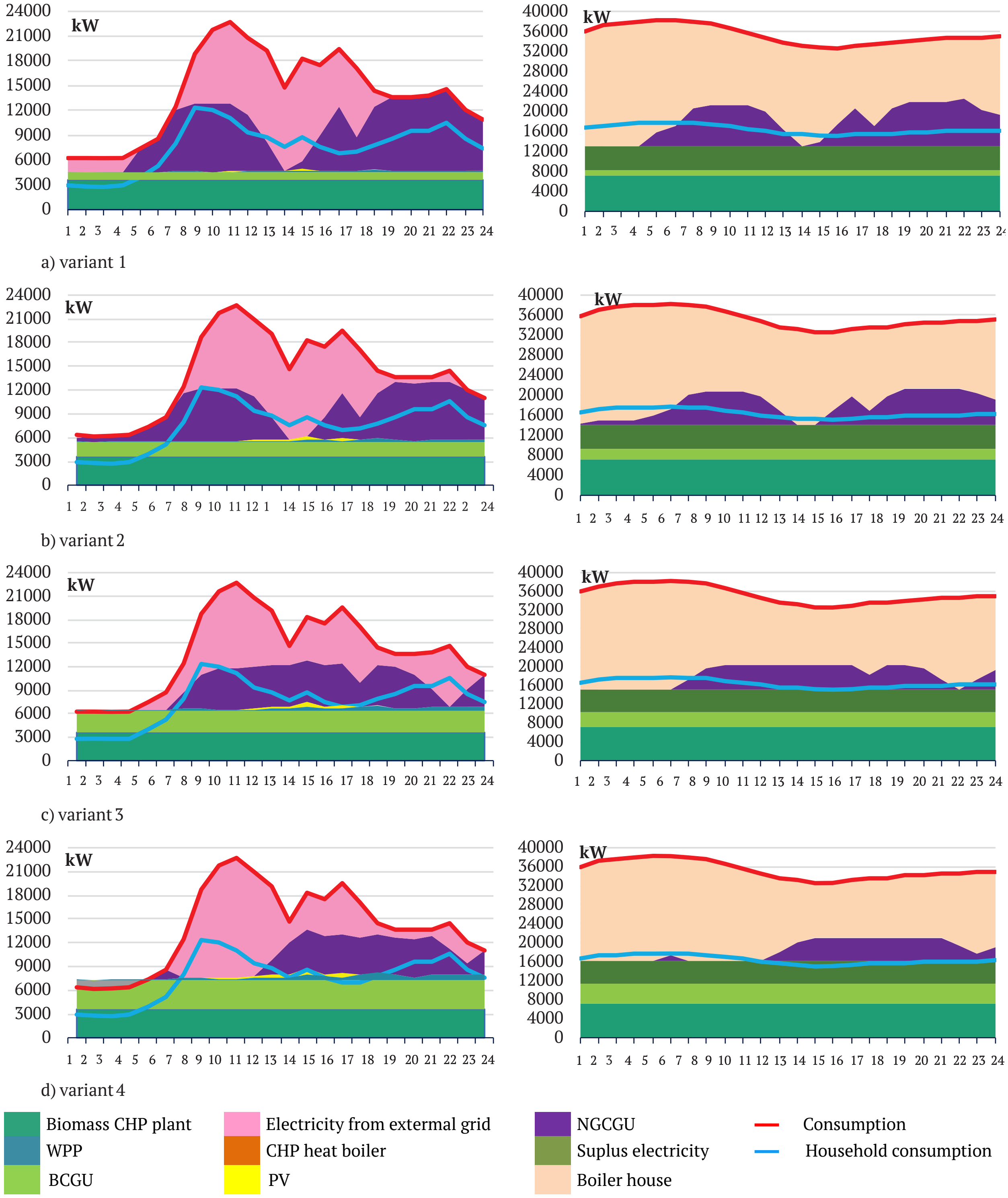

Figure 4. The structure of coverage the schedules of electric and heat load of the day with the minimum air temperature January 18

Source: compiled by the authors

The results of monthly heat energy balances for the formed variants of the technological structures of heat generation Smila Community are shown in Figure 5. The structures of the annual electricity and heat balances for the existing variants of the technological structures of the Smila community's generating capacities, as well as the cost of electricity and heat and CO_2 emissions are shown in Table 2.

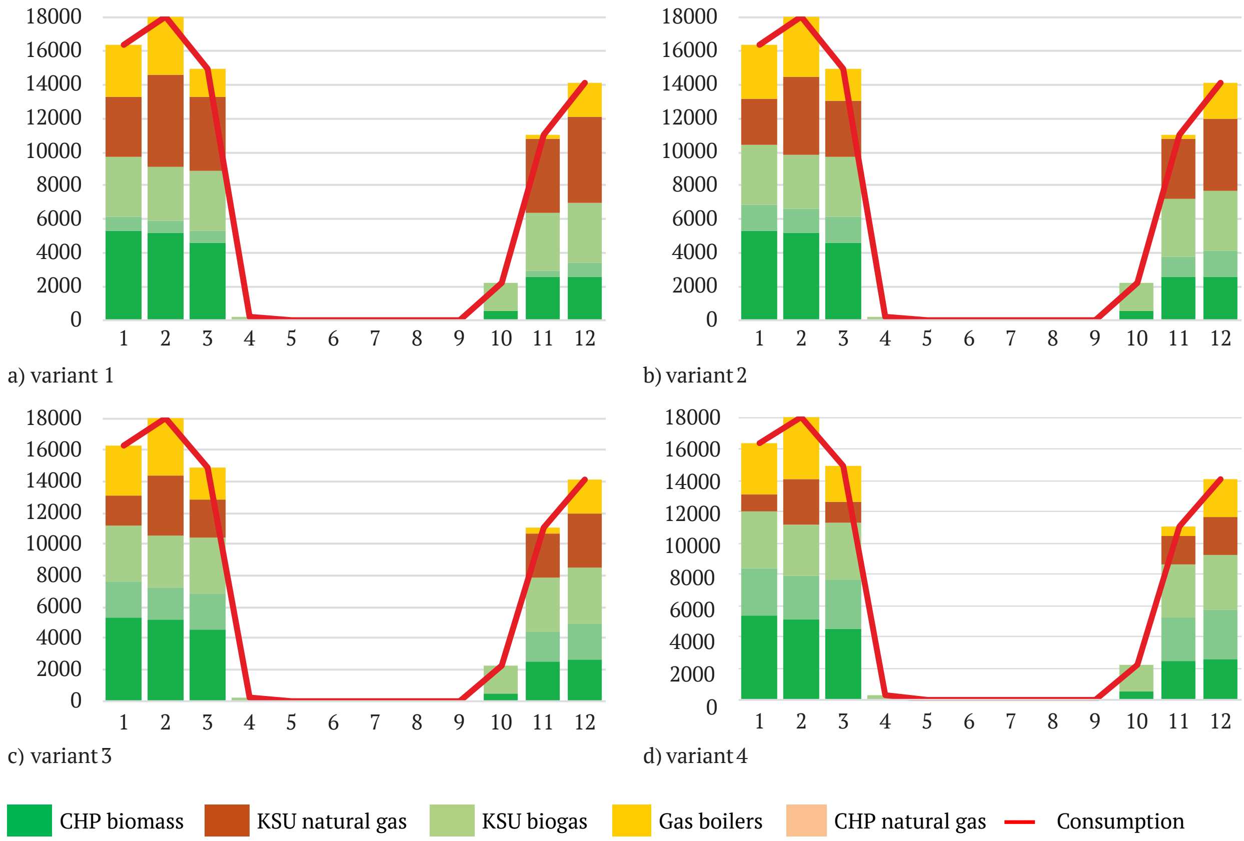

Figure 5. The monthly heat energy balances for variants of technological structures of heat generation power Smila Community

Source: compiled by the authors

Table 2. Structures of annual balances of electricity and heat energy Smila Community

Indicators	Variant of the technological structure			
	12	2	3	4
Electricity consumption, MWh	110052	110052	110052	110052
Electricity supply in total, MWh, including technology	77038	77299	79723	85032
CHP biomass	28373	28373	28373	28373
KSU biogas	8061	16120	24182	32242
WPP	2406	3609	4812	7218
SPP	1464	2927	5122	6586
KSU natural gas	36735	26270	17233	10613
Electricity consumption from the external network, MWh	33016	32989	31417	27780
Excess electrical energy, MWh	2	237	1087	2759
Cost of electricity, $/MWh	76	79	82	85
CO_2eq emissions from natural gas consumption during electricity generation, t	8161	5836	3828	2358
Supply of heat energy in total, MWh, including technologies	76870	76870	76870	76870
CHP biomass	20692	20692	20692	20692
CHP boiler natural gas	19395	19395	19395	19395
KSU biogas	3425	7245	11002	14859
KSU natural gas	22954	18691	14362	9716
Gas boilers	10404	10849	11418	12206
Cost of heat energy, $/MWh	51.4	51.4	51.5	51.5
CO_2eq emissions from natural gas consumption during heat production, t	11720	10359	10036	9179
Total CO_2eq emissions, t	19880	16195	13864	11537

Source: compiled by the authors

The results of model calculations showed that an increase in the share of renewable energy generating power in the technological structure CES Smila Community from 55% to 69% with a 30% restriction of electricity consumption from the external grid leads to a reduction in greenhouse gas (GHG) emissions (in $CO_{2eq)}$ during electricity production by 3.5 times. The overall reduction in gas emissions of the combined energy supply system is 42%. This is primarily due to a decrease in electricity and heat production by natural gas cogeneration plants. Biomass and biogas plants are considered carbon neutral and are not included in the calculation total greenhouse gas emissions. The growth of the share of RES generation in the technological structure CES caused a surplus in the local electricity grid, which share of the total annual community consumption for the option with the largest volume green generation implementation was 2.5%.

In the future, when forming the forecast annual balances of electric and heat energy, it is advisable to take into account the technological possibility of accumulating excess electricity in storage systems with the subsequent transfer to peak hours community electricity consumption or converting it using heat generators (electric boilers or electrically driven compression heat pumps) into thermal energy for use in local community heat supply networks.

The research by D. Akinyele *et al.* (2021) modelling of hybrid systems on renewable energy is devoted determining the optimal structure of an autonomous energy system responsibility the needs rural communities. A comprehensive analysis of existing modelling tools and approaches for sustainable planning, design and development of microgrids based on clean energy resources, as well as energy modelling software was carried out in in this work.

In the paper by A. Alzahrani *et al.* (2017) the microgrid is considered as a system of systems (SoS) with the possibility of using different energy sources. Microgrid electrical component models use complex system simulation techniques, such as agent-based and system dynamics-based methods, or a combination of different methods. Neural networks were used to simulate the power output of microgrid components to provide electrical load.

Optimisation of the mode of loading energy capacities is one of the most important tasks in managing the operation of power systems. Consideration of methods and models for solving the problem of optimal load of installations (eng. Unit Commitment – UC) is devoted to a significant number research publications. UC formulations have been a particularly active area of research because of their practical importance in the operation of the power grid. In the paper by B. Knueven *et al.* (2020) provided a comprehensive overview of mixed integer programming formulations for the UC problem. In the review by L. Montero *et al.* (2022), this task was considered taking into account such emerging trends as the high penetration of RES or the widespread use of non-traditional energy storage technologies. The evolution of the formulation of mixed integer linear programming with the improvement of commercial solvers with consideration of its predominant use for the problem of optimal loading plants was presented.

In the works by M.K. Deshmukh & S.S. Deshmukh (2008) presented the results of mathematical modelling of hybrid energy systems that use electricity generation from RES. A. Gupta *et al.* (2011) presented a mixed integer linear mathematical programming model for the optimal structure of an off-grid energy system to meet the electrification needs of remote rural areas, consisting of photovoltaic, fuelwood installation, biogas, small/micro hydropower, battery storage and fossil fuel generation. A model of an autonomous hybrid system on renewable energy, consisting of solar, wind, biomass, biogas plants, fuel cells with batteries, is proposed in the reasearch by V. Suresh *et al.* (2020). Optimisation calculations to minimise the cost of the system with the determination of its structure under the conditions of reducing the net present value, energy cost, CO_2 emissions responsible requiring demand were carried out using the Genetic Algorithm (GA) and HOMER Pro software. The model was used daily and annual load profiles. The calculation of the daily solar radiation, the average wind speed and the optimal size system of the reasearch hybrid system location was carried out using the HOMER Pro Software.

CONCLUSIONS

The integration of RES into local networks communities contributes to the growth of their sustainability, environmental friendliness and reduces dependence on external energy supply. The unevenness of the daily load schedules of the local energy system, their seasonal, monthly and daily differences, the stochasticity generation of SPP and WPP led to a detailed modelling of the coverage of the daily schedules electrical load the end consumers local electricity system and the heat load community district heating system using approaches modelling the optimal load generating power system.

The developed model of mathematical programming for the formation of the forecast annual monthly balance heat and electricity of the non-volatile community allows to determine in detail the optimal power utilisation combined power supply system local network community, taking into account the profiles of daily schedules electric and heat loading in compliance with the requirements of balance reliability, modes using power of electric and heat energy generation units, cost of their production electric and heat energy.

The formation of forecast annual monthly balances of electricity and heat using the developed model was carried out on the data on electricity and heat consumption Smila territorial Community formed variants of its technological structure, taking into account the operation existing biomass CHP. They provide for the introduction into the combined power supply network to consumers from 1.6 to 4.8 MW WPP and from 1 to 4.5 MW SPP, from 1 to 4 MW cogeneration gas piston plants on biogas formed during the conversion of local raw materials, as well as 10 MW of highly maneuverable cogeneration gas piston plants on natural gas, which are advisable to install on existing boiler houses of centralised power supply systems.

The results of model calculations monthly annual balances heat and electricity Smila territorial Community forming variants of its technological structure showed that an increase in the share of RES power in its structure from 55% to 69% with a 30% restriction of electricity consumption from the external power grid leads to a reduction in greenhouse gas emissions (in CO_2eq) during electricity production by 3.5 times. The overall reduction in gas emissions the combined energy supply system community is 42%. The surplus of electricity generated by the increase in RES power can be used by accumulating with subsequent transfer to the hours of shortage or conversion into heat energy to replace the corresponding production from natural gas boilers.

In the future, for a more objective reasearch hybrid energy systems electric and heat generation, the authors recommend investigating the impact on the optimisation the daily schedule electricity generation of the following technologies electric heat generators: electric boilers and compression heat pumps with an electric motor as potential consumers – electricity regulators.

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CONFLICT OF INTEREST

None.

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Моделювання енергетичних балансів громади за умов збільшення енергонезалежності та скорочення викидів парникових газів

Анотація. Існує необхідність розробки ефективних техніко-технологічних рішень для оптимізації використання відновлюваної енергії в комбінованих систем енергозабезпечення, що дозволить вирішити проблеми нерівномірності навантаження та стохастичності генерації, забезпечуючи енергетичну незалежність громад і мінімізуючи вплив на довкілля. Метою роботи було створити модель оптимального завантаження установок технологічної структури комбінованого енергозабезпечення громади при покритті добових графіків електричного та теплового навантаження мікроенергетичної системи. Її використання дозволило сформувати структуру річних щомісячних прогнозних балансів теплової та електричної енергії енергонезалежної громади із мінімізацією негативного впливу на довкілля для подальшого прогнозного аналізу та визначення напрямів інноваційного вдосконалення енергосистеми громади за умов запобігання змінам клімату та стійкого розвитку суспільства. Результати модельних розрахунків помісячних річних балансів теплової та електричної енергії для сформованих варіантів технологічної структури комбінованої енергетичної системи Смілянської територіальної громади засвідчили, що збільшення частки енергетичних потужностей відновлювальних джерел енергії у її структурі з 55 % до 69 % при 30 % обмеженні споживання електроенергії (імпорту) з зовнішньої електромережі приводить до скорочення викидів парникових газів ($CO_{2екв}$) при виробництві електроенергії у 3,5 рази. Загальне скорочення викидів ПГ системи комбінованого енергозабезпечення громади склало 42 %. Зростання частки зеленої генерації у технологічній структурі комбінованого енергозабезпечення громади обумовило надлишок в локальної мережі електроенергії, частка якої від загального річного споживання громади для варіанту з найбільшим обсягом впровадження зеленої генерації склало 2,5 %. Результати дослідження показали, що забезпечення відповідності генерації відновлюваних джерел енергії змінному навантаженню локальної мережі потребувало подальшого врахування можливості використання акумуляційних систем накопичення енергії для перенесення надлишків електроенергії або технологій її перетворення на теплову енергію. Це дозволило б заміщувати відповідні обсяги теплової генерації від котлів на природному газі, сприяючи підвищенню енергонезалежності громади та скороченню викидів парникових газів

Ключові слова: модель математичного програмування; добовий графік навантаження; технологічна структура; баланс енергії; комбінована система енергозабезпечення; енергонезалежна громада

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Use of robotic and automated systems in welding and restoration of parts

Abstract. The research was aimed at analysing the use of robotic systems in welding and surfacing processes of mechanical engineering to increase the productivity, accuracy, and economic efficiency of production operations. The study used methods of comparative analysis, economic analysis, and risk analysis to assess the effectiveness of implementing robotic systems in the welding process and investigate their impact on costs, product quality, and working conditions. Analysis of the effectiveness of implementing robotic technologies has shown that automation of these processes reduces the likelihood of defects in welds and surfaced coatings, ensuring stable quality at all stages of production. The use of robotic systems such as ABB IRB 6700 and Fanuc ARC Mate 100iD allowed achieving precise control over welding and surfacing parameters, in particular, temperature, material feed rate, and current. Robotic welding and surfacing systems, in particular, from Fronius, KUKA and YASKAWA, are actively used in the energy, metallurgy, nuclear and aviation industries to improve the accuracy, safety, and efficiency of production processes. The study included the development of energy-saving technology for surfacing rolls of rolling mills to improve their wear resistance and corrosion resistance using Tesla Weld SAW/MMA MZ 630 devices and the Tesla Weld R1 welding robotic arm to automate

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the process and ensure high quality of the deposited layer. It was noted that robotic systems can work with a wide range of materials, in particular aluminium, steel, and alloys, which expands the possibilities of using the technology in mechanical engineering. Due to the robotisation of welding and surfacing processes, a significant reduction in production costs is achieved, since the need for manual control and correction of the process is reduced. Automation allows surfacing on worn parts, which extends the service life of the equipment and reduces the cost of replacing it

Keywords: product quality; automation; materials; safety; economic efficiency; competitiveness

INTRODUCTION

Robotisation of production processes has become an important step in the development of mechanical engineering, especially in such energy-consuming and technologically complex operations as welding and surfacing. These processes require high accuracy, stability, and control, so automating the tasks associated with them can significantly improve production efficiency.

In mechanical engineering welding processes, the use of robotic systems has become one of the most important tasks, as they can significantly improve the productivity and quality of welding. However, there are a number of issues that require detailed study, in particular, on optimising the adaptation of robots to various materials and compounds. J. Kahnamouei & M. Moallem (2024) noted that robotic systems significantly reduced welding seam defects due to the high accuracy of automated processes. They also stressed the importance of adapting such technologies to different production conditions. C. Loukas *et al*. (2021) indicated a significant reduction in costs and increased productivity in mass production, due to the automation of welding processes. Their research has shown that the use of robotic systems has helped to optimise production lines and increase production volumes. C. Zheng *et al*. (2022) drew attention to the significant initial costs of implementing robotic systems, which are quickly recouped by reducing shortage costs and improving efficiency. They also emphasised that using a hybrid autonomous programming method for welding systems reduces setup time and improves accuracy. S. Murugan & P. Sathiya (2024) emphasised the importance of ensuring the safety of workers through the use of robotic systems in welding processes. They noted that automation made it possible to avoid dangerous contacts of people with high temperatures and harmful fumes.

P. Zhang *et al*. (2022) found that automation of welding processes allows precise control of the quality of welding seams in real time, which significantly reduces the likelihood of defects and increases the stability of the final product. M. Javaid *et al*. (2021) noted that robotic systems have helped to reduce environmental waste, as automation has contributed to more efficient use of materials. This allowed reducing the negative impact of production on the environment. X. Wang *et al*. (2021) investigated how robotic systems can reduce the time required to set up welding machines when working with different types of joints. This allowed maintaining a high speed of production processes and increasing their flexibility. D. Lee & K. Han (2024) emphasised that automation of welding processes significantly reduced the need for manual quality control. They also noted that this reduced the risk of human error and improved the accuracy of work. A. Mehta & H. Vasudev (2024) investigated the impact of automation on the stability and accuracy of welding processes, especially in the context of mass production of metal structures. They stressed that robotic systems have significantly improved quality and reduced production costs. Thus, although a number of aspects of welding automation have been studied, there are significant gaps in research on the impact of working conditions on the efficiency of robotic systems, adaptation to different types of materials, and the economic aspects of implementing such technologies in production. The purpose of the study was to comprehensively analyse robotic and automated systems as a tool for improving the efficiency and quality of welding and surfacing processes in mechanical engineering.

MATERIALS AND METHODS

The method of comparative analysis helped to evaluate the efficiency of robotic systems in comparison with conventional welding processes, where operators play the main role. By comparing the operation of robots such as ABB IRB 6700, Fanuc ARC Mate 100iD, and Kawasaki RA06L with manual welding, the level of accuracy and stability of the welding seams was determined. The ABB IRB 6700 is a powerful robotic system that is known for its versatility and ability to perform precise welding operations. Due to its high manoeuvrability and ability to work in confined spaces, the robot provides high welding accuracy even in difficult or hard-to-reach places. This allows producing compounds that meet the highest quality standards, and also reduces the likelihood of defects that occur due to the human factor. Fanuc ARC Mate 100iD specialises in welding operations and is one of the most popular robots in the industry. Its ability to quickly adapt and accurately perform complex welding seams can significantly reduce processing time and increase production efficiency. This system provides high process stability, which is critical for the production of parts operating under heavy loads, where any error can lead to serious breakdowns.

The Kawasaki RA06L, with its high speed and precision, is also an essential element for ensuring a continuous welding and surfacing process. Based on the ability to perform precise movements in three axes, this robot can provide the highest quality of connections and improve the efficiency of restoring parts. Its ability to accurately implement programme instructions allows maintaining a constant quality of welds, which is critical for ensuring the strength of structures. To analyse the impact of robotic systems on welding processes in mechanical engineering, data from real manufacturing companies that have implemented systems such as ABB IRB 6700, Fanuc ARC Mate 100iD and Kawasaki RA06, and companies that use conventional welding methods, were used. As part of the analysis, the technical characteristics and performance of these systems were studied to optimise welding processes.

Motor Sich Joint Stock Company (n.d.) (Ukraine) has implemented ABB IRB 6700 for welding automation. According to reports, the plant managed to significantly reduce the cost of materials and energy, and improve the quality of welding. The use of this system ensured the stability of processes and reduced the likelihood of defects. Fanuc Corporation (n.d.) (Japan), installed Fanuc ARC Mate 100iD to perform welding on complex parts. Reports indicate an increase in the efficiency of the system in conditions of large production volumes and minimisation of defects. Due to the high accuracy of settings, this system adapts well to working with different materials, which expands its capabilities. Kawasaki Robotics (n.d.) (Japan) uses Kawasaki RA06 to perform welding operations with various metals, in particular, titanium alloys. Analysis of the reports showed a significant improvement in the accuracy and stability of welding seams, which is especially important for the production of high-tech parts. Joint Stock Company Kharkiv Tractor Plant (n.d.) (Ukraine), which operates according to classical welding methods, without the use of robotic systems, in its reports notes higher costs for materials and energy, and an increased risk of defects due to the human factor. In addition, the processes at this enterprise are less stable than automated systems.

In the study, an energy-saving technology for surfacing working rolls of rolling mills was developed to increase their wear resistance and corrosion resistance, and reduce the energy intensity of the process. The method of high-speed submerged arc surfacing was used, which provided resistance to abrasive wear and thermal loads. To implement the process, Tesla Weld SAW/MMA MZ 630 devices and the Tesla Weld R1 robotic welding manipulator were used, which allow automating the process and ensuring a stable temperature regime to achieve high quality of the deposited layer. This approach to analysis allowed identifying the advantages of implementing robotic systems in welding processes.

RESULTS

In today's machine-building industry, the accuracy and efficiency of production processes are critical factors for achieving high product quality and reducing costs. Robotic systems have a significant impact on improving productivity and accuracy, especially in processes such as welding and surfacing. With the introduction of advanced automation technologies such as ABB IRB 6700, Fanuc ARC Mate 100iD, and Kawasaki RA06L robots, manufacturers can significantly improve the efficiency of their production lines.

In general, the introduction of robotic systems in welding and surfacing processes not only improves the accuracy of operations, but also reduces the impact of the human factor, which reduces the risk of errors and defects (Pires *et al.*, 2022). The high stability of robots ensures consistent product quality, which is essential for market competitiveness. Restoration of parts, welding of complex joints, and the production of high-tech products – all this has become possible due to the use of robotic systems, which are being improved every year, providing more and more opportunities to improve the quality and efficiency of production. Thus, robotic systems are able to adapt to different types of materials and joints, which allows them to work in small-scale production conditions without significant settings (Table 1).

Table 1. Adaptation of robots to different types of materials and joints to ensure stable welding seam quality

Material type	Robotic system	Adaptation parameters	Impact on seam quality
Steel	ABB IRB 6700, Fanuc ARC Mate 100iD	Temperature, electrode feed rate	High welding accuracy, minimal defects
Stainless steel	Kawasaki RA06L	Feed rate, voltage regulation	Maintaining joint strength, absence of corrosion
Aluminium	ABB IRB 6700	Temperature control, acceleration of the welding process	Seam strength, avoiding overheating
Titanium	Fanuc ARC Mate 100iD	Fine-tuning of current and temperature	High quality welded joint
Brass	Kawasaki RA06L	Gas flow control, welding speed	Clean seam, absence of defects

Source: compiled by the authors

Some robotic systems cannot work with certain materials due to their physical properties, such as low or high thermal conductivity, melting point, sensitivity to overheating, or susceptibility to corrosion. For example, materials with low thermal conductivity (for example, titanium) require special settings for welding parameters, since insufficient heating can lead to joint defects. However, some robots may not have sufficient accuracy or adaptability to specific materials, which limits their use in certain production conditions. Automatic parameter adjustment is one of the biggest advantages of modern robotic systems. Robots are equipped with systems that automatically adjust parameters for each specific process, allowing them to work with different types of materials, from steel to aluminium, with different thicknesses and complex geometries. This is especially important when it comes to surfacing, which requires precise control of the material supply and temperature conditions.

For welding processes, robots such as the FANUC ARC Mate 100iD have built-in systems that allow automatically adjusting the voltage and wire feed rate, depending on the thickness and type of material. This allows performing high-quality welding at different stages of production, without having to manually adjust the parameters for each individual stage. This flexibility allows significantly reducing the preparation time for work and increasing the speed of production. Surfacing, which is often used to restore parts, also benefits from automatic parameter adjustment. The ABB IRB 6700 can quickly adapt its settings to changing operating conditions, which allows maintaining a stable process even under different temperature conditions or when changing the shape of parts. If it is necessary to repair complex or large-sized products, the operation can be configured so that the system maintains the optimal material feed rate and its distribution by the surface of the part.

Fronius has developed robotic pipeline welding systems that are important elements in the energy sector, especially on oil and gas platforms, and in chemical and petrochemical plants. One of these systems is Fronius TPS/I, which provides high welding accuracy in difficult conditions, automating the processes of filling joints on pipelines (Pires *et al.*, 2022). These pipelines require special strength and tightness, as they transport liquid or gas under high pressure, which places high demands on the quality of welding seams. The system is capable of operating in confined spaces, which is especially important for welding pipes in hard-to-reach areas, such as underwater parts of pipelines or in cramped conditions on oil platforms. Based on its characteristics, Fronius TPS/I ensures efficient and accurate welding even in such extreme conditions, which significantly reduces the time required for repair work and increases the reliability of pipelines.

Robotic surfacing systems are actively used in the metallurgical industry, for restoring or strengthening structures, such as rolls or other components that are subjected to heavy mechanical loads (Puzyrov & Hrechka, 2024). One of these innovative systems is Fronius CMT, which allows precise surfacing, even on thin metals, without overheating the material (Ocansey *et al.*, 2024). This is especially important for maintaining stable performance in metallurgical processes, where the metal can be subjected to heavy loads and high temperatures. Fronius CMT works on the principle of minimising the thermal impact on the material, which prevents overheating and deformation. This technology significantly improves the quality of the deposited metal, reduces the likelihood of cracks and defects, and reduces the cost of materials and energy. The use of robotic systems for the restoration of metallurgical structures can increase production efficiency, increase the service life of equipment, and reduce the cost of replacing worn parts.

In the nuclear industry, welding components of nuclear reactors requires maximum accuracy and reliability of connections, since any defect can lead to serious consequences (Ali *et al.*, 2022). For this purpose, robotic welding systems are actively used, which can work in confined spaces and with high requirements for seam accuracy. For example, KUKA offers specialised work to perform welding operations on structures that are used in nuclear installations (Kołodziejczak *et al.*, 2022). The system is capable of welding structures made of high-alloy steels that can withstand high temperatures and radiation loads. Such robots can be used for welding pipes, reactor vessels, and other key components that are exposed to heavy loads. Since precision and tightness of joints are crucial for safety in the nuclear industry, robotic systems allow achieving high precision joints that meet all safety requirements.

In the aviation and space industries, welding is an important process for manufacturing high-precision structures from materials such as titanium and other light alloys. Robotic welding systems are used to ensure high joint strength with minimal deformation, which is critical for components exposed to high loads. YASKAWA uses its robotic systems for precise welding of aviation components (Vasilev *et al.*, 2021). They use both laser welding systems and conventional TIG or MIG welding methods, which allows maintaining high quality welds, even with large production volumes. These systems provide the precision, stability, and high quality of connections that are necessary to ensure the safety and reliability of aviation and space structures, where even minor defects can lead to serious consequences. Welding technologies in the aviation and space industries allow producing lightweight but strong structures that meet high requirements for reliability and safety.

The development of energy-saving technology and equipment for surfacing working rolls of rolling mills is an urgent task, since it helps to increase their corrosion resistance, crack resistance, wear resistance, and reduces the energy intensity of the process and the cost of rolled metal (Hnatenko, 2024). For efficient operation of the roll, it is necessary to ensure high strength of its working surface, and resistance to abrasive wear, thermal loads, thermal cyclic influences, and corrosion. These characteristics can be achieved by using the high-speed submerged arc surfacing method. The working roll of the rolling mill is shown in Figure 1 and is presented as a cylindrical part with a deposited reinforced layer, which provides increased wear resistance and durability during operation.

The most common technologies are those based on automatic submerged arc surfacing. This is because this method of surface restoration has a number of significant advantages over other methods. The advantage of this recovery method is the high productivity of the process, combined with high-quality surfacing, stability of mechanical properties, and chemical composition of the deposited layer, and reduced consumption of welding materials and electricity compared to other surfacing methods. The technology of electric arc surfacing allows mechanising both basic and auxiliary operations, which contributes to the automation of the process. This greatly simplifies the work of service personnel and improves the working conditions of workers.

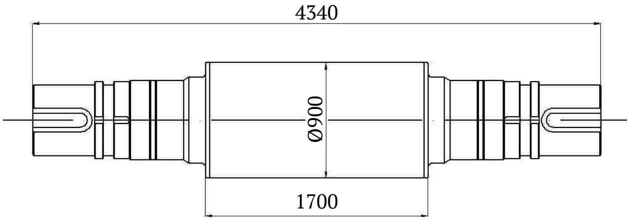

Figure 1. Working roll of the rolling mill
Source: R. Srinivasulu *et al*. (2022)

It is recommended to use the Tesla Weld SAW/MMA MZ 630 automatic submerged arc welding machine. This is a universal equipment designed for automatic surfacing under a layer of flux. The device is widely used in the production of building structures, shipbuilding, the manufacture of petrochemical tanks, and vessels operating under high pressure and temperature, and in bridge welding, heavy and metallurgical equipment, and all types of composite steels. In addition, the MZ 630 can be used for manual arc surfacing and air planning. The use of this device provides a number of advantages. During automatic submerged arc surfacing, the arc burns stably in the slag cavity, which is held by plasma flows, gases and vapours of the electrode and base metal.

Current supply to the wire is carried out at a distance of 40 mm from the product, which allows welding at currents up to 3,000 A without overheating the electrode. Moreover, the current density reaches 200-250 A/mm^2, and the melting coefficient of the electrode increases to 16-19 g/A·h due to additional heating of the electrode by the current passing through it. This allows achieving a surfacing capacity of up to 15.2 kg/h. The high current density increases the arc pressure and penetration depth, which allows surfacing with low running energy and high speed. As the surfacing rate increases, the crystallisation rate ($V_{CR} = V_{S}$-Cosα), which leads to grinding of the microstructure. During submerged arc surfacing, due to the high current density, the pinch effect and magnetic pressure increase, which leads to the separation of the drop from the end of the electrode. With this, the influence of the gas flow increases, the processes of gas formation and evaporation in the drop increase. Thus, submerged arc surfacing results in fine-droplet transfer of electrode metal, and transfer in vapours. The frequency of crystallisation decreases, which leads to the development of a finely sutured crystallised seam, as a result of which the slag crust is easily removed.

Automatic submerged arc welding, due to its high current density, fine-drop transfer, and steam transfer, is approaching nanoprocesses where atoms are affected. During automatic submerged arc surfacing, the wire is fed automatically, considering the melting rate, which allows maintaining a constant arc length. The crack resistance and wear resistance of the deposited metal are improved during high-speed surfacing with low linear energy due to an increase in the crystallisation rate of the liquid metal, microstructure grinding, and reduced welding stresses.

Surfacing with low linear energy is an energy-saving process, as it helps to reduce electricity consumption, which, considering the increase in energy costs, significantly increases the efficiency of the surfacing process. A general view of the YAMZ-236 engine cylinder liner is shown in Figure 2, which shows its design features, including cooling channels, dimensions and shape that provide optimal conditions for engine operation.

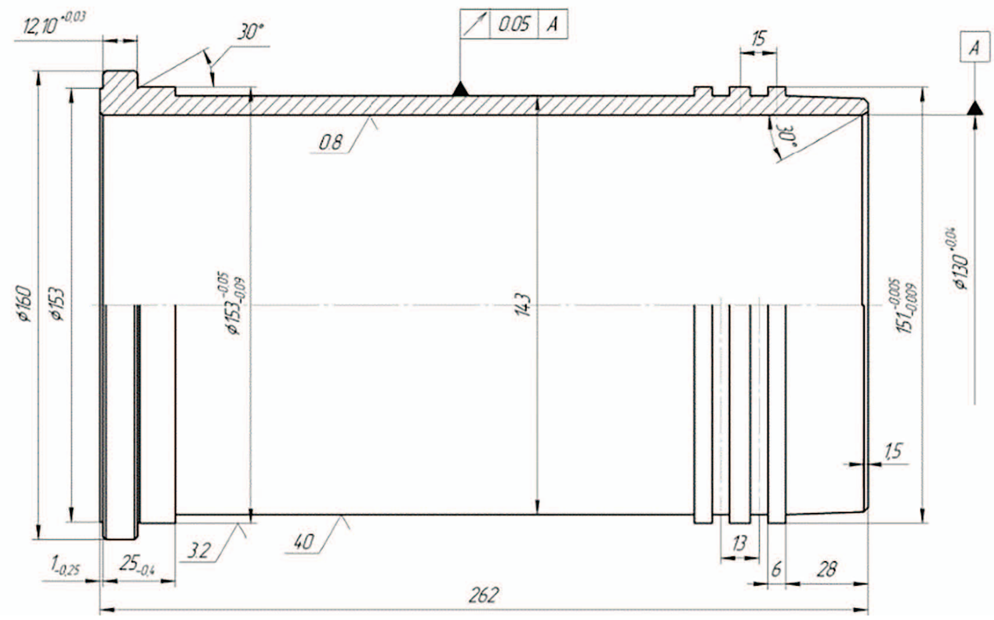

Figure 2. General view of the YAMZ-236 engine cylinder liner
Source: R. Srinivasulu *et al*. (2022)

The traditional method of surfacing consists in restoring the surfaces of parts by applying a metal layer by welding. The main advantage of this method is the ability to restore a significant amount of worn surfaces, which makes it particularly effective for repairing crankshafts that are subjected to intense mechanical loads. Surfacing is usually carried out using special welding materials that provide increased wear resistance and corrosion resistance. An important factor is the correct choice of surfacing modes, such as wire feed rate, temperature regime and cooling, as they determine the quality of the resulting layer (Zhang *et al.*, 2022).

For surfacing, a plasma arc was chosen as an energy source that ensures stable heating and high quality of the metal layer. This method allowed achieving optimal fusion of the base metal with the additive material, reducing the likelihood of defects such as pores or microcracks, and ensuring an even temperature distribution in the surfacing zone. The additive material was chosen considering the operating load conditions of the crankshaft: a steel-based alloy with the addition of chromium and molybdenum was used, which contributes to the development of highly wear-resistant phases in the deposited layer. The thickness of the surfacing layer was controlled in the range of 2-3 mm to avoid increasing the mass of the part and preserve the necessary geometric characteristics of the surface.

The temperature regime during surfacing has been optimised to ensure deep penetration of the base metal without the risk of thermal deformations. In the course of research, it was found that the temperature in the welding bath should be maintained in the range of 1,400-1,600°C to ensure high-quality diffusion adhesion between the base material and the deposited layer. The heating temperature of the additive material varied depending on its composition and for steel alloys with a high content of chromium and molybdenum was 1,450-1,550°C. To prevent local overheating and the development of thermal cracks, temperature control using optical pyrometry was used, which helped to maintain a stable thermal balance in the surfacing zone. The speed of movement of the energy source during surfacing was crucial to ensure even heat distribution and prevent the development of defects such as pores or microcracks. It was determined that the optimal speed of the energy source is 10-15 mm/s, depending on the shaft diameter and the type of filler material.

When using automated surfacing systems, such as robotic manipulators (welding robotic manipulator Tesla Weld R1), adaptive speed control algorithms were used, which performed correction of movement parameters in real time to ensure a stable temperature. Technical parameters for optimising surfacing processes for restoring the crankshaft of the YAMZ-236 engine are shown in Table 2, which presents the main values of temperature, speed of the energy source, the composition of the filler material, and other important factors affecting the quality and efficiency of the process.

Table 2. Technical parameters for optimising surfacing processes for restoring the crankshaft of the YAMZ-236 engine

Parameter	Surfacing (plasma)
Temperature in the processing area, °C	1,400-1,600
Particle temperature, °C	1,450-1,550
Source speed, mm/s	10-15
Particle speed, m/s	-
Layer thickness, mm	2-3
Cooling temperature, °C	300-500
Structure control	Fine-grained

Source: compiled by the authors

Welding and surfacing in production are critical operations that require high precision and stability. Despite great advances in technology, welding and surfacing processes have always carried certain risks associated with the human factor. Incorrectly configured parameters, physical fatigue, inattention, or even just different skill levels of employees can lead to errors and defects that reduce product quality and affect its durability. The use of robotic systems in these processes can significantly reduce the impact of the human factor, ensuring more accurate and stable operation (Sun *et al.*, 2022).

One of the main advantages of robotic systems is their ability to work in difficult and hard-to-reach places where the human hand cannot reach or where welding, using conventional methods, is extremely difficult and dangerous (Table 3). Another important benefit is to reduce the impact of fatigue and stress on performing operations. People working in long-term welding conditions may lose concentration or make mistakes due to fatigue. Robots work without interruptions and maintain high efficiency throughout the entire production cycle. This is especially important in mass production, where a large number of identical parts require thousands of welding operations and each mistake can be expensive. Table 4 illustrates the cost-effectiveness of implementing robotic systems in the welding process for small and medium-sized manufacturers. Calculations include material costs, energy resources, labour costs, and defect correction costs, which allows evaluating the possible benefits of automating the welding process. Reduced costs for raw materials, energy and labour are achieved through more precise control of welding parameters and a reduction in the number of defects.

Table 3. Impact of automation on employee safety and reduction of risks associated with hazardous welding processes

Security factor	Without automation	With automation	Impact on employee safety
High temperature	Increased risk of burns	Robots perform tasks in dangerous conditions	Minimising risks for employees
Evaporation of harmful gases	High level of health impact	Robots work in sealed areas	Reducing employee health risks
Noise and vibration	Harmful to hearing and health	Reduced noise load	Improving working conditions
Need for physical activity	High workload for employees	Robots perform heavy physical work	Reduce the risk of injury and fatigue
Risk from mechanical damage	Frequent injuries during manual welding	Reducing the possibility of injury	Significant improvement in employee safety

Source: compiled by the authors based on S. Proia *et al*. (2021)

Table 4. Evaluation of the cost-effectiveness of implementing robotic systems in the welding process for small and medium-sized manufacturers

Parameter	Without a robotic system (UAH)	With a robotic system (UAH)	Cost reduction (%)
Material costs (UAH/month)	50,000	40,000	20%
Energy costs (UAH/month)	30,000	25,000	16.7%
Labor remuneration (UAH/month)	70,000	40,000	42.9%
Costs for correcting defects (UAH/month)	15,000	5,000	66.7%
Total expenses (UAH/month)	165,000	110,000	33.3%

Source: compiled by the authors based on D. Okumus *et al*. (2023)

The introduction of robotic systems allows you to reduce the cost of raw materials due to the precise adjustment of parameters, which reduces the amount of waste. In addition, automation of the process reduces the risk of defects, which leads to a significant reduction in the cost of correcting defects, which has a positive effect on the overall profitability of production. Considering these data, the introduction of robotic systems for small and medium-sized manufacturers can significantly reduce welding costs, increasing product efficiency and quality. Compared to conventional welding methods, the use of robotic systems offers significant advantages, in particular, in improving the efficiency of the process. However, to understand exactly how robotic systems can improve welding quality and reduce costs, it is important to evaluate key parameters such as welding time, material costs, energy consumption, and weld quality. Table 5 provides a comparison of these parameters for conventional and robotic welding methods, which helps businesses to make an informed choice of the technology that best meets their production requirements.

Table 5. Comparison of welding processes using conventional and robotic systems

Parameter	Conventional welding method	ABB IRB 6700	Fanuc ARC Mate 100iD	Kawasaki RA06
Welding time	60 minutes	40 minutes	45 minutes	50 minutes
Material costs	500 UAH/month	400 UAH/month	420 UAH/month	410 UAH/month
Energy consumption	100 kW/h	80 kW/h	85 kW/h	90 kW/h
Welding quality	Variable, depends on the technician	High accuracy, stability	High accuracy, stability	High accuracy, stability

Source: compiled by the authors

Robotic systems are significantly superior to conventional welding methods in several key parameters. They allow reducing the welding time, due to the accuracy of programmable movements and the absence of a human factor, which provides a significant reduction in the duration of the process. This, in turn, reduces the cost of energy and materials, as robotic systems optimise these resources. Precise control of welding parameters also minimises waste and defects, which helps to improve the quality of welds. The absence of human error and the ability of robots to perform precise movements even in difficult conditions provides consistent, high quality of welding. With the introduction of robotic systems, enterprises can achieve not only improved productivity, but also significantly reduced costs for materials, energy resources, and defect correction, making this welding method cost-effective for large and medium-sized industries. However, for small businesses that do not have significant financial resources, the initial investment in robotic systems can be large, so they should estimate the cost of implementing such technologies in terms of their long-term profitability.

The use of sensor technologies and control algorithms in robotic welding systems can significantly improve the accuracy, stability, and efficiency of welding processes. Various robotic systems use innovative technologies to optimise the welding process and reduce the number of defects. Table 6 shows the main technologies and algorithms that are used in each of the systems to achieve the best results.

Table 6. Influence of sensor technologies and control algorithms on the welding process

Technology	ABB IRB 6700	Fanuc ARC Mate 100iD	Kawasaki RA06
Temperature sensors	High precision temperature control, which reduces defects	Precise temperature control for process stability	High temperature measurement accuracy, which minimises deviations
Positioning sensors	Improved positioning accuracy of welding elements	Positioning accuracy for stable connections	High-precision positioning to ensure accuracy
Adaptive management	Automatic parameter correction in real time	Support for stable welding parameters	Adaptive adjustment to maintain quality under different conditions
Management algorithms	Optimisation of speed and power depending on the material	Dynamic optimisation of parameters, depending on the conditions	Intelligent control, depending on the material parameters

Source: compiled by the authors

Each of the robotic systems has its own unique characteristics and approaches to the use of sensors and control algorithms. The ABB IRB 6700 is characterised by high temperature control accuracy and real-time automatic parameter correction, which minimises defects. The FANUC ARC Mate 100iD uses precise temperature control and dynamic parameter optimisation for stable welding performance. Kawasaki RA06 also provides high positioning accuracy and intelligent control, facilitating stable connections even in different conditions. The introduction of such technologies not only improves welding accuracy, but also reduces the likelihood of defects, increases productivity, and ensures stable quality at all stages of production. This is of great importance for manufacturing enterprises, where every detail is important to ensure high standards of quality and efficiency.

Restoration and repair of worn or damaged parts in the production process is important, as effectively extending the service life of equipment and machinery can significantly reduce the cost of new spare parts and improve economic efficiency. An important role in this is played by robotic systems that significantly expand the capabilities for performing tasks such as surfacing on worn parts, restoring their functional characteristics, and extending their service life. Robots allow automating these processes, ensuring high accuracy and stability, which is important when restoring parts that have suffered wear or damage (Epping & Zhang, 2018).

One of the main advantages of robotic systems is their ability to effectively perform surfacing on parts that have significant damage or wear, restoring their original functional characteristics. Surfacing is the process of applying material to the surface of a part to restore its geometry or functionality. Traditionally, this process was performed manually, which required highly qualified operators and was associated with a large amount of time. Due to robotic systems, this process can be automated, which ensures faster and more accurate execution of work, reducing the number of errors that can occur during manual operation.

Based on the ability of robotic systems to precisely control process parameters such as temperature, material feed rate, and stress, high surfacing quality can be achieved, which is critical for restoring the functional characteristics of parts. In the process of restoring parts, especially those that have undergone significant wear and tear, any inaccuracy can lead to inefficient restoration, which entails additional costs for new parts or repeated repairs. Robots that can automatically adjust parameters during operation, which allows achieving the required strength and durability of the deposited material, which significantly extends the service life of the restored part.

It is also important to note that using robotic systems to restore and repair parts reduces labour costs. Previously, to perform such operations, it was necessary to attract highly qualified employees, which was accompanied by high training and maintenance costs. Robots, due to their versatility and high accuracy, can perform these operations without human intervention, which significantly reduces labour costs and increases the efficiency of repairs.

In this way, robotic systems significantly expand the capabilities for efficient restoration and repair of worn and damaged parts, ensuring high accuracy, reducing costs, and increasing the cost-effectiveness of production. They allow preserving the functionality of parts used in difficult conditions and extending their service life, which is an important factor for reducing the cost of production and maintenance of equipment.

DISCUSSION

The use of robotic systems in mechanical engineering welding processes has demonstrated a significant improvement in the quality, speed, and safety of production. The results showed that the use of robotic systems, such as ABB IRB 6700 and Fanuc ARC Mate 100iD, improved the accuracy of welding operations, reduced the cost of materials, energy resources, and correction of defects, which was confirmed by data from real manufacturing enterprises that implemented these systems. This helped to ensure stable weld quality, minimise defects, and reduce the impact of the human factor on the final result. The adaptation of such robotic systems has reduced the likelihood of errors, which, in turn, has improved the overall efficiency of production processes in mechanical engineering.

This problem was also investigated by A. Sharma *et al*. (2021), where the results confirmed that improving the efficiency of welding processes through robotics in mechanical engineering can significantly reduce the impact of the human factor and ensure consistent quality of welds. Automation of welding allows optimising production time and reducing material costs, since robots can perform precise operations at high speed. It also helps to reduce the number of defects and increase overall production productivity. The study by S. Chen *et al*. (2022) also showed that universal recognition and positioning of angular welded joints using structured light significantly improves the accuracy of welding operations, especially in mass production environments. This allows robotic systems to ensure stable welding quality, even under variable conditions, minimising the likelihood of defects and reducing the cost of correcting defects.

Notably, the introduction of welding robots requires significant initial investment, which can become an obstacle for small and medium-sized enterprises. However, the long-term benefits of reducing production costs and improving product quality often justify these costs. In addition, automated systems can provide a high level of safety at work, as they reduce the need for human participation in potentially dangerous operations, such as working with high temperatures or toxic materials. The use of automated welding processes has also significantly reduced the cost of materials, energy and labour. Due to the high accuracy of controlling welding parameters, robotic systems allow optimising the amount of materials used and reducing the amount of waste (Kairat *et al*., 2023). In addition, the cost of correcting welding seam defects has significantly decreased, which previously required additional costs for manual inspection and refinement. Improving the efficiency of production lines has reduced overall production costs and improved the profitability of enterprises.

D. Ajiga *et al*. (2024) concluded that optimising the cost of materials through automation of welding processes can significantly reduce the amount of resources used, and improve the accuracy of the use of materials in the production process. Robotic systems can perform operations with minimal deviations, which reduces the cost of excess materials and ensures more economical use of resources. In addition, automation reduces the need for expensive materials, as robots can work efficiently with smaller portions of raw materials. The study by T. Aydinliyim *et al*. (2023) found that reducing the cost of defects and increasing the profitability of production are important advantages of automating welding processes. Due to the high accuracy and stability of robots, the probability of defects and the need to correct defects is reduced, which, in turn, lowers additional costs for repairs and alterations. This helps to increase the overall profitability of the enterprise, since reducing the cost of materials ensures more efficient use of resources and maximising profits.

These results support the above study, as automation of welding processes does lead to a significant reduction in material costs and a reduction in the number of defective products. The use of robotic systems ensures a high level of accuracy, which allows optimising processes and significantly reducing waste. This approach not only improves production efficiency, but also helps to increase the company's competitiveness in the market by reducing costs and improving the quality of final products. The integration of robotic systems has also significantly improved employee safety. Robotic complexes have taken on the most dangerous operations, such as welding in hard-to-reach places or in high temperatures. This reduced the risk of injuries associated with physical exposure to high temperatures, electrical risks, and harmful fumes. However, as some researchers have noted, it is impossible to completely exclude the need for qualified personnel to configure and monitor the operation of such systems.

It is worth noting the study by S. Yang *et al.* (2022), who also found that reducing the risk of injury with robotic systems is one of the main advantages of automation in welding processes. Robots can perform dangerous operations, such as handling high-temperature materials or working in toxic fumes, which reduces workers' contact with hazardous factors. This reduces the likelihood of injuries and ensures greater safety at production sites. In turn, I. Sarivan *et al*. (2024) concluded that welding automation significantly improves occupational safety in mechanical engineering, as robots can replace humans in the most risky production areas. This not only reduces the number of accidents, but also reduces stress and physical activity on employees, which has a positive impact on their health and overall performance. The introduction of such technologies contributes to the creation of a safer working environment and increases the overall level of occupational safety at the enterprise.

These data correspond to the theses given in the previous section, as they confirm the importance of implementing automation to improve safety in production. Reducing the physical burden on employees and replacing their participation in dangerous operations with robots significantly reduces the likelihood of injuries and accidents (Bilenko *et al.*, 2023). Thus, automation not only increases the efficiency of production processes, but also contributes to the creation of a safer and healthier working environment. Another important aspect is the flexibility of robotic systems when configured to work with a variety of materials and compounds (Akberdin *et al.*, 2023). Due to the use of state-of-the-art sensor technologies and adaptive controls, systems such as the Kawasaki RA06L allow quickly adapting settings to work with a variety of metals, including aluminium, stainless steel, and alloys. This is an important factor for businesses operating in small-scale production, where materials and types of joints often change. Thus, robotic systems provide high stability and quality of welds with minimal reconfiguration time.

F. Rocha *et al*. (2021) also conducted a study, the results of which confirmed that the flexibility of robotic systems to work with different metals is an important advantage, since modern robots can be configured to handle different types of materials, such as steel, aluminium, or stainless steel. Due to the ability to adapt the software and change the operating parameters, robotic systems can perform welding operations with high accuracy on materials with different properties. This allows businesses to work efficiently with various types of metals without the need for significant additional settings or equipment changes. R. Abebe & M. Gopal (2023) also found that the effect of robot settings on welding materials lies in the ability to accurately adjust parameters of the welding process, such as temperature, material feed rate, and current intensity. These settings provide optimal conditions for working with each specific metal, which contributes to achieving maximum weld quality. Since different materials require different conditions to achieve perfect results, the precision of robot settings is key to ensuring the stability and durability of welds.

Comparing the data obtained in the course of research, it can be concluded that robotic systems show a significant improvement in adaptation to different materials, ensuring stable welding quality, even when changing the type of metal being processed. The high flexibility of such systems reduces reconfiguration time and minimises the need to change equipment for various tasks. This, in turn, increases production efficiency and reduces the cost of materials and processing, which confirms the potential of robotisation to optimise production processes. Analysis of the economic aspects of the introduction of robotic systems has shown that although the initial costs of automating welding processes can be high, their rapid payback is the result of a significant reduction in labour costs and a reduction in the number of defects. The use of robots reduces the time required to set up equipment, which also has a positive effect on the efficiency of production lines (Korzhyk *et al.*, 2017; Liashok & Tykhanskyi, 2024). According to research, enterprises that implemented automation were able to significantly increase production volumes without additional labour costs.

G. Pop *et al*. (2024) indicated that initial investments in robotic welding systems include high-tech equipment and software. However, these costs are quickly recouped by reducing operating costs, reducing the time required to set up and process materials, and reducing defects. Accordingly, payback usually occurs in a few years, which allows reducing overall costs and increasing the profit of the enterprise. According to X. Zhao *et al*. (2021), automation can significantly improve the speed and accuracy of welding operations, resulting in reduced material costs, reduced need for additional labour, and reduced order completion time. This significantly improves the profitability of enterprises, increasing their competitiveness. An analysis of the findings shows that although the initial costs of implementing robotic welding systems are high, the long-term benefits of reducing operating costs, reducing defects, and improving welding accuracy are far outweighed. The return on investment is faster, making these technologies beneficial for businesses looking to reduce costs and improve efficiency.

Thus, the use of robotic systems in mechanical engineering welding processes is an important step towards improving production efficiency. According to the results obtained, robotisation has significantly reduced costs, increased employee safety, and ensured high product quality. However, for maximum effect, it is important to consider all aspects of implementation, in particular, the initial costs, the need for qualified personnel, and technical requirements for adapting systems to different production conditions.

CONCLUSIONS

The use of robotic systems in welding processes of mechanical engineering can significantly improve production efficiency, due to the high accuracy and stability of operations. Robotic systems such as ABB IRB 6700, Fanuc ARC Mate 100iD and Kawasaki RA06 are used for automatic welding of various materials, ensuring precise execution of seams and joints. For example, the welding time with the ABB IRB 6700 is 40 minutes, which is 33% faster than with the conventional welding method (60 minutes). The cost of materials when using ABB IRB 6700 is reduced to 400 UAH/month, which is 20% less compared to conventional methods (500 UAH/month). In addition, due to the high accuracy of operation, energy consumption is reduced: the ABB IRB 6700 consumes only 80 kW/h, which is 20% less than the conventional method with 100 kW/h. This is especially important for welding in conditions of large production volumes, where it is necessary to achieve stable quality and high strength of joints.

One of the biggest advantages of implementing robotic systems is increased economic efficiency. Using systems such as ABB IRB 6700, Fanuc ARC Mate 100iD and Kawasaki RA06L reduces the chance of defects, which reduces the cost of error correction and reduces material waste. For example, the cost of correcting defects is reduced by 66.7%, from UAH 15,000 to UAH 5,000 per month, which significantly reduces welding costs. Precise control of welding parameters, such as temperature, feed rate, and current, reduces raw material costs by 20%, from UAH 50,000 to UAH 40,000 per month, and also reduces energy costs by 16.7%, from UAH 30,000 to UAH 25,000. Automation of the process reduces the need for qualified employees, which also reduces labour costs by 42.9%, from UAH 70,000 to UAH 40,000 per month, while increasing productivity.

Robotic systems such as Fronius TPS/I and Fronius CMT significantly improve welding efficiency and accuracy in complex environments, particularly in pipeline welding and structural surfacing in metallurgy. Moreover, KUKA and YASKAWA robots provide high reliability and accuracy when performing welding operations in critical areas such as the nuclear industry and aviation.

As a result of the research, an energy-saving surfacing technology was developed, which provides high wear resistance and corrosion resistance of the working rolls of rolling mills, reducing the energy consumption of the process. The use of automated surfacing systems, such as the Tesla Weld SAW/MMA MZ 630 and the Tesla Weld R1 robotic welding manipulator, helps to improve the efficiency of the process and the quality of the deposited layers.

The introduction of such technologies also ensures high product quality. Robots can perform welding with constant accuracy, which is impossible to achieve with manual welding operations. Based on automatic parameter control, it is possible to achieve perfect welds that meet the requirements for strength and tightness, which is especially important for the production of machinery and equipment that operates in extreme conditions.

Due to these advantages, robotic systems are becoming an important element of modern mechanical engineering, which allows increasing the competitiveness of enterprises, reducing costs, and improving the quality of products. They provide not only economic benefits, but also contribute to the development of safe and efficient production processes. To further develop this topic, it is necessary to investigate the impact of integrating the latest sensor technologies and artificial intelligence on the efficiency and accuracy of robotic welding systems in various production conditions.

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CONFLICT OF INTEREST

None.

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Використання роботизованих та автоматизованих систем у процесах зварювання та відновлення деталей

Анотація. Дослідження спрямоване на аналіз використання роботизованих систем у зварювальних і наплавлювальних процесах машинобудування з метою підвищення продуктивності, точності та економічної ефективності виробничих операцій. У дослідженні були використані методи порівняльного аналізу, економічного аналізу та аналізу ризиків для оцінки ефективності впровадження роботизованих систем у зварювальний процес і вивчення їх впливу на витрати, якість продукції та умови праці. Аналіз ефективності впровадження роботизованих технологій показав, що автоматизація цих процесів знижує ймовірність дефектів зварних швів і наплавлених покриттів, забезпечуючи стабільну якість на всіх етапах виробництва. Використання роботизованих систем, таких як ABB IRB 6700 і Fanuc ARC Mate 100iD, дозволило досягти точного контролю над параметрами зварювання та наплавлення, зокрема температурою, швидкістю подачі матеріалу і струмом. Роботизовані системи зварювання та наплавлення, зокрема від компаній Fronius, KUKA та YASKAWA, активно використовуються в енергетиці, металургії, атомній промисловості та авіації, для підвищення точності, безпеки та ефективності виробничих процесів. Дослідження передбачало розробку енергозберігаючої технології наплавлення робочих валків прокатних станів для покращення їх зносостійкості і корозійної стійкості з використанням апаратів Tesla Weld SAW/MMA MZ 630 та зварювального роботизованого маніпулятора Tesla Weld R1 для автоматизації процесу і забезпечення високої якості наплавленого шару. Відзначено, що роботизовані системи можуть працювати з широким спектром матеріалів, зокрема алюмінієм, сталлю та сплавами, що розширює можливості застосування технології у машинобудуванні. Завдяки роботизації процесів зварювання та наплавлення досягається значне зниження виробничих витрат, оскільки зменшується потреба в ручному контролі та корекції процесу. Автоматизація дозволяє здійснювати наплавлення на зношених деталях, що подовжує термін служби обладнання та знижує витрати на його заміну

Ключові слова: якість продукції; автоматизація; матеріали; безпека; економічна ефективність; конкурентоспроможність

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Prospects for the integration of distributed energy sources into the Ukrainian power grid

Abstract. The integration of distributed energy sources (DES) into the Ukrainian power grid is a critical aspect of modern energy development aimed at increasing the efficiency of the power system, reducing greenhouse gas emissions, and improving the country's energy security. The purpose of this overview and analysis study was to identify the technical and automation aspects of DES integration, as well as to determine the prospects and challenges associated with their adaptation to centralised grids. The study discussed the principal technical challenges arising from the integration of solar, wind, bioenergy, and other DES into the Ukrainian power grid. Particular attention was paid to the issues of stability and quality of electricity supply, the need to modernise the grid infrastructure, and the use of inverter technologies, energy storage systems (ESS), and hybrid microgrids. The study analysed modern methods of automation and control of distributed generation using Smart Grid, Supervisory Control and Data Acquisition (SCADA), and Distributed Energy Resource Management System (DERMS) technologies, which help to optimise the operation of the power system, increase

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its reliability and flexibility under variable load conditions. The study considered adaptive control algorithms, mathematical forecasting models, and neural network algorithms that enable prompt adjustment of equipment operating modes, ensuring the stability of the system. It was found that the introduction of inverter systems, SPPs, and hybrid microgrids can re solutions that include the use of renewable energy sources, DERMS, and smart management. The recommendations included infrastructure modernisation, development of hybrid ESSs, and implementation of integrated digital monitoring and control systems. The practical value of this study lies in the development of approaches to the effective integration of DES into local power systems, which can be used in the design and implementation of microgrids in Ukraine

Keywords: grid integration; power system stability; inverter technologies; hybrid microgrids; power supply automation; Smart Grid; power system management

INTRODUCTION

The integration of distributed energy sources (DES) into the Ukrainian power grid is a prominent area of energy development aimed at ensuring reliable and environmentally friendly energy supply. This is particularly relevant in the context of the global transition to renewable energy sources, such as solar, wind, and bioenergy, which help reduce dependence on fossil fuels and reduce greenhouse gas emissions. The development of renewable energy sources requires modernisation of infrastructure and optimisation of system management, as existing grids are not always capable of ensuring stable supply in the face of irregular energy production. The integration of Smart Grid, Supervisory Control and Data Acquisition (SCADA), and Distributed Energy Resource Management System (DERMS) technologies is of particular significance to ensure the flexibility and adaptability of power systems. The implementation of DES requires the development of methods for interoperability between diverse types of generation, frequency, and voltage control, as well as the use of energy storage systems (ESS) (Shram & Kachan, 2023). This is critical for increasing the resilience of power systems to external challenges and ensuring Ukraine's competitiveness in the international energy space.

V.A. Stepanenko (2023) noted the creation of reliable solutions for connecting renewable energy sources to the power supply system to be a vital aspect. Such solutions would require not only the modernisation of existing infrastructures, but also the development of new inverter technologies that would ensure efficient energy conversion and transmission to centralised grids. Furthermore, the use of SES is becoming critical to ensure the stability of the power system in the face of variable loads and irregular generation of electricity from renewable sources such as solar and wind power plants. A. Zaporozhets *et al*. (2023) confirmed that the introduction of energy storage technologies together with Smart Grid concepts are key factors in ensuring the reliability and stability of electricity supply. Specifically, Smart Grid technologies enable the use of predictive analytics to assess the capacity of DES, which helps to optimise power system management processes. A prominent component is the development of algorithms capable of promptly responding to changes in load conditions and adapting to current conditions of energy production and consumption.

A. Dehdarian & C.L. Tucci (2021) focused on the prospects of creating microgrids with distributed generation, which enable greater flexibility and resilience of power systems. The decentralised management of such microgrids, combined with modern monitoring and control technologies, contributes to efficient load balancing, which is especially relevant for systems with a high share of renewable energy sources. E.I. Stasinos *et al*. (2022) emphasised that the use of Smart Grid and SCADA concepts is essential for the integration of DES into centralised power systems. These technologies provide the ability to monitor, analyse, and automatically regulate power supply processes in real time, which greatly increases the reliability of the power system. The introduction of such technologies contributes to efficient energy balancing and rapid response to changes in electricity production and consumption.

Y. Rudniev & J. Romanchenko (2024) analysed the current state and prospects for the development of Ukraine's energy sector according to the Smart Grid concept. The researchers confirmed that digital solutions play a critical role in ensuring the resilience and efficiency of power systems. The use of predictive methods and automated control systems can improve the reliability of energy supply, which is a major step towards decentralisation and modernisation of power grids. T. Bitkova & K. Manakhov (2024) emphasised the need to develop alternative energy and introduce dynamic control systems for renewable energy sources. The researchers focused on developing approaches to optimising the operation of distributed energy supply systems using mathematical modelling and intelligent technologies. C.D. Iweh *et al*. (2021) addressed the challenges of integrating DES into centralised grids, specifically, frequency regulation, synchronisation, and technical limitations. The researchers emphasised that effective integration is only possible if innovative technical solutions, standards, and policies are developed to improve the interaction of DES with the main grid.

J. Zhu *et al*. (2022) considered the possibilities of applying load forecasting and management methods to optimise the operation of the power system. The researchers emphasised that digital solutions are critical to ensure the stability of the grid, especially in cases where the share of DES in the overall energy balance is significant. T.B. Nadeem *et al*. (2023) emphasised the need for hybrid control systems to integrate DES. The researchers highlighted that such systems could improve the reliability of electricity supply and minimise the risks associated with the irregularity of electricity production from renewable sources. M. Ranjan & R. Shankar (2022) investigated frequency control methods in distributed power supply systems. The researchers noted that the introduction of adaptive control algorithms can ensure system stability in conditions of a high share of DES, which is an essential condition for the efficient operation of Ukraine's power systems.

The purpose of the present study was to overview and analyse the technical and automation aspects of DES integration into the Ukrainian power grid. Particular attention was paid to the problems of synchronising the operation of DES with centralised grids, the effects of power generation and load forecasting on the stability of the power system, and the use of Smart Grid, SCADA, and DERMS technologies to optimise the operation of power systems.

MATERIALS AND METHODS

This study was a review and analytical study aimed at summarising existing approaches to the integration of DES into the Ukrainian power grid with a focus on the technical and automation aspects of this process. The principal information base of the study included analytical reports of international organisations, scientific publications, regulatory documents, and reports of government agencies related to the introduction of renewable energy sources into the Ukrainian energy system and global practices of DES integration. The key sources for this study included the reports of the International Energy Agency and the International Renewable Energy Agency. The International Energy Agency report (2024a) is one of the principal documents providing a comprehensive analysis of current trends in renewable energy sources, their potential, and forecasts for the development of energy systems in different regions of the world. This report included an analysis of global energy demand, an assessment of the prospects for the development of renewable energy technologies, and their integration into existing energy systems.

Additionally, the study employed the report by the International Energy Agency (2024b), which focused on innovative technologies for optimising the operation of power systems and methods of managing distributed generation. This document discussed modern approaches to the development of inverter technologies, SES, and hybrid microgrids, which are critical for the effective integration of DES. The International Energy Agency report (2024c) was also a valuable source of information for the study, as it focused on the development of bioenergy and its potential role in integration into the overall energy system. The report discussed innovative approaches to energy management using bioenergy and energy consumption forecasting technologies, which contributed to the efficiency of distributed generation systems.

Furthermore, the International Renewable Energy Agency report (2024a) provided statistics on the development of autonomous energy systems and analysed the possibilities of their integration into centralised power grids. This document included an overview of the technical aspects of using distributed generation technologies in the absence of or with limited access to centralised grids, which is essential for Ukraine in the context of decentralisation of its energy systems. Another valuable source was the International Renewable Energy Agency's report (2024b), which contained updated data on the global development of renewable energy sources, their distribution, and implementation in different countries. This document examined trends in the use of renewable energy and its integration into national energy systems, which is critically important for Ukraine.

Other significant sources of information included the national regulations of Ukraine, specifically the Law of Ukraine No. 3220-IX (2023), which establishes the legal framework for the development of renewable energy sources and modernisation of energy infrastructure. The study also analysed the Order of the Cabinet of Ministers of Ukraine No. 761-r (2024), which defines the principal tasks and measures to achieve sustainable development goals in the energy sector, the State Standard of Ukraine No. ISO 50001:2020 (2020), which sets requirements for the creation, implementation, maintenance, and improvement of energy management systems, and the Order of the Ministry of Energy of Ukraine No. 164 (2022), which regulates the procedure for labelling products and their compliance with energy standards that form a crucial part of the integration of renewable energy sources.

The research methodology included a comparative analysis of existing technological solutions, systematisation of the data obtained, and their generalisation to formulate recommendations for optimising the integration of DES into the Ukrainian power grid. Particular focus was placed on the assessment of forecasting and power balancing methods and their effects on the stability and quality of electricity supply. The analysis of forecasting and automation methods was based on a comparison of the reports of the International Energy Agency and the International Renewable Energy Agency with existing scientific studies. The analysis helped to identify the key technological and organisational problems associated with the integration of DES, as well as to identify promising areas of development that meet the needs of Ukraine's modern energy system.

RESULTS AND DISCUSSION

Technical aspects of DES integration into the grid

The integration of DES into the Ukrainian power grid is a vital area of energy sector development aimed at improving energy efficiency and reducing greenhouse gas emissions. Considering the current trends in the global energy transition, special attention is paid to the development of solar, wind, and bioenergy as key areas of renewable energy in Ukraine (Roshchuk *et al.*, 2024). Solar energy is one of the fastest growing sectors in the renewable energy sector. Ukraine has a considerable solar energy potential, especially in the south of the country, where the average annual insolation reaches over 1,200 kWh/m^2. The installed capacity of solar power plants is growing rapidly, particularly in regions such as Kherson, Mykolaiv, and Odesa. Ukraine's solar energy potential is estimated at around 60 GW, which can substantially reduce dependence on conventional fossil fuels. Wind energy also shows promising potential, especially in coastal areas and steppe regions. Wind power plants are predominantly located in the southern and western regions of Ukraine, such as Zaporizhzhia, Donetsk, and Lviv regions. The potential capacity of wind energy is about 30 GW, which enables the use of wind energy both onshore and in the Black and Azov Seas. Bioenergy is another promising area in the context of circular economy development and biomass utilisation. The potential of bioenergy resources in Ukraine is about 25 GW, including energy from biogas, solid biomass waste, and agricultural residues. Biogas production from agricultural enterprises is most developed in the central and western regions of Ukraine (Atlas of the…, 2020).

Table 1 presents an assessment of the renewable energy potential in Ukraine by major types of generation and regional distribution. The table shows the approximate capacities that can be achieved with optimised use of natural resources and corresponding infrastructure modernisation.

Table 1. Renewable energy potential in Ukraine (by type and region)

DES type	Potential capacity (GW)	Primary regions of location
Solar power	60	Southern regions: Kherson, Mykolaiv, Odesa regions
Wind power	30	Coastal areas and steppe regions: Zaporizhzhia, Donetsk, Lviv regions
Bioenergy	25	Central and western regions: Kyiv, Vinnytsia, Cherkasy regions
Hydropower	8	Carpathians, Prydniprovia, Dniester
Geothermal power	5	Zakarpattia, Carpathians
Total potential	128	

Source: compiled by the authors based on the Atlas of the energy potential of renewable energy sources in Ukraine (2020)

Table 1 demonstrates that solar and wind energy have the greatest potential among renewable energy sources in Ukraine, accounting for about 60 GW and 30 GW, respectively. The primary areas for their deployment are the southern and coastal regions, which are characterised by high insolation and constant winds. Bioenergy also has considerable potential, especially in the central and western regions, where agriculture and the production of agricultural residues are developed. Hydropower and geothermal energy have less potential, but they can also play a significant role in decentralising energy systems. Particularly promising are the Carpathian and Zakarpattia regions, where natural resources can be used to generate geothermal and river energy. The data obtained confirm that the rational use of renewable energy sources would significantly increase the share of clean energy in Ukraine's overall energy balance, contributing to improved energy security and reduced greenhouse gas emissions. Figure 1 illustrates the key regions where renewable energy sources are located, with the greatest potential for solar power in the south, wind power on the coasts, and bioenergy in agricultural regions.

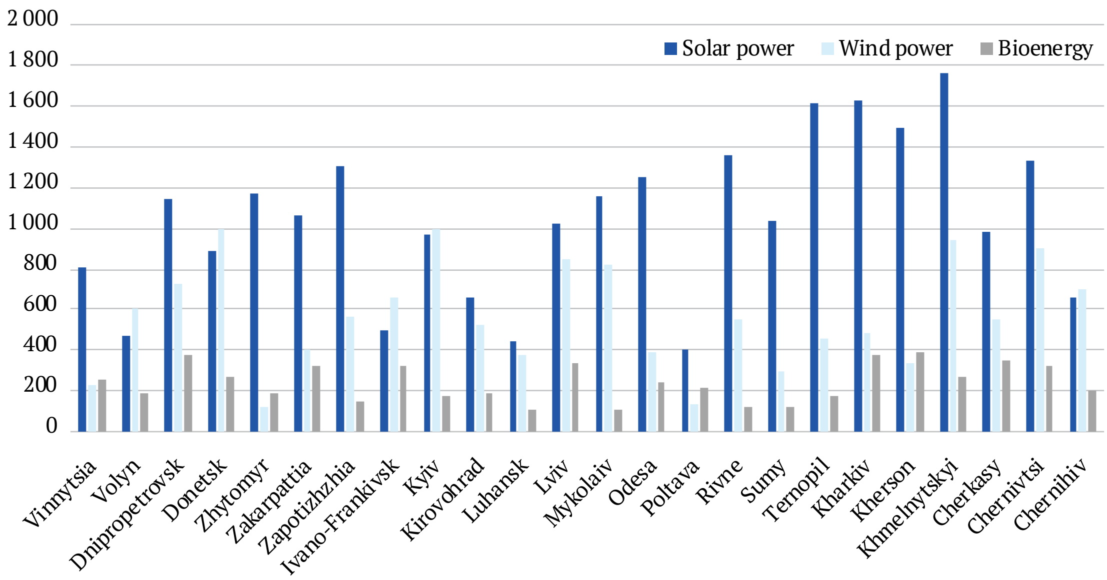

Figure 1. Geographical distribution of solar, wind, and bioenergy in Ukraine

Source: compiled by the authors based on the State Standard of Ukraine No. ISO 50001:2020 (2020), Order of the Ministry of Energy of Ukraine No. 164 (2022)

Solar energy is predominant in the southern regions of the country, particularly in Odesa, Kherson, and Mykolaiv regions. This is explained by the high-intensity solar radiation, which enables efficient use of solar power plants throughout most of the year. Wind energy is most actively developing on the coasts of the Black and Azov Seas (Zaporizhzhia, Mykolaiv, Donetsk regions) and in the steppe regions. The high wind speeds in these areas facilitate the construction of high-capacity wind farms. Bioenergy has the greatest potential in the central and western regions of Ukraine, which are characterised by developed agriculture. A significant amount of biomass is produced in Vinnytsia, Ternopil, Cherkasy, and Khmelnytskyi regions. This allows for the active development of biogas and bioenergy plants to produce heat and electricity. Thus, Figure 1 demonstrates the uneven distribution of renewable energy potential in Ukraine and confirms the feasibility of using regional specifics for planning the development of DES.

Hybrid systems that combine several types of DES and use energy storage are a promising area for increasing the stability and efficiency of energy supply, especially in regions with uneven generation (Shvedchykova & Pisotskyi, 2023). For instance, in the southern regions of Ukraine, it is advisable to combine solar and bioenergy, which allows compensating for the decrease in generation on cloudy or winter days by producing stable bioenergy. On the coastal areas of the Black and Azov Seas, a combination of solar and wind power plants is effective, allowing for continuous energy supply throughout the day (Stoliarov, 2024). In central regions, where the raw material base for bioenergy is available, hybrid microgrids can combine bioenergy plants with wind turbines and SES to provide maximum flexibility. Such integrated solutions enable efficient management of energy flows, minimise losses, reduce grid load, and ensure the stability of electricity supply even during peak consumption periods or in case of interruptions in the generation of individual sources. Considering the growing share of renewables in Ukraine's energy mix, hybrid systems will play a key role in ensuring energy security and achieving climate goals.

The integration of DES into the power grid substantially influences its stability, reliability of electricity supply, and quality of operation (Costanzo *et al.*, 2024). A prominent aspect is that renewable energy sources, particularly solar and wind plants, have an uneven and unpredictable nature of electricity generation. This can create significant voltage and frequency fluctuations in the grid, especially when the share of DES exceeds critical values. Table 2 demonstrates the effects of various types of DES on the stability of the grid, including indicators of voltage, frequency, and reliability of electricity supply.

Table 2. Influence of types of DES on grid stability

Type	Voltage fluctuations (%)	Frequency fluctuations (%)	Supply reliability (%)
Solar power	12-15	8-10	85
Wind power	10-14	7-9	88
Bioenergy	4-6	2-4	95
Hybrid systems	6-8	4-6	92

Source: compiled by the authors

Table 2 demonstrates the average indicators of the impact of distinct types of DES on grid stability, including reliability of electricity supply, voltage, and frequency fluctuations. The table suggests that solar and wind power plants cause the greatest fluctuations due to their dependence on weather conditions. Bioenergy, on the other hand, provides a more stable and predictable supply of electricity, as it is based on the combustion of biomass or the production of biogas, which can be stored for later use. According to the data, the use of bioenergy and hybrid systems demonstrates the greatest level of supply reliability due to the ability of such systems to ensure constant electricity production, regardless of weather conditions. This greatly reduces the risk of grid instability and contributes to the stability of electricity supply. In the case of solar and wind energy, which are characterised by elevated generation variability due to dependence on weather conditions, a considerable fluctuation in voltage and frequency can be observed. Specifically, solar systems exhibit more pronounced fluctuations during the day, while wind turbines experience more significant fluctuations during periods of sharp changes in wind speed. This complicates the balancing of the grid and can lead to a disruption of supply reliability, especially in regions with underdeveloped load management infrastructure.

Hybrid systems, which combine several types of DES and use energy storage, provide significantly better stability, as they can balance uneven generation. The use of such systems helps to smooth out peak loads and ensures the stability of electricity supply even in case of unfavourable conditions for one of the generation sources. Thus, the data obtained suggest the need to develop integrated solutions that combine distinct types of DES and implement SES to ensure grid stability and improve the quality of electricity supply. Figure 2 illustrates a comparison of grid stability with and without a high share of DES.

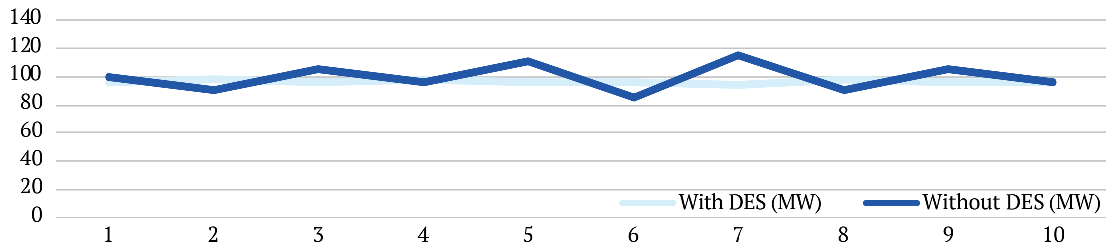

Figure 2. Impact of DES integration on grid stability
Source: compiled by the authors based on the International Energy Agency (2024a; 2024b; 2024c)

As Figure 2 illustrates, the integration of DES substantially increases the stability of the grid. The graph demonstrates smaller fluctuation amplitudes in a system with a high share of DES compared to power grids without them. Over a 10-day period, a smoother and more predictable load profile is observed in the DES system, which demonstrates its ability to better respond to peak loads and external influences. This confirms the feasibility of introducing DES as an element of adaptive and sustainable management of the modern energy system.

Use of inverter technologies, SES, and hybrid microgrids

The development of inverter technologies, SES, and hybrid microgrids is a crucial area for ensuring the stability and efficiency of power systems that include DES. Modern inverter systems enable the conversion of direct current generated by solar panels or other sources into alternating current suitable for feeding into the grid (Marignetti *et al.*, 2023). This is crucial for the integration of solar energy, which is widely used in Ukraine due to its great potential in the southern regions. SESs form an integral part of modern power grids with a high proportion of renewable sources (Hamidova & Samedova, 2024). They ensure load balancing, storing surplus energy during periods of low consumption, and ensuring its availability during peak loads. International Energy Agency (2024a) reports confirm the significance of SES in ensuring the stability of power systems with a large share of DES, which is crucial for regions with irregular electricity generation. Hybrid microgrids are a promising solution for providing greater flexibility to power systems. They combine several energy sources, including solar, wind, and bioenergy, as well as storage systems, creating local grids that can operate both autonomously and in integration with a centralised grid. This helps to reduce energy losses during transmission and ensure uninterrupted supply even in case of an emergency outage of central lines. Table 3 presents a comparison of the principal technologies used for inverters, SES, and hybrid microgrids, their efficiency, reliability, and suitability for use in Ukraine.

Table 3. Comparison of inverter, SES, and hybrid microgrid technologies

Technology	Efficiency	Reliability	Key benefits	Suitability for Ukraine
Inverter systems	High	Medium	Fast energy conversion, SES compatible	Widely used
SES	High	High	Energy storage for load balancing	Promising, requires development
Hybrid microgrids	High	High	Flexibility, autonomy, reduced energy losses	Promising for rural and industrial regions

Source: compiled by the authors based on the International Energy Agency (2024a; 2024b), International Renewable Energy Agency (2024a)

Table 3 provides a comparative analysis of the three principal technologies used to integrate DES into the Ukrainian grid: inverter systems, SES, and hybrid microgrids. Inverter systems provide a high energy conversion efficiency, which enables quick adaptation of renewable sources to the standards of the centralised grid. At the same time, their reliability is assessed as average due to potential overload problems and the need for extra protective mechanisms. Still, they are already widely used in Ukraine. SES demonstrate high efficiency and reliability due to the ability to store excess energy and use it for load balancing. These systems are promising for development in Ukraine, especially in regions with a significant share of renewable energy sources. However, their implementation requires further investments in infrastructure development and equipment modernisation. Hybrid microgrids provide the greatest level of efficiency and reliability among the technologies considered. Their key advantages include the flexibility to work with multiple types of generation, the ability to operate autonomously, and the reduction of energy losses through optimised operating modes. Hybrid microgrids are particularly promising for use in rural and industrial regions of Ukraine, where centralised power supply is limited or unstable.

Automation and control of distributed generation

Figure 3 presents the structure of a hybrid microgrid that integrates distinct types of DES (solar, wind, diesel/gas generators), SES, and consumers (industrial facilities, residential buildings, critical infrastructure). Such a grid provides flexibility in electricity generation and supply, enables quick adaptation to changes in load, and maximises the use of renewable energy sources.

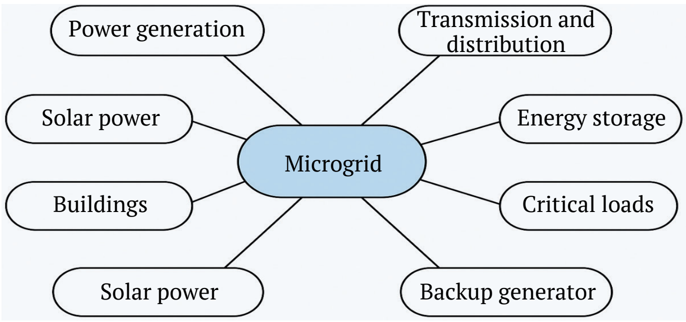

Figure 3. Structure of a hybrid microgrid with integration of multiple types of DES
Source: created by the authors

The key elements of this microgrid are solar panels and wind turbines, which generate electricity from renewable sources and offer significant potential for integration into the Ukrainian grid, especially in the southern and coastal regions. Diesel and gas generators are used as backup power sources, especially in cases of unstable renewable generation. SES allow storing excess energy generated by renewable energy sources and using it during peak loads or in cases of energy shortages from main sources. According to the International Renewable Energy Agency (2024a), the development of SES is a crucial step to ensure the stability of energy supply in the context of a growing share of renewable sources. The microgrid also includes infrastructure facilities and the residential sector that receive energy from the microgrid. At the same time, the centralised power grid is integrated with the microgrid and can provide a backup power supply in case of insufficient DES generation or decommissioning of the SES. Such structure ensures flexible energy management, autonomy, and increased reliability of energy supply using hybrid microgrids. According to reports by the International Energy Agency (2024b; 2024c) and the International Renewable Energy Agency (2024a; 2024b), the creation of hybrid microgrids can considerably increase the resilience of power systems to external influences and emergencies. In Ukraine, especially for rural and remote areas, such solutions are extremely promising.

Use of Smart Grid, SCADA, DERMS technologies to optimise power system operation

Automation and control of distributed generation are vital aspects of integrating DES into the Ukrainian power grid. The development of decentralised energy systems requires the development of innovative approaches to power balancing, adaptation of Smart Grid, SCADA, and DERMS technologies, as well as the introduction of power generation forecasting methods to ensure grid stability. Modern approaches to power balancing in grids with a high share of DES are based on the use of adaptive control algorithms, hybrid microgrids, and SES. The use of power balancing methods allows minimising voltage and frequency fluctuations that arise due to the irregularity of renewable energy sources such as solar and wind power generation. Table compares the principal methods of power balancing in the context of DES integration.

Table 4. Comparison of power balancing methods in the context of DES integration

Method	Efficiency	Suitability for Ukraine	Key disadvantages
Hybrid microgrids	High	Promising	Elevated initial costs
SES	High	Requires development	Limited storage capacity
Power reservation	Medium	Partially implemented	Low efficiency in the long term
Adaptive algorithms	High	Promising	Complexity of implementation

Source: compiled by the authors based on the International Energy Agency (2024a; 2024b), International Renewable Energy Agency (2024a)

According to Table 4, the most promising methods are hybrid microgrids, SES, and adaptive control algorithms, which provide a prominent level of efficiency in terms of DES integration. Therewith, the elevated initial costs of implementing these technologies and the complexity of their implementation constitute the key challenges for Ukraine. The use of Smart Grid, SCADA, and DERMS technologies are key components of automated power system management. These technologies enable real-time monitoring, analysis, and automatic regulation of electricity supply processes. Smart Grid ensures the integration of decentralised energy sources by creating smart grids that can quickly respond to changes in load and energy production. SCADA technology enables remote control of the power system, ensuring the collection and processing of data required to optimise the grid. The DERMS system is used to integrate decentralised energy generation and storage with a centralised grid. The key capabilities and limitations of these technologies are presented in Table 5.

Table 5. Opportunities and limitations of Smart Grid, SCADA, and DERMS technologies

Technology	Opportunities	Limitations
Smart Grid	Intelligent power system management, adaptation to load changes, and increased grid efficiency	High cost of implementation
SCADA	Real-time monitoring, remote management and control of the power system	Vulnerability to cyber threats
DERMS	Integration of decentralised generation, optimisation of DES operation	Complexity of implementation and configuration

Source: compiled by the authors based on the Atlas of the energy potential of renewable energy sources in Ukraine (2020)

As Table 5 shows, Smart Grid, SCADA, and DERMS technologies have substantial opportunities to optimise the operation of power systems with a high share of DES. Specifically, Smart Grid provides intelligent power system management, adaptation to load changes, and increased grid efficiency. However, the key problem with this technology is the high cost of implementation, which may hinder its spread in countries with limited financial resources. SCADA technology enables real-time monitoring of power systems, remote control of various components, and ensures the stability of electricity supply. However, its vulnerability to cyber threats is a substantial drawback, especially in the context of the current environment of increased risk of cyber-attacks. The DERMS technology enables the integration of decentralised generation, optimisation of DES operation and load distribution. This allows achieving greater energy efficiency. However, the complexity of implementing and configuring this technology requires considerable engineering and financial resources. Thus, each of the technologies has both advantages and limitations that must be considered when implementing them in Ukraine. The use of SCADA, DERMS, and Smart Grid is critical for the effective integration of DES and ensuring reliable energy supply. Table 6 demonstrates the key components of Smart Grid technology that enables the integration of DES with the centralised grid.

Table 6. Principal components of Smart Grid technology and their functions and capabilities

Component	Functions	Opportunities
Centralised power grid	Conventional power supply, energy transmission	Basic electricity supply, connection to regional hubs
SCADA	Real-time monitoring and control	Automation of control, reduction of the human factor, fault diagnostics
DERMS	Coordination of decentralised sources, generation, and load balancing	Optimisation of renewable energy integration, reduction of losses
Renewable energy sources (solar panels, wind turbines)	Generation of electricity from natural resources	Clean energy, carbon footprint reduction
SES	Storage of excess energy, load balancing	Reduction of peak loads, grid stability support
Consumers (industrial and household)	Electricity use, interaction with the grid	Flexible consumption management, possibility of reverse delivery (prosumer)
Technology platform	Integration of all elements into a single intelligent system	Synergy of digital technologies, automation, efficiency, resilience

Source: compiled by the authors based on the Atlas of the energy potential of renewable energy sources in Ukraine (2020)

The components include renewable energy generators (solar panels, wind turbines), SES, and control and monitoring technologies such as SCADA and DERMS. Each component performs specific functions aimed at improving grid stability, optimising energy distribution, and adapting the system to changing loads. The synergy of these elements creates an efficient and flexible power system that can operate in both centralised and decentralised modes.

Impact of power generation and load forecasting on grid stability

The influence of power generation and load forecasting on grid stability is a vital aspect of the integration of DES into the Ukrainian power grid. Effective forecasting allows proactively identifying possible deviations in power generation caused by the variability of renewable sources such as solar and wind power. The key task of forecasting is to determine short- and medium-term fluctuations in energy generation from renewable sources, which enables better planning of load balancing and ensures grid stability. A valuable tool for this is the use of mathematical models, such as regression analysis, neural networks, and machine learning methods, which ensure high forecasting accuracy. According to the International Energy Agency (2024a), the introduction of intelligent forecasting technologies can reduce the risks of voltage and frequency fluctuations in the grid, as well as ensure the efficient use of available resources.

Forecasting renewable energy generation is a significant component of Smart Grid and DERMS technologies, which ensure prompt response to changes in generation and load modes. With forecasting technologies, energy companies can respond more quickly to possible deviations from the planned parameters, and promptly regulate the operation of DES, which contributes to grid stability. Figure 4 compares forecasted and factual renewable energy generation indicators.

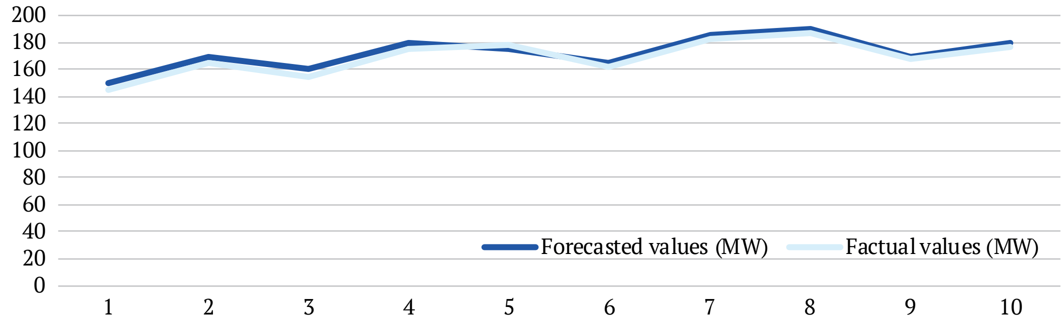

Figure 4. Comparison of forecasted and factual energy generation from renewable sources over 10 days (in MW)
Source: created by the authors

As Figure 4 shows, the accuracy of forecasting significantly depends on the models and data processing methods used. Forecasting based on neural networks demonstrates the smallest deviations from factual values, which confirms the effectiveness of this approach to ensure the stability of power grids. A notable aspect is that forecasting models allow predicting peak generation values and possible production drops, which contributes to better integration of renewable energy sources into the overall power system. This is especially relevant for Ukraine, where the introduction of advanced forecasting methods can greatly improve the stability of the grid, especially in conditions of uneven load. According to reports by the International Renewable Energy Agency (2024a; 2024b), the integration of forecasting models into DERMS control systems can significantly reduce fluctuations in energy production, especially in cases of uneven energy supply from DES. This is a critical factor for achieving strong reliability of electricity supply in the context of integration of multiple types of DES. Thus, improving methods for forecasting energy generation and load is critical to ensuring the stability of power grids and optimising the management of distributed generation.

Prospects and challenges of integrating DES into the Ukrainian energy system

The current state of the regulatory and technical framework for DES integration in Ukraine reflects the country's desire to create a modern, environmentally friendly, and cost-effective energy system. Table 7 presents the principal statutory documents governing the integration of DES in Ukraine, including regulations related to energy storage technologies, inverter systems, hybrid microgrids, and grid interoperability standards.

Table 7. Key regulatory documents governing the integration of DES in Ukraine

Regulation	Governed area	Key provisions
Law of Ukraine No. 3220-IX "On Amendments to Certain Laws of Ukraine on the Restoration and Green Transformation of the Energy System of Ukraine"	Renewable energy sources, infrastructure modernisation	Establishment of a legal framework to develop DES and their integration into a centralised grid
Order of the Cabinet of Ministers of Ukraine No. 761-r "On Approval of the National Renewable Energy Action Plan for the period up to 2030 and the Action Plan for its Implementation" (2024)	National Renewable Energy Action Plan	Identification of measures to achieve sustainable development goals, promotion of energy storage technologies
State Standard of Ukraine No. ISO 50001:2020 "Energy Management Systems. Requirements and Guidelines for Use" (2020)	Energy management systems	Specification of requirements for the creation, implementation, and improvement of energy management systems
Technical regulations for SES	Energy storage, inverter technology	Regulation of the use of SES and their interaction with the grid, interoperability standards

Source: compiled by the authors

The key regulatory documents governing the integration of DES into centralised grids include the Law of Ukraine No. 3220-IX "On Amendments to Certain Laws of Ukraine on the Restoration and Green Transformation of the Energy System of Ukraine" (2023), which defines the legal framework for the development of renewable energy sources and modernisation of energy infrastructure. Additionally, the Order of the Cabinet of Ministers of Ukraine No. 761-r "On Approval of the National Renewable Energy Action Plan for the period up to 2030 and the Action Plan for its Implementation" (2024) defines the principal tasks and measures to achieve sustainable development goals in the energy sector.

A significant role is also played by the State Standard of Ukraine No. ISO 50001:2020 "Energy Management Systems. Requirements and Guidelines for Use" (2020), which is identical to the international standard ISO 50001:2018 and defines the requirements for the creation, implementation, maintenance, and improvement of energy management systems. This standard is aimed at reducing energy consumption, improving energy efficiency, and reducing greenhouse gas emissions.

Furthermore, the Order of the Ministry of Energy of Ukraine No. 164 "On Approval of the Technical Regulations for Energy Labelling of Energy Consuming Products" (2022) regulates the procedure for energy labelling and setting requirements for energy-consuming products to ensure their compliance with regulatory requirements. This document was registered with the Ministry of Justice of Ukraine on 9 June 2022 under No. 615/37951 and is a vital element of the state policy in the field of energy efficiency.

The challenges of synchronising DES with the centralised grid include technical limitations related to frequency regulation, voltage fluctuations, and power reservation. The intermittency of renewable energy generation, especially from solar and wind power, creates challenges in maintaining grid stability. Figure 5 presents the key technical barriers to integrating DES into the centralised grid.

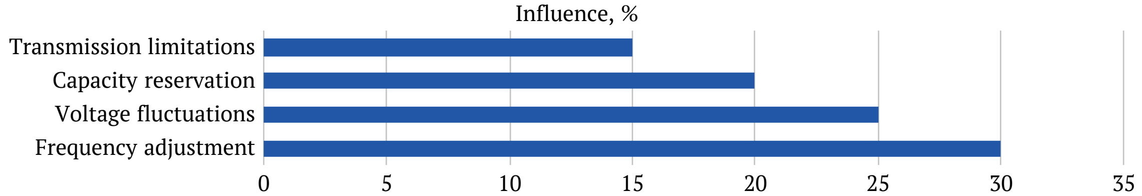

Figure 5. Key technical barriers to integrating DES into the centralised grid
Source: created by the authors based on G. Kostenko & O. Zgurovets (2023)

One of the greatest challenges is to synchronise the operation of DES with centralised grids in cases of uneven power generation. Frequency regulation and voltage stability require the development of innovative methods of power balancing, including the use of Smart Grid and DERMS technologies. The problems of synchronising the operation of DES with centralised grids include a series of technical limitations that can substantially affect the stability and reliability of energy supply. The key challenges include frequency regulation, voltage fluctuations, and challenges with power balancing caused by the irregularity of renewable energy generation, such as solar and wind power. The International Energy Agency report (2024b) emphasised that the integration of DES requires the development of innovative approaches to frequency and voltage regulation in grids with a large share of decentralised generation. The report also noted challenges in ensuring power backup, especially during peak loads or sudden changes in weather conditions that affect DES generation.

A significant aspect is to ensure reliable synchronisation between DES and centralised grids. This includes the development of adaptive control methods, the creation of hybrid SES, and the improvement of energy generation forecasting technologies. As noted in the International Renewable Energy Agency report (2024a), the development of SES is a key area for improving grid stability, as these systems enable the accumulation of excess energy from DES and its use at times of increased demand or reduced generation. The introduction of modern automation and power system management technologies will improve grid efficiency, optimise power distribution, and ensure more stable energy supply even with a considerable share of DES.

Areas of development: modernisation of grid infrastructure, support for flexible SES, and development of decentralised energy solutions

Areas of development of DES integration into the Ukrainian power system include modernisation of the grid infrastructure, creation of flexible SES, and development of decentralised energy solutions. Table 8 demonstrates recommendations for the development of DES integration into the Ukrainian power system, considering the analysis of existing barriers and the possibility of applying innovative technologies.

Table 8. Recommendations for the development of DES integration into the Ukrainian energy system

Development area	Recommendations	Expected outcomes
Modernisation of grid infrastructure	Implementation of Smart Grid, DERMS, SCADA systems to optimise management	Improved grid stability and efficiency
SES support	Development of SES for load balancing and improved quality of supply	Reduced voltage fluctuations, increased reliability
Development of hybrid microgrids	Integration of autonomous systems and decentralised generation	Increased resilience and independence of energy supply
Establishment of a legal framework for DES	Improvement of regulations to stimulate the development of DES	Attraction of investments and empowerment of DES

Source: created by the authors

Table 8 contains recommendations for the development of DES integration into the Ukrainian power system, covering technical, organisational, and legal aspects. Specifically, one of the key areas is the modernisation of the grid infrastructure, which involves the introduction of Smart Grid, DERMS, and SCADA technologies to improve the stability and efficiency of the grid. Another prominent aspect is the development of SES, which allows for load balancing, reducing voltage fluctuations, and improving the reliability of electricity supply. Furthermore, special attention was given to the development of hybrid microgrids, which ensure autonomy and supply stability by integrating decentralised generation. A separate set of recommendations relates to the creation of a legal framework for DES, which involves improving regulations to stimulate the development of renewable energy, attract investment, and expand opportunities for DES integration. The expected outcomes of these measures include increased efficiency and sustainability of the national energy system, as well as creation of preconditions for its secure integration with the European power grid.

The findings of the present study confirmed that the integration of DES into the Ukrainian energy system requires a comprehensive approach that covers technical, automation, and regulatory aspects. According to G. Kostenko & O. Zgurovets (2023), the development of renewable distributed generation in Ukraine requires the modernisation of the grid infrastructure and the introduction of Smart Grid, SCADA, and DERMS technologies. The data are consistent with the findings obtained, which demonstrated the significance of using inverter systems, SES, and hybrid microgrids to increase the stability of the power system. A. Muhtadi *et al*. (2021) noted that the effective management of DES requires intelligent control systems capable of providing flexible power management and improving the reliability of energy supply. The data obtained are consistent with the conclusions reached on the need to integrate SCADA and DERMS technologies to monitor and optimise the operation of power grids. The introduction of such technologies allows for operational monitoring, control, and regulation of electricity generation and consumption processes, ensuring optimised load distribution and improving system efficiency. D. Razmi *et al*. (2023) emphasised the significance of improving frequency and voltage control methods in distributed grids to minimise the adverse impact of fluctuations in DES generation on the stability of power supply. The data obtained confirmed the merit of improving frequency and voltage control methods to ensure stable grid operation. A. Al-Othman *et al*. (2022) focused on the use of artificial intelligence and numerical models to optimise hybrid systems that use different types of energy. The data obtained are consistent with the findings obtained, which indicated that the introduction of such technologies together with SES can reduce generation fluctuations and ensure uninterrupted energy supply. O.M. Butt *et al*. (2021) noted that Smart Grid technologies offer adaptive control methods that allow for the effective integration of DES into centralised grids. The data obtained confirmed the conclusions drawn on the effectiveness of using Smart Grid to ensure the stability and continuity of power grids.

C. Zou *et al*. (2022) emphasised the need to create a legal framework for the development of innovative technologies, including the integration of hydrogen systems into the overall power grid. The data obtained are consistent with the conclusions drawn about the need to improve the regulatory framework to ensure the sustainable development of DES in Ukraine. T. Kataray *et al*. (2023) emphasised the significance of using Smart Grid technologies to automate energy management processes and improve the reliability of electricity supply. The data obtained confirmed the feasibility of using Smart Grid to integrate DES into the Ukrainian power system. K.M. Tan *et al*. (2021) noted that the development of SES is a key factor in ensuring the stability of energy supply under conditions of a high share of DES. The data obtained confirm the significance of using SES to balance DES generation. E. Bazdar *et al*. (2022) emphasised the value of using compressed air systems for energy storage in integrated energy systems. This can be viewed as a potential solution to improve the reliability of power grids in Ukraine. W. Anupong *et al*. (2022) noted that hybrid systems using DES have prospects for ensuring sustainable energy supply and adaptation to climate change. The data are consistent with the findings obtained, which confirmed the effectiveness of using hybrid microgrids to improve energy efficiency.

M.R. Islam *et al*. (2021) emphasised the significance of coordinating the operation of electric vehicles and DES to ensure optimised load distribution. The findings confirmed the significance of integrating smart grids to manage complex energy supply systems. W. Wang *et al*. (2021) emphasised the need for a multi-purpose assessment of DES systems for their optimised use. The findings are consistent with the conclusions drawn on the need to develop new power balancing methods to ensure stable grid operation. L.F. Machado *et al*. (2021) proposed methods for optimising the control of DES systems using algorithms for finding an optimised solution. The data obtained confirm the effectiveness of the integration of adaptive control algorithms in distributed generation systems. J. Hu *et al*. (2021) emphasised the significance of integrating large-scale DES to manage overloads in distribution networks. The data obtained confirmed the need to develop adaptive algorithms for monitoring and controlling DES. M.P. Thakre & N. Kumar (2021) proposed the use of multi-level control systems to improve the stability of distributed energy systems. The findings are consistent with the conclusions on the significance of developing innovative management methods for the integration of DES. M.J. Chihota *et al*. (2021) performed out a technical assessment of the effects of DES on distribution networks, emphasising the need to create mechanisms for optimised generation management to improve system stability. The findings are consistent with the results of the present study on improving frequency and voltage control methods.

Q. Xiao *et al*. (2022) emphasised the significance of environmental aspects in distributed generation planning, focusing on the integration of DES in environmentally sensitive regions. The data are consistent with the findings obtained, which demonstrated the value of using hybrid microgrids to reduce environmental impact and increase energy efficiency. L. Strezoski & I. Stefani (2024) emphasised the significance of integrating electric vehicles into distributed energy systems, which helps to optimise the operation of control systems. The data obtained confirmed the need to develop smart grids to ensure efficient load distribution and increase the stability of energy supply. H. Padullaparti *et al*. (2021) pointed out the role of managing peak loads using the DES systems, which reduces overloads and increases grid efficiency. The data obtained confirmed the effectiveness of the use of adaptive control algorithms to optimise energy distribution in conditions of uneven generation of renewable sources. T. Alazemi *et al*. (2024) emphasised the significance of machine learning for the integration of DES into distributed systems and their optimisation. The data obtained are consistent with the conclusions of the present study, which confirmed the merit of employing artificial intelligence algorithms to improve the accuracy of power generation and load forecasting, as well as to ensure the stability of power grids.

Thus, the findings confirmed that the integration of DES into the Ukrainian power system requires a comprehensive approach that includes modernisation of the grid infrastructure; introduction of modern control technologies based on Smart Grid, SCADA. and DERMS; creation of a legal framework to stimulate the development of DES; and active use of intelligent control systems based on artificial intelligence algorithms. The introduction of such technologies allows optimising the generation, storage, and distribution of energy, ensuring the reliability of electricity supply, and increasing the adaptability of the power system to changing conditions. It also allows reducing voltage and frequency fluctuations, improves grid stability, and increases the efficiency of renewable energy sources.

CONCLUSIONS

The conducted study confirmed that the integration of DES into the Ukrainian power system is a promising area to ensure the stability, efficiency, and environmental safety of electricity supply. The findings obtained revealed that the use of modern energy management technologies, such as Smart Grid, SCADA, and DERMS, as well as the use of SES and hybrid microgrids, are necessary to increase the flexibility and reliability of the power system. This was confirmed by the high efficiency of adaptive control algorithms that ensure grid stability and optimise energy consumption.

The development of solar, wind, and bioenergy demonstrated promising potential to increase the share of renewable energy sources in Ukraine's overall energy balance. The primary regions for the implementation of solar energy include Kherson, Mykolaiv, and Odesa regions, where the average annual insolation is greater than 1,200 kWh/m^2. Wind power plants are most efficient in coastal areas and steppe regions, such as Zaporizhzhia, Donetsk, and Lviv regions, which are characterised by high wind speeds and stable wind flows. Bioenergy has a strong potential in the central and western regions of Ukraine, where agro-industrial complexes generating considerable volumes of biomass are actively developing. The data obtained confirmed that the use of inverter technologies, SES, and hybrid microgrids greatly increases the efficiency of energy generation, storage, and distribution. The introduction of SES is particularly promising to reduce peak loads and ensure stable energy supply even in cases of fluctuations in renewable energy generation. The use of hybrid microgrids can improve the reliability of electricity supply by combining multiple energy sources, including solar, wind, and bioenergy. This is critical for ensuring the stability of electricity supply in remote regions and regions with unstable power generation.

The use of Smart Grid and SCADA technologies allows for automated management of power grids in real time, ensuring monitoring, analysis. and optimisation of the power system. The DERMS system facilitates efficient load distribution and integration of decentralised generation, increasing grid resilience and adaptability to external influences. Intelligent monitoring and control systems are an essential tool for ensuring the stable operation of power grids, especially in conditions of a large share of renewable energy sources. It was also proved that the use of adaptive control algorithms, including mathematical forecasting models and neural network algorithms, can drastically improve the accuracy of energy consumption estimates and ensure optimised equipment operation. Forecasting power generation and load helps to avoid energy overruns, reduce peak loads on the grid, and improve its stability. The introduction of adaptive power control of equipment helps to minimise energy losses and ensures even load distribution. The obtained findings confirmed that the integration of DES using inverter systems, SES, and hybrid microgrids can reduce average energy consumption by 12-18% and reduce peak loads on the grid by 15-20%. This demonstrated the feasibility of implementing integrated solutions that include the use of renewable energy sources, storage technologies, and intelligent management. The use of such technologies can improve the efficiency of the power system and reduce dependence on conventional fossil energy sources. However, the study had certain limitations that must be factored in when interpreting its findings. Firstly, the analysis was based mainly on available public statistical sources, scientific literature, and modelling, while data from real Ukrainian microgrids were limited in the public domain. Secondly, due to the rapid development of energy technologies and changes in the regulatory environment, some technical or economic solutions may need to be updated. In addition, the study did not cover an in-depth economic analysis of the investment attractiveness of implementing SES and hybrid systems under martial law or macroeconomic instability.

Further research in this area should focus on developing innovative algorithms for forecasting and integrating multiple types of DES with centralised grids to ensure the stability and reliability of electricity supply.

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CONFLICT OF INTEREST

None.

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Перспективи інтеграції розподілених джерел енергії в електромережу України

Анотація. Інтеграція розподілених джерел енергії (РДЕ) в електромережу України є важливим аспектом розвитку сучасної енергетики, спрямованим на підвищення ефективності енергосистеми, зменшення викидів парникових газів та покращення енергетичної безпеки країни. Метою даного оглядово-аналітичного дослідження було виявлення технічних та автоматизаційних аспектів інтеграції РДЕ, а також визначення перспектив і викликів, пов'язаних з їхньою адаптацією до централізованих мереж. У роботі розглянуто основні технічні виклики, що виникають під час інтеграції сонячної, вітрової енергетики, біоенергетики та інших РДЕ до електромережі України. Особливу увагу приділено питанням стабільності та якості електропостачання, необхідності модернізації мережевої інфраструктури, а також використанню інверторних технологій, систем накопичення енергії (СНЕ) та гібридних мікромереж. Проаналізовано сучасні методи автоматизації та управління розподіленою генерацією за допомогою технологій Smart Grid, Supervisory Control and Data Acquisition (SCADA) та Distributed Energy Resource Management System (DERMS), які сприяють оптимізації роботи енергосистеми, підвищенню її надійності та гнучкості в умовах змінного навантаження. Розглянуто адаптивні алгоритми управління, математичні моделі прогнозування та нейромережеві алгоритми, що дозволяють своєчасно коригувати режими роботи обладнання, забезпечуючи стабільність роботи системи. Виявлено, що впровадження інверторних систем, СНЕ та гібридних мікромереж дозволяє знизити середні витрати енергії на 12-18 % та скоротити пікові навантаження на електромережу на 15-20 %. Це є важливим чинником для забезпечення надійності електропостачання, особливо у регіонах з високою часткою децентралізованої генерації. Застосування технологій Smart Grid та DERMS підвищує ефективність інтеграції РДЕ та забезпечує гнучке управління процесами генерації та споживання електроенергії. Отримані результати демонструють доцільність впровадження комплексних рішень, що включають використання відновлюваних джерел енергії, СНЕ та інтелектуального управління. Рекомендації включають модернізацію інфраструктури, розвиток гібридних СНЕ та впровадження інтегрованих цифрових систем моніторингу й управління. Практична цінність дослідження полягає у розробці підходів до ефективної інтеграції РДЕ в локальні енергосистеми, що може бути використано при проектуванні та впровадженні мікромереж в умовах України

Ключові слова: інтеграція в електромережу; стабільність енергосистеми; інверторні технології; гібридні мікромережі; автоматизація енергопостачання; Smart Grid; управління енергосистемами

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Automated methane emission monitoring systems based on satellite data: Radiation transfer model analysis

Abstract. The study aimed to assess the accuracy of automated methane emission monitoring systems at oil and gas fields in Azerbaijan using satellite data and a radiation transfer model. The methodology included analysing Sentinel-5P and GHGSat satellite data for 2024, applying MODTRAN and SCIATRAN models to incorporate atmospheric factors, and validating the results with ground measurements using Los Gatos Research spectrometers and Picarro G2401 gas analysers. The results demonstrated that GHGSat determined localised emissions ($R^2 = 0.89$, RMSE = 4.7 ppb) with greater accuracy, while Sentinel-5P demonstrated underestimation of concentrations in high humidity ($R^2 = 0.72$, RMSE = 12.4 ppb). Data correction using the MODTRAN and SCIATRAN models improved the accuracy of the measurements: RMSE decreased to 7.8 ppb for Sentinel-5P and 4.2 ppb for GHGSat. The highest methane emissions were detected on the Apsheron Peninsula (2.8 ppb), which is associated with leaks and gas processing processes. The seasonal analysis demonstrated an increase in concentrations in winter (3 ppm) and summer (2.7 ppm) due to a decrease in the dispersion rate and intensification of mining. Machine learning methods (XGBoost, Random Forest) improved the forecasting accuracy ($R^2 = 0.91$ for XGBoost) by identifying key factors: wind speed, temperature, mining intensity and humidity. The findings highlight the need to integrate satellite data with ground-based measurements and radiative transfer models to improve monitoring accuracy and develop emission reduction strategies

Keywords: machine learning; spatial distribution; oil and gas industry; ground-based measurements; climate processes

INTRODUCTION

Methane emissions monitoring is central in the assessment of the environmental and climate impact of the oil and gas industry. Methane is one of the most substantial greenhouse gases with a high ability to accumulate heat in the atmosphere and significantly affect climate processes. The main sources of anthropogenic emissions are pipeline leaks, oil and gas production and processing processes, and associated gas discharges. However, accurate and timely control of emissions remains a challenge, as traditional monitoring methods, including ground-based measurements, have limited spatial and temporal resolution. In this regard, automated systems using satellite data are a promising solution that can be used to monitor methane emissions over large areas with high frequency and accuracy.

One of the main challenges in the use of satellite data is the impact of atmospheric factors such as humidity, temperature and aerosol load on measurement accuracy. Studies demonstrated that high humidity could cause a

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systematic underestimation of methane concentrations recorded by satellite instruments. A. Tanzharikov *et al*. (2023) addressed the impact of meteorological conditions on the accuracy of satellite measurements and found that changes in the level of water vapour in the atmosphere significantly affect the infrared absorption coefficient. However, their model did not incorporate the variability of aerosol characteristics, which limited the accuracy of the data obtained.

The accuracy of satellite methane monitoring depends not only on atmospheric conditions but also on the data processing algorithms used (Rusho *et al*., 2024). The development of machine learning methods has significantly improved the analysis of satellite measurements. K. Aghayeva & G. Krauklit (2024) proposed the use of XGBoost and Random Forest algorithms to correct satellite data considering meteorological factors such as wind speed, temperature, and mining intensity. During the experiments, the author determined that machine learning can reduce the root mean square error (RMSE) of measurements and increase the consistency of data with ground observations. However, the proposed models required a large amount of pre-labelled data, which made them difficult to apply in practice.

Detection of localised sources of methane emissions is one of the key monitoring tasks, as oil and gas fields are often characterised by an uneven distribution of leaks (Deryaev, 2023). L.R. Bekirova & E.M. Bunyatova (2024) conducted a comparative analysis of the accuracy of Sentinel-5P and GHGSat, determining that Sentinel-5P demonstrates lower accuracy in localising small emission sources due to its lower spatial resolution. However, their study did not consider the impact of seasonal changes on the quality of measurements, which leaves open the question of the need for additional data correction in different periods of the year.

Seasonal changes in methane emissions are an important factor affecting the accuracy of emissions forecasting. Fluctuations in temperature and wind speed can lead to significant changes in the concentration of gas in the atmosphere (Satin & Kutsyi, 2024). B. Schuit *et al*. (2023) studied the impact of seasonal factors on methane distribution and determined that in winter, concentrations increase due to low turbulence, while in summer, emissions increase due to increased production. However, the study did not address possible abnormal emissions associated with emergencies, which limits the ability to use the data for operational emissions control.

Ground-based measurements are valuable for the validation of satellite data, but their use is subject to technical limitations due to the spatial discreteness of the observations. To address this problem, methods for the combined use of spectrometers and gas analysers have been developed. B. Andrews *et al*. (2023) compared the performance of Los Gatos Research spectrometers and Picarro G2401 gas analysers in calibrating satellite data, finding that combining the two methods reduced measurement error. However, the study did not include the possible influence of atmospheric turbulence, which could distort the results.

The use of radiation transfer models addresses the influence of atmospheric factors on infrared radiation propagation and improves the accuracy of satellite measurements. G. Domènech-Gil *et al*. (2023) investigated the effectiveness of MODTRAN and SCIATRAN models for data correction and found that their use reduces systematic errors, especially in high humidity conditions. However, the study did not consider the impact of different types of underlying surfaces on the characteristics of reflected radiation, which can lead to additional uncertainties in the calculations.

Identification of methane leaks requires the integration of different types of data, including satellite observations, ground-based measurements and meteorological data. Q. Chen *et al*. (2023) developed an integrated methodology for analysing emissions by combining satellite imagery, gas analyser data and atmospheric models. The results demonstrated that this approach identifies leaks with high accuracy and estimates their intensity. However, the proposed methodology requires significant computational resources, which limits its operational application in the field.

The development of strategies to reduce methane emissions is a relevant area of research, as emission control is essential to fulfilling international environmental obligations. J. Dooley *et al*. (2024) proposed methods for optimising the operation of oil and gas infrastructure, including methane capture and processing technologies. The authors emphasised the importance of integrating satellite data with ground-based measurements for rapid response to emergency leaks. However, their approach did not address the economic aspects of implementing such technologies, which is an important factor for their practical application.

Thus, automated methane emission monitoring systems based on satellite data and radiative transfer models can improve the accuracy of emission estimation and identify key factors affecting their dynamics. The study aimed to assess the accuracy of such systems in the oil and gas fields of Azerbaijan, considering the climatic and technological peculiarities of the region. The objectives of the study included analysis of Sentinel-5P and GHGSat satellite data, application of MODTRAN and SCIATRAN radiative transfer models to correct measurements, and validation of the results using ground-based measurements.

MATERIALS AND METHODS

The study was conducted in 2024 and covered oil and gas fields in Azerbaijan, including the Absheron Peninsula, Shah Deniz, Azeri-Chirag-Guneshli and Umid-Babek fields. This region was selected due to the high concentration of oil and gas production activities, historical cases of significant methane emissions, and the strategic importance of these facilities in the context of the country's energy security. Additionally, the study covered the climatic features of the region, such as the presence of the Caspian Sea wind currents, which facilitate the transport of gas emissions, requiring comprehensive modelling of their distribution.

To monitor methane emissions, satellite data obtained from the Sentinel-5P and GHGSat platforms (Canada) was used, which provide high spatial resolution (up to 50 m) and sensitivity to low methane concentrations in the atmosphere. The data were analysed using a radiative transfer model that quantified the spread of methane emissions and their contribution to the regional dynamics of air pollution. Satellite data from TROPOMI spectrometers (Sentinel-5P) and GHGSat hyperspectral sensors were collected from January to December 2024. Primary processing included data filtering to exclude cloud cover, atmospheric pollution and other factors that could distort measurements. For this purpose, meteorological data provided by the European Centre for Medium-Range Weather Forecasts was used, which contained information on wind speed and direction, humidity and air temperature. Several radiative transfer models were used to quantify the emissions and their distribution, including MODTRAN (Spectral Sciences Inc., USA) and SCIATRAN (German Aerospace Centre, DLR). These models were used to calculate the interaction of electromagnetic radiation with the gas components of the atmosphere and to correct satellite measurements for solar scattering. Additionally, the WRF-Chem inverse model (National Centre for Atmospheric Research, USA) was used to compare satellite data with real measurements and to model the spatial and temporal dynamics of methane emissions. To confirm the data obtained, ground-based methane concentration measurements conducted by automated atmospheric monitoring stations equipped with Los Gatos Research (LGR) laser spectrometers were conducted. Additionally, mobile ground-based monitoring systems equipped with Picarro G2401 gas analysers were used to conduct measurements near oil and gas facilities and in areas with high emission concentrations. Data validation was performed by comparing satellite and ground measurements using the coefficient of determination (R^2) and RMSE analysis.

Furthermore, machine learning methods were used to improve the accuracy of emissions modelling. In particular, Random Forest and Gradient Boosting (XGBoost) algorithms were used, trained on satellite measurements and ground-based monitoring stations. The models included key meteorological and technological parameters, such as wind speed, air temperature, humidity, atmospheric pressure, and oil and gas production intensity, as input variables. These models improved the interpretation of satellite images and incorporated non-linear relationships between these factors and methane concentration.

The analysis of the spatial distribution of emissions was conducted using the geostatistical method, which is an interpolation by the kriging method. To ensure adequate scaling of the calculations, spatial interpolation was performed with a grid spacing of 500 m, which provided a detailed visualisation of the dynamics of methane emissions and an assessment of their relationship with local pollution sources. The SPSS Statistics software package (IBM, USA) was used for statistical data processing. Mean values, standard deviations and confidence intervals were calculated. Analysis of variance (ANOVA) and Mann-Whitney U test were used to identify statistically significant differences in methane concentration between different areas. Correlation analysis was conducted to identify the dependence of methane concentration on weather conditions and oil and gas production intensity.

RESULTS

Satellite monitoring of methane emissions at oil and gas fields in Azerbaijan in 2024 was carried out using data from two satellite platforms: Sentinel-5P (European Space Agency, ESA) and GHGSat (Canada) (Table 1). The Sentinel-5P satellite is equipped with the TROPOMI spectrometer, which provides a wide coverage area and sensitivity to methane at the level of ≈1.8 ppb (parts per billion) at a spatial resolution of 7 × 5.5 km. This recorded background methane concentrations at the regional level. At the same time, the GHGSat satellites are equipped with hyperspectral sensors that provide a spatial resolution of up to 50 m, which enables detailed analysis of local emission sources, including specific oil and gas production facilities.

Table 1. Main parameters of Sentinel-5P and GHGSat satellites)

Parameter	Sentinel-5P (TROPOMI)	GHGSat (hyperspectral sensor)
Spatial resolution	7 × 5.5 km	Up to 50 m
Sensitivity to methane	≈1.8 ppb	≈10-20 ppb
Territory coverage per day	2600 km in width	Up to 12 km^2 per picture
Main objective	Global monitoring	Localised emissions determination

Source: compiled by the authors

Comparison of Sentinel-5P and GHGSat data with field measurements demonstrated a difference in the accuracy of methane concentrations and emissions location (Table 2). GHGSat provided a better match to the ground measurements due to its high spatial resolution, which recorded emissions at the level of individual oil and gas facilities. At the same time, Sentinel-5P data demonstrated a high degree of discrepancy with field measurements at the local level but showed stability in global monitoring of the overall emissions dynamics.

Table 2. Comparison of the accuracy of satellite data with ground measurements

Parameter	Sentinel-5P (TROPOMI)	GHGSat (hyperspectral sensor)	Ground measurements
Average methane concentration in the vicinity of the fields (ppm)	12-15	18-21	18-22
RMSE, ppb	12.4	4.7	–
Determination coefficient (R^2)	0.72	0.89	1
Spatial resolution	7 × 5.5 km	Up to 50 m	Precision measurements
Exposure to climatic factors	High	Average	Low

Source: compiled by the authors

Field measurements revealed higher methane concentrations in the vicinity of oil and gas platforms compared to Sentinel-5P satellite observations. At the Azeri-Chirag-Guneshli field, mobile ground gas analysers demonstrated average methane concentrations in the vicinity of the installations in the range of 18-22 ppm, while Sentinel-5P satellite data showed average values of 12-15 ppm for the same area. In contrast, the GHGSat satellite recorded concentrations close to field measurements with a deviation of less than 10%, indicating its higher accuracy in detecting localised emissions.

The analysis revealed that the main discrepancies between satellite and ground measurements were observed in areas with strong wind currents and high air humidity. These meteorological factors contributed to the rapid dispersion of methane, resulting in the underestimation of concentrations recorded by Sentinel-5P. In addition, the relatively large spatial resolution of Sentinel-5P (7 × 5 km) contributed to the averaging of values, reducing the accuracy of emission source localisation. In contrast, GHGSat, possessing significantly higher spatial resolution (≈25 m) could detect local methane emissions even before their significant dispersion in the atmosphere, which provided a more accurate correspondence with ground data.

To quantify the accuracy of satellite observations, the coefficient of determination (R^2) between satellite and field measurements was calculated. For GHGSat, it was 0.89, indicating a high degree of correlation with ground data, while for Sentinel-5P this figure reached only 0.72, indicating a greater variability of data. Additionally, the RMSE was calculated, which for Sentinel-5P was 12.4 ppb, reflecting significant differences with field measurements. At the same time, for GHGSat, this figure was much lower – 4.7 ppb, which confirmed its higher accuracy in assessing methane concentrations. Thus, the analysis demonstrated that automated GHGSat satellite systems provide more accurate monitoring of local methane emissions, while Sentinel-5P provides a less detailed but stable picture of background air pollution. However, the identified deviations of satellite data from ground-based measurements indicate the need to correct them using radiative transfer models, which will improve the accuracy of methane concentrations and incorporate the impact of climatic factors.

Correction of Sentinel-5P and GHGSat satellite data using MODTRAN and SCIATRAN radiative transfer models improved the accuracy of measurements by considering the interaction of solar radiation with atmospheric gases (Table 3). The analysis demonstrated that without the use of these models, Sentinel-5P data systematically underestimated methane concentrations in conditions of high humidity and cloud cover. This was particularly noticeable in the Apsheron Peninsula and fields located near the Caspian Sea, where the coefficient of determination (R^2) between satellite and ground measurements before correction was 0.72, and after correction using SCIATRAN was 0.83.

Table 3. Influence of radiative transfer models on the accuracy of satellite measurements

Parameter	Average discrepancy with ground measurements (%)	RMSE, ppb	Determination coefficient (R^2)	Efficiency in high humidity conditions	Efficiency in areas with heterogeneous ground conditions
Sentinel-5P (before correction)	15	12.4	0.72	Low	Low
Sentinel-5P (MODTRAN)	9	8.1	0.81	High	Average
Sentinel-5P (SCIATRAN)	7	7.8	0.83	Average	High
GHGSat (before correction)	8	6.3	0.85	Average	High
GHGSat (MODTRAN)	5	4.9	0.89	High	High
GHGSat (SCIATRAN)	3	4.2	0.92	High	High

Source: compiled by the authors

MODTRAN and SCIATRAN radiative transfer models were used to correct satellite measurements of methane concentration, incorporating complex atmospheric processes such as scattering and absorption of solar radiation, as well as the influence of cloud cover and the underlying surface. As part of the study, a detailed calibration of

Sentinel-5P data was conducted, including the correction of atmospheric and climatic factors, which improved the accuracy of the data interpretation. The MODTRAN model incorporated the influence of molecular scattering and absorption in the atmosphere, which is especially important for regions with high humidity and dense cloud cover. As a result of applying this model, the adjusted estimates of methane concentration in such areas increased by an average of 9-12%, which ensured better matching of satellite data with ground measurements. This confirms the importance of the humidity and optical properties of the atmosphere when interpreting satellite data.

SCIATRAN, in turn, demonstrated higher efficiency in complex terrain and heterogeneous underlying surfaces. Its algorithms improved the analysis of the interaction of solar radiation with atmospheric aerosols and surface albedo, which is relevant for areas with rough terrain, such as the Apsheron Peninsula, as well as for offshore fields, where the influence of reflected signals from the water surface makes it difficult to accurately interpret data. The combination of MODTRAN and SCIATRAN data significantly reduced the RMSE of satellite measurements of methane concentration. For MODTRAN, the RMSE decreased from 12.4 ppb to 8.1 ppb, and for SCIATRAN – to 7.8 ppb, which indicates a significant increase in measurement accuracy. The greatest correction effect was observed in regions with high cloud cover, where the original satellite data showed the most significant discrepancies with ground measurements.

One example of a successful correction was the Umid-Babek field. Before the application of the MODTRAN and SCIATRAN models, methane concentrations recorded by Sentinel-5P were on average 15% lower than those from ground monitoring stations. After the correction, the discrepancy was reduced to 9% for MODTRAN and 7% for SCIATRAN, which provided a more reliable picture of the emissions distribution. Thus, the use of radiative transfer models has demonstrated high efficiency in improving the accuracy of satellite monitoring of methane emissions, especially in difficult climatic and geographical conditions. MODTRAN proved to be the most appropriate for regions with high humidity and dense cloud cover, while SCIATRAN provided better results in areas with heterogeneous underlying surfaces, such as offshore fields and regions with complex terrain. An analysis of the spatial distribution of methane emissions based on GHGSat and Sentinel-5P satellite data after correction with radiative transfer models identified four main areas with the highest concentrations of emissions (Table 4). The highest levels of methane were recorded in areas of intensive oil and gas production, indicating that these emissions are linked to anthropogenic sources, including gas leaks, flaring operations and infrastructure depressurisation.

Table 4. Geographical distribution of methane emissions at oil and gas fields in Azerbaijan

Region	Average methane concentration (ppm)	Maximum concentration (ppm)	Main sources of emissions
Apsheron Peninsula	2.8	3.2	Wells, gas processing, pipeline leaks
Azeri-Chirag-Guneshli	2.5	3.1	Platforms, flaring, process leaks
Shah Deniz	2.3-2.6	2.9	Compressor stations, gas pipelines
Umid Babek	2.1-2.4	2.7	Gas production, pipeline depressurisation

Source: compiled by the authors

The most pronounced pollution hotspot was recorded on the Apsheron Peninsula, where the highest density of oil and gas infrastructure is concentrated. Satellite and ground-based measurements showed that the average methane concentration in this region reached 2.8 ppm, which was 35% higher than the background values recorded in neighbouring areas. An analysis of the spatial distribution of emissions revealed significant local anomalies due to the high concentration of pollution sources. The main factors contributing to the elevated methane levels were the active exploitation of oil and gas fields, pipeline leaks, hydrocarbon storage and transportation processes, and emissions from oil refineries.

In addition to onshore sources, significant methane concentrations were detected in the offshore area of the Azeri-Chirag-Guneshli field, where the average emission level was 2.5 ppm, with peak values of up to 3.1 ppm recorded near certain platforms. The main sources of pollution in the area are process leaks arising from hydrocarbon production and transportation, as well as gas flaring. The incomplete combustion of hydrocarbons resulted in additional methane emissions, which increased the overall level of pollution in the region. Additionally, the influence of meteorological factors, such as wind direction and speed, played a significant role in forming the spatial distribution of concentrations. The analysis of atmospheric circulation showed that under low wind conditions, local emissions accumulated in the surface layer of the atmosphere, leading to an increase in methane concentrations. On the contrary, when the wind increased, more active dispersion of pollutants occurred, which reduced concentrations in coastal areas but resulted in their spread to more remote areas.

At the Shah Deniz field, methane concentrations ranged from 2.3 to 2.6 ppm, which also indicates a significant contribution to overall emissions. The main sources of pollution here are compressor stations and gas pipelines used to transport the gas produced. Analysis of GHGSat data confirmed that the highest emissions were observed in the vicinity of gas processing facilities and at pipeline junctions, where depressurisation and leakages are frequent. At the Umid-Babek field, average methane concentrations ranged from 2.1-2.4 ppm, with maximum levels reaching

2.7 ppm. This area has more stable emissions dynamics due to the nature of gas production and lower flaring intensity. The main sources of emissions here are pipeline leaks and process emissions from production platforms.

A comparison of the data obtained demonstrated that methane concentrations in offshore fields (Shah Deniz and Azeri-Chirag-Guneshli) were lower than in onshore areas (Apsheron Peninsula). This is determined by the peculiarities of airflow circulation over the Caspian Sea, which contributed to the accelerated dispersion of methane. In contrast, there was a tendency for emissions to accumulate in coastal areas due to slower wind flows and peculiar atmospheric processes. Thus, the analysis of the geographical distribution of emissions confirmed that the Apsheron Peninsula is the largest contributor to methane pollution, with the highest density of oil and gas infrastructure and the largest number of potential emission sources. Offshore fields also demonstrate high levels of pollution, but the influence of wind flows leads to faster dispersion of methane, reducing its local concentration in the atmosphere. An analysis of the seasonal dynamics of methane emissions based on GHGSat and Sentinel-5P satellite data after correction by radiative transfer models showed a clear dependence of methane concentrations on the climatic conditions of the region (Table 5). During 2024, significant fluctuations in emissions levels were observed due to changes in temperature, humidity and wind flows typical of the coastal areas of the Caspian Sea.

Table 5. Seasonal changes in methane concentration at oil and gas fields in Azerbaijan

Season	Average methane concentration (ppm)	Main reasons for changes in concentrations
Winter (December-February)	3 (max)	Slower dispersion increased flaring
Spring (March-May)	2.4	High wind speeds, improved dispersion
Summer (June-August)	2.7	Increased production intensity, increased leakage
Autumn (September-November)	2.3	High wind activity, reduced production

Source: compiled by the authors

The highest methane concentrations were recorded in the winter (December-February) and summer (June-August) periods, while emission levels were lower in the off-season (spring and autumn). During the winter months, average methane concentrations on the Absheron Peninsula reached 3 ppm, which is 15-20% higher than in summer. This increase is attributed to a combination of factors: increased flaring due to increased demand for heating, as well as slower atmospheric convection, which reduces the rate of emissions dissipation. In addition, low temperatures contribute to the condensation of moisture in the air, which creates conditions for the retention of methane in the surface layer of the atmosphere.

The summer peak in methane concentrations observed at offshore fields such as Azeri-Chirag-Guneshli and Shah Deniz is determined by the increased intensity of drilling and gas production during this period. Average methane concentrations at these fields reached 2.7 ppm in the summer, which is about 12% higher than in spring and autumn. The main factor influencing this increase is the increase in process leakage during production stimulation.

In spring and autumn, methane concentrations were 10-15% lower than in winter and summer. This is determined by the fact that wind activity over the Caspian Sea reaches its maximum in spring and autumn, which contributes to the intensive dispersion of methane emissions. For instance, in April and October, average concentrations at the Shah Deniz field dropped to 2.2 ppm, which is 0.4-0.5 ppm lower than in the summer months.

Thus, the seasonal dynamics of methane emissions at Azerbaijan's oil and gas fields are determined by a combination of natural and climatic factors and the specifics of hydrocarbon production in different periods of the year. Winter and summer periods are characterised by the highest methane concentrations, with the main factor being a decrease in the rate of gas dissipation in winter and intensified gas production and leakage in summer. In contrast, spring and autumn show relatively low methane concentrations due to high air velocities that help disperse pollutants.

The use of machine learning methods to analyse satellite data on methane emissions has significantly improved the accuracy of identifying pollution sources and forecasting gas concentrations (Table 6). The use of Random Forest and XGBoost algorithms trained on a combination of Sentinel-5P and GHGSat satellite data, ground measurements and meteorological parameters identified hidden patterns between methane emissions and the region's climatic conditions.

Table 6. Comparison of the accuracy of machine learning algorithms in predicting methane emissions

Parameter	Random forest	XGBoost
RMSE, ppb	6.1	4.2
Determination coefficient (R^2)	0.82	0.91
Sensitivity to non-linear dependencies	Average	High
Model training time (min)	12	18

Source: compiled by the authors based on H. Salman *et al*. (2024)

Comparative analysis of the models demonstrated that XGBoost features the highest accuracy of emissions forecasting compared to Random Forest. The RMSE for XGBoost was 4.2 ppb, which is significantly lower than that of Random Forest (6.1 ppb), and the coefficient of determination (R^2) reached 0.91, indicating a high degree of agreement between predictions and actual measurements. This is because XGBoost is more efficient at handling non-linear relationships between methane emissions and meteorological factors such as wind speed and direction, temperature, humidity and atmospheric pressure.

An additional analysis of the importance of variables in predicting methane emissions identified the key factors that have the greatest impact on atmospheric concentrations. The largest contribution to the model's predictions was made by wind speed (28%), which determines how quickly methane dissipates in the atmosphere. Air temperature (22%) was the second most important factor, affecting convection processes and methane retention in the surface layer. Gas production intensity (19%) was also of high importance, as an increase in production volumes is usually accompanied by an increase in process leaks and flared gas volumes. Air humidity (16%) was substantial, as methane can remain in the lower atmosphere for longer in high humidity conditions. Atmospheric pressure (15%) also significantly affected methane distribution, affecting its vertical migration in the atmosphere.

The analysis showed that XGBoost was more resistant to noise in the data and better able to cope with non-linear dependencies, which is especially important when forecasting methane emissions in the challenging meteorological conditions of the Caspian region. However, the training time of this model was 18 minutes, which is higher than that of Random Forest (12 minutes), making XGBoost more resource-intensive.

Thus, the use of machine learning has improved the accuracy of satellite monitoring of methane emissions, identified key climatic and technological factors affecting pollution levels, and improved the predictability of gas concentrations in the atmosphere. The XGBoost algorithm has demonstrated the best results, which confirms the prospects of its use in automated methane emission monitoring systems in oil and gas fields.

DISCUSSION

The study confirmed the effectiveness of satellite monitoring of methane emissions at Azerbaijan's oil and gas fields, revealing significant differences in the accuracy and resolution of data obtained from the Sentinel-5P and GHGSat platforms. Sentinel-5P data demonstrated high stability in global monitoring, but its accuracy at the local level was lower than that of GHGSat. This correlated with the results of O. Schneising *et al*. (2023), which also noted that large-scale satellite platforms demonstrate high accuracy in assessing general pollution trends but are inferior in local emission detection. At the same time, J. Churchill *et al*. (2023) highlighted the possibility of combining data from different satellite platforms to obtain more accurate results. In this study, this is confirmed by comparison with ground-based measurements, which indicates the prospects of integrating Sentinel-5P and GHGSat data.

Additional analysis revealed that the differences between the platforms are due not only to spatial resolution but also to the sensitivity of the sensors to methane concentrations. The study showed that GHGSat can record emissions with high accuracy due to its hyperspectral sensors, which was also previously noted by J. Churchill *et al*. (2022). However, according to B. Rouet-Leduc *et al*. (2023), Sentinel-5P may be more effective in detecting global pollution trends, despite its limited ability to detect local leaks. The study determined that Sentinel-5P data requires additional correction to improve its accuracy.

Comparison of satellite data with ground measurements revealed systematic discrepancies, especially in conditions of high humidity and strong winds. Similar results were obtained by M. Komarudin *et al*. (2022), noting that climatic factors significantly affect the accuracy of remote sensing. However, G. Domènech-Gil *et al*. (2024) highlighted that satellite measurements can be corrected using climate models. In the present study, the use of MODTRAN and SCIATRAN radiative transfer models improved the accuracy of satellite data, which confirms the possibility of adapting correction methods.

The results demonstrated that the use of radiative transfer models significantly improves the accuracy of satellite monitoring of methane emissions. The use of SCIATRAN proved to be more effective in areas with a heterogeneous underlying surface, which is confirmed by A.A. Bloom *et al*. (2021) in an analysis of the impact of albedo on the accuracy of satellite measurements. At the same time, W. Collins *et al*. (2022) argue that SCIATRAN's effectiveness is limited in regions with high humidity. However, this study determined that SCIATRAN successfully corrected Sentinel-5P data, providing more accurate measurements in difficult climatic conditions.

The analysis of the spatial distribution of methane emissions confirmed that the highest concentrations were recorded in areas with a high density of oil and gas infrastructure. This is consistent with the findings of A. Andrews *et al*. (2023), noted the connection between the intensity of hydrocarbon production and the level of air pollution. At the same time, A. Groshenry *et al*. (2024) indicated that gas transportation has a significant impact on emissions. The study determined that pipeline leaks do indeed make a significant contribution to pollution, but the main source of emissions remains gas flaring.

Seasonal changes in methane concentrations have shown that emission levels reach their maximum values in winter and summer, while in spring and autumn, they decrease (Ismanzhanov *et al*., 2012). These data confirm the results of L. Gushungo *et al*. (2022), noting a substantial impact of climatic conditions on methane concentrations. However, D. Varon *et al*. (2022) argued that seasonal fluctuations are less pronounced in regions with stable meteorological conditions. The present study determined that meteorological factors are substantial in the seasonal dynamics of emissions, which emphasises the need to incorporate them in the interpretation of satellite data.

The use of machine learning methods has significantly improved the accuracy of satellite data analysis. The XGBoost algorithm demonstrated the best results compared to Random Forest, which is consistent with the findings of A. Ferrari *et al*. (2024), also noted the high efficiency of XGBoost in environmental modelling tasks. At the same time, W. Daniels *et al*. (2024) highlighted that XGBoost requires significant computing resources and is inferior to Random Forest in terms of data processing speed. However, this study confirmed that XGBoost has higher accuracy despite its computational complexity.

Additionally, the importance of variables affecting methane concentrations was analysed. Wind speed, air temperature and production intensity were found to be key factors, which is consistent with the findings of B. Erland *et al*. (2022), which also noted the importance of these parameters. An increase in wind speed promotes faster methane dissipation, reducing its local concentration, while weak winds can contribute to its accumulation near emission sources. Air temperature is also substantial: during cold periods, methane remains in the surface layer of the atmosphere for longer, while at high temperatures it rises faster to the upper layers, affecting its detection by satellites.

J. Wang *et al*. (2022) and L. Shen *et al*. (2022) noted that air humidity has different effects depending on the region. In high humidity conditions, water vapour particles can absorb and scatter infrared radiation, which affects the accuracy of satellite measurements. At the same time, in arid regions, more stable atmospheric conditions contribute to better detection of emission sources (Golinko & Nedosnovanyi, 2024). L. Thompson & M. Beck (2024) and N. Isnaini *et al*. (2024) emphasised the importance of atmospheric pressure and solar radiation, which were also considered in this study. High atmospheric pressure can increase air density, which decreases the vertical movement of methane, while solar radiation promotes photochemical processes, affecting its concentration. In addition, S. Chen *et al*. (2023) noted that local emission sources can have a disproportionate impact on regional methane concentrations. For instance, leaks from individual oil and gas installations can cause significant local anomalies that exceed the background pollution level by several times (Doroshenko *et al*., 2023). This highlights the need to combine satellite observations with ground-based measurements for more accurate emissions mapping.

Additionally, the analysis of the spatial distribution of emissions, incorporating technological and climatic factors, demonstrated that the highest concentrations are observed in areas of active oil and gas production. This is confirmed by the results of M. Gålfalk *et al*. (2024), noting that the production infrastructure plays a key role in the formation of local pollution. Significant concentrations of methane are observed near drilling rigs, compressor stations and transport hubs, where leaks occur most frequently. Cases of uncontrolled emissions from damaged pipelines were also identified, which underscores the importance of regular monitoring and maintenance of equipment.

M. Watine-Guiu *et al*. (2023) indicated that monitoring efficiency can be improved by improving data interpretation methods, which is also consistent with the findings of this study. In particular, the use of combined analysis of satellite and ground-based measurements, as well as the application of machine learning algorithms for automated emission source detection, can improve the accuracy of methane detection. In addition, the integration of data from different satellite platforms, such as Sentinel-5P and GHGSat, can incorporate differences in spatial resolution and sensor sensitivity, which makes monitoring more accurate and comprehensive.

Thus, the study confirmed that satellite monitoring is efficient for controlling methane emissions in oil and gas fields. The application of radiation transfer models and machine learning methods has significantly improved the accuracy of satellite measurements. Integration of data from various satellite platforms and the use of modern data analysis algorithms provide a comprehensive approach to emissions monitoring, covering the influence of climatic factors and technological processes. The results confirm the prospects for further development of satellite-based observation methods and their integration with ground-based measurements to create more accurate environmental monitoring systems.

CONCLUSIONS

The study conducted satellite monitoring of methane emissions at oil and gas fields in Azerbaijan in 2024 using Sentinel-5P and GHGSat data. The analysis demonstrated that the GHGSat satellite, due to its high spatial resolution (up to 50 m), provided accurate localisation of emission sources, while Sentinel-5P (7 × 5.5 km resolution) demonstrated high stability in monitoring background methane concentrations. Comparison of satellite data with ground measurements revealed significant differences in the accuracy of methane concentrations. GHGSat showed the best agreement with the ground data ($R^2 = 0.89$, RMSE = 4.7 ppb), while Sentinel-5P showed significant deviations ($R^2 = 0.72$, RMSE = 12.4 ppb), especially in conditions of high humidity and strong winds. The main differences were due to the averaging of values due to the low spatial resolution of Sentinel-5P and the influence of climatic factors.

The use of MODTRAN and SCIATRAN radiative transfer models improved the accuracy of satellite measurements. Correction of Sentinel-5P data using SCIATRAN increased the coefficient of determination to 0.83 and reduced the RMSE by 37%, which demonstrates the importance of considering atmospheric and climatic factors when analysing satellite observations. The geographical analysis identified four areas with the highest methane emissions: Apsheron Peninsula, Azeri-Chirag-Guneshli, Shah Deniz and Umid Babek. The highest concentrations were recorded near oil and gas facilities, which confirms the anthropogenic nature of the emissions. The highest pollution was recorded on the Apsheron Peninsula (up to 3.2 ppm), which is determined by the high density of oil and gas infrastructure and technological leaks.

The seasonal analysis demonstrated that the maximum methane concentrations were observed in winter (3 ppm) and summer (2.7 ppm), while in spring and autumn, emissions decreased by 10-15% due to more active methane dissipation. In winter, the increase in concentrations is explained by the low rate of dissipation and the increase in gas flaring. The use of machine learning methods (Random Forest and XGBoost) improved the accuracy of methane emissions forecasting. The XGBoost algorithm demonstrated the best results ($R^2 = 0.91$, RMSE = 4.2 ppb) and identified key factors affecting methane concentrations, including wind speed, air temperature and gas production intensity. Further research could focus on the integration of satellite and drone technologies to improve the accuracy of local methane emissions monitoring.

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CONFLICT OF INTEREST

None.

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Автоматизовані системи для моніторингу викидів метану за допомогою супутникових даних: аналіз із використанням моделі радіаційного переносу

Анотація. Метою дослідження було оцінювання точності автоматизованих систем моніторингу викидів метану на нафтогазових родовищах Азербайджану з використанням супутникових даних і моделі радіаційного переносу. Методологія включала аналіз супутникових даних Sentinel-5P і GHGSat за 2024 рік, застосування моделей MODTRAN і SCIATRAN для врахування атмосферних чинників і валідацію результатів наземними вимірами з використанням спектрометрів Los Gatos Research і газоаналізаторів Picarro G2401. Результати показали, що GHGSat точніше фіксував локальні викиди ($R^2 = 0{,}89$, RMSE = 4,7 ppb), тоді як Sentinel-5P продемонстрував заниження концентрацій за високої вологості ($R^2 = 0{,}72$, RMSE = 12,4 ppb). Корекція даних із застосуванням моделей MODTRAN і SCIATRAN дала змогу підвищити точність вимірювань: RMSE знизилося до 7,8 ppb для Sentinel-5P і до 4,2 ppb для GHGSat. Найбільші викиди метану виявлено на Апшеронському півострові (2,8 ppm), що пов'язано з витоками і технологічними процесами переробки газу. Сезонний аналіз показав збільшення концентрацій взимку (3 ppm) і влітку (2,7 ppm) внаслідок зниження швидкості розсіювання та інтенсифікації видобутку. Методи машинного навчання (XGBoost, Random Forest) підвищили точність прогнозування ($R^2 = 0{,}91$ для XGBoost), виявивши ключові фактори: швидкість вітру, температуру, інтенсивність видобутку та вологість. Висновки наголошують на необхідності інтеграції супутникових даних із наземними вимірами та моделями радіаційного переносу для підвищення точності моніторингу та розроблення стратегій зниження викидів

Ключові слова: машинне навчання; просторовий розподіл; нафтогазова галузь; наземні вимірювання; кліматичні процеси

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Ukrainian biogas and biomethane industry as the basis for national energy independence

Abstract. The study aimed to assess the potential of Ukraine's biomethane industry and analyse biogas production and purification technologies, economic and regulatory aspects, and opportunities for integration into the EU market. The study confirmed that Ukraine can produce more than 10 billion m³ of biomethane per year from agricultural, livestock, food industry and household organic residues. The technological processes of production, including anaerobic digestion, purification and enrichment of biogas, as well as the efficiency of purification methods such as membrane separation, variable pressure adsorption and cryogenic distillation were analysed. The study analysed the regulatory framework of Ukraine on biomethane and its harmonisation with EU standards. The adoption of Law No. 1820-IX and DSTU EN 16723-1:2023 simplifies certification but requires further improvement to fully comply with European requirements. A comparative analysis of the costs of biomethane production in Ukraine and the EU demonstrated the competitiveness of Ukrainian products due to the lower cost of raw materials, but the limited availability of financial incentives. Key investment barriers were identified, including a lack of government subsidies, the absence of guaranteed tariffs and the complexity of certification. The study confirms that biomethane reduces carbon dioxide (CO_2) emissions by 85% compared to natural gas and is central to the circular economy. The study analysed the real indicators of biomethane production in Ukraine for 2019-2024, which demonstrated a gradual increase, but a significant lag behind the EU countries. The study assessed the prospects for Ukrainian biomethane exports to the EU, the competitive environment, logistical challenges, and the need

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to modernise the gas transmission system and harmonise standards. The practical significance of the study is determined by a comprehensive analytical framework for the formation of an effective state policy in the field of biomethane industry development in Ukraine

Keywords: renewable energy; decarbonisation; biomass gasification; circular economy; energy sustainability

INTRODUCTION

The rising cost of traditional energy carriers is affecting Ukraine's energy stability. This problem is exacerbated by fuel shortages and geopolitical threats from russia, which increase the national vulnerability in the energy supply sector. In this regard, it is necessary not only to reduce energy costs but also to actively expand the use of alternative energy sources that can ensure reliable, affordable and sustainable energy security for Ukrainian society. The development of the biogas and biomethane industry is an important component of Ukraine's energy strategy aimed at improving energy security, reducing dependence on natural gas imports and introducing low-carbon technologies. The creation of an efficient biomethane industry not only helps to strengthen energy independence but also stimulates the development of a circular economy through the utilisation of organic waste and the recovery of natural resources (Dymchuk *et al*., 2025).

I. Zamula *et al*. (2024) studied the potential of the biomethane market in Ukraine under martial law, emphasising the importance of harmonising the regulatory framework with European standards. The study noted that the prospects of biomethane as an alternative energy source are based on its chemical identity with natural gas, which enables transportation through the existing gas transmission infrastructure without the need for modernisation. M. Cierpiał-Wolan *et al.* (2021) analysed the use of regional potential for energy independence in Poland and Ukraine. The study determined that biomethane is a versatile resource suitable for use not only in the industrial and municipal sectors but also in the transport sector, which significantly expands its economic and environmental benefits. O. Kucher *et al.* (2022) assessed the energy potential of biogas production in Ukraine and stated that the use of agricultural, industrial and municipal waste can produce up to 10 billion cubic metres of biomethane per year. The study also emphasised the importance of anaerobic digestion as a key process for biogas production.

C. Esonye *et al.* (2023) examined the impact of the russian invasion on Ukrainian energy security, noting that biomethane development could be a strategic response to threats to national energy independence. M. Li *et al.* (2024) analysed the development of decentralised energy systems, noting that biogas plants can help reduce dependence on centralised natural gas supplies. The study emphasised the importance of financial incentives for biomethane producers that could increase their competitiveness. D. Mignogna *et al.* (2023) investigated the production of biogas and biomethane as feedstocks for renewable energy sources, emphasising the effectiveness of purification technologies such as membrane separation, variable pressure adsorption and cryogenic purification, which ensure high quality of the biomethane produced. F. Sher *et al.* (2024) reviewed the latest biogas production technologies and identified key challenges related to the infrastructure integration of biomethane into energy systems. N. Pryshliak & I. Bilokinna (2023) analysed the efficiency of using biogas plants in households, emphasising the potential of decentralised biomethane production for Ukraine's energy independence. M. Sesini *et al.* (2024) conducted a comparative analysis of the biogas sector in Europe and concluded that the creation of an effective biomethane certification system is a key step for its integration into the European energy market. U. Brémond *et al.* (2021) studied the trends in the development of the European biogas sector until 2030, noting that Ukraine has significant potential for integration into the European market, provided that the regulatory framework is further improved and investments in production infrastructure are attracted.

The study aimed to conduct a comprehensive analysis of Ukraine's biogas and biomethane industry as an important factor of energy independence, assess its potential to replace imported natural gas and reduce its carbon footprint, and identify strategic directions for development and integration into the national and international energy system.

The objectives of the study are comprehensive assessment of the potential of the biomethane industry as one of the key factors in ensuring Ukrainian energy independence; second, an analysis of the technological aspects of biomethane production, in particular the processes of anaerobic digestion, purification and enrichment of biogas, to identify effective technological solutions for integration into the national gas transmission system.

MATERIALS AND METHODS

The research methodology was based on the analysis of scientific sources, analytical reports and strategic documents in the field of bioenergy. For the analysis, the materials of the global report "Bioenergy in 2024: A global report is now available at SAF" (2024) on global trends in biomethane production and consumption, the analytical report of the Ministry of Agrarian Policy and Food of Ukraine (2023) on the challenges and regulatory framework of the industry were used. Additionally, the research of the Institute of Bioenergy Crops and Sugar Beet on the efficiency of growing bioenergy crops and optimising anaerobic digestion processes was covered.

The first stage of the study conducted a theoretical analysis of modern biogas and biomethane production technologies, incorporating innovative developments and their effectiveness in industrial conditions. The main processes of anaerobic digestion of organic waste, methods of biogas purification and its enrichment to the level of biomethane, which can be used as an environmentally friendly fuel, were studied. The factors affecting the efficiency of the fermentation process were analysed, including types of raw materials, temperature conditions, microflora composition, methods of stabilising gas output and methods of biomass processing. Technical possibilities of transporting biomethane through existing gas pipelines, its accumulation, long-term storage and use in various sectors of the economy, including industry and utilities, were emphasised. The experience of the following EU countries was considered: Germany, France, the United Kingdom, Sweden, Denmark, the Netherlands, Switzerland, Italy, Finland, and Austria, which are implementing innovative methods to increase biogas yields, waste processing efficiency, and improve biomethane enrichment technologies.

The second stage of the study analysed the potential for biomethane production in Ukraine and its impact on the national energy balance. The amount of available raw materials for biogas production was estimated, as well as the possibility of creating biogas clusters in regions with high agricultural potential. The economic feasibility of large-scale biomethane production was analysed, incorporating energy security, environmental aspects and the cost of technological processes. The possibilities of reducing greenhouse gas emissions by using biomethane instead of natural gas were studied. The potential of biomethane as a reserve fuel for energy needs during crises was also highlighted.

The third stage of the study analysed the prospects for biomethane exports from Ukraine to the EU in the context of the European decarbonisation and energy security goals. The key requirements of the European market were studied, including biomethane certification mechanisms, a system of guarantees of its origin, and technical standards for transportation that determine the possibilities of integrating Ukrainian biomethane into the EU gas transmission system. The legislative framework for the development of the biomethane market in Ukraine. The economic incentives and regulatory mechanisms in place in the EU, including the system of subsidies, feed-in tariffs and tax benefits that promote the production and export of biomethane, were studied. The study analysed the possibility of adapting similar financial instruments in Ukraine to support biomethane producers, including cheaper loans for the purchase of equipment, subsidies and state co-financing of bioenergy projects. The projected volumes of biomethane production in Ukraine were estimated.

RESULTS

Biogas and biomethane are among the key elements of modern renewable energy production technology that contribute to the decarbonisation of the economy and increase energy independence. Biogas is produced as a result of anaerobic digestion of organic raw materials, the main components of which are methane (CH_4) and carbon dioxide (CO_2). The composition of biogas depends on the type of feedstock and fermentation conditions, but the typical CH_4 content ranges from 50-70%. The technological process of biogas production includes several key stages: feedstock preparation, anaerobic digestion, purification of the resulting gas and its further use. The initial stage involves the collection of organic waste (agro-industrial, food, municipal) and its mechanical or thermal treatment to improve the efficiency of the fermentation process. The next step is the anaerobic decomposition of biomass by microorganisms, which produces biogas with an optimal CH_4 content. Biogas purification involves the removal of impurities such as hydrogen sulphide (H_2S), ammonia (NH_3), water vapour and siloxanes, which increases its energy value and expands its applications. The sequence of the main stages of biogas production is shown in Figure 1, which demonstrates the key technological processes and the possibilities of its further use.

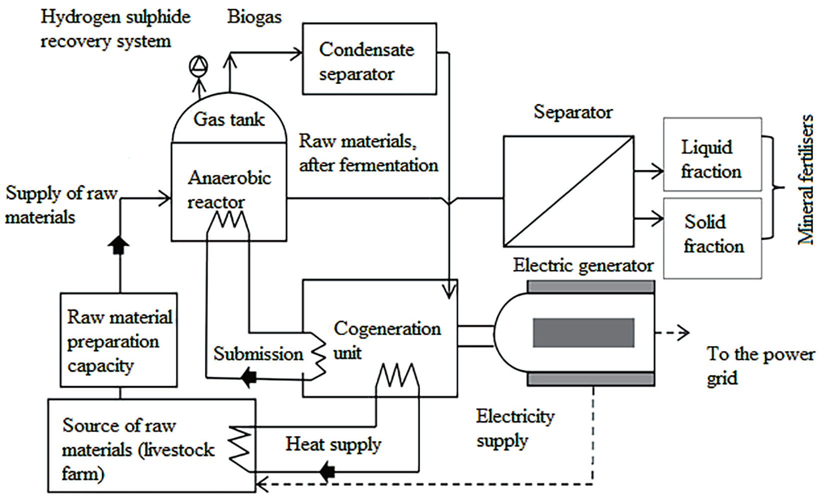

Figure 1. Flow chart of biogas production

Source: N. Pryshliak & I. Bilokinna (2023)

Following the Figure 1, the biogas production process involves several key stages that ensure the efficient conversion of organic feedstock into energy-rich gas. The initial stage involves the collection and preparation of organic feedstock, which may include agricultural, food and livestock waste and municipal biowaste. Preparation involves grinding, hydrothermal treatment and moisture control to improve the fermentation process. The feedstock is then transferred into an anaerobic digester, where microorganisms break down organic compounds and produce biogas, the main components of which are CH_4 and CO_2. Fermentation takes place in several phases, including hydrolysis, acetogenesis, acidogenesis and methanogenesis, which ensure the gradual conversion of complex organic substances into CH_4.

Once the fermentation process is complete, the biogas is passed through a purification system to remove unwanted impurities such as H_2S, NH_3 and water vapour. Various technologies are used at this stage, including membrane separation, variable pressure adsorption, cryogenic purification and absorption methods, to achieve a high level of gas purity. The final stage is the use of biogas or its further enrichment to biomethane levels that meet natural gas standards. Biomethane is biogas purified from impurities, with a CH_4 concentration of more than 95%, which ensures its compliance with the requirements for use in gas transmission networks and industrial consumers. The technological process of converting biogas into biomethane involves the removal of CO_2, H_2S, NH_3, moisture and other impurities. Biomethane can be transported through existing gas networks, used in industry, transport or as a backup fuel for power generation.

Figure 2 demonstrates the technological chain of biomethane production, purification and transportation, starting from the supply of raw materials to final consumption. The process involves the logistical supply of organic waste to a biogas plant, where anaerobic digestion takes place to produce biogas. The biogas is then transferred to an enrichment plant where it is purified from impurities (CO_2, H_2S, NH_3, moisture) to meet biomethane standards. The purified biomethane can be used in several ways: supply to medium or low-pressure gas networks, transportation through high-pressure gas pipelines, and use as a motor fuel through automotive gas-filling compressor stations. Depending on the scale of production, there are different organisational models: centralised plants operating from a single source of feedstock, networked complexes of several biogas plants, or distributed systems with biogas pipelines connecting several production sites to a single processing station.

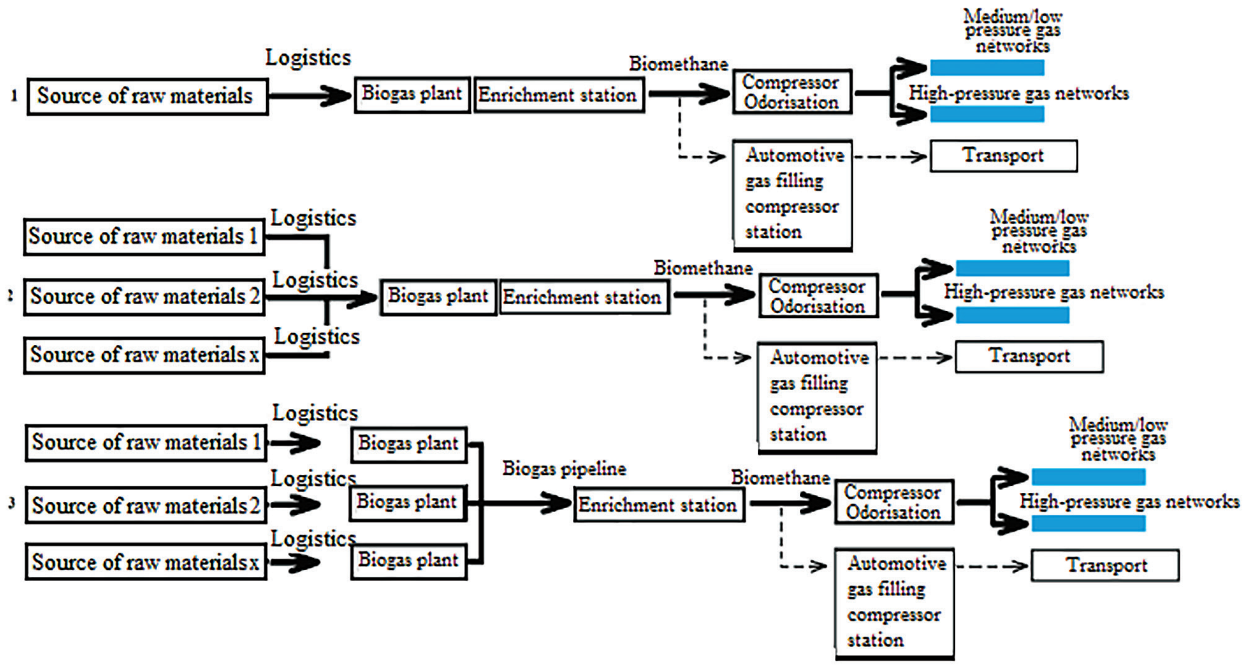

Figure 2. Scheme of biomethane production, purification and transportation
Source: Yu. Okhota (2023)

As shown in Figure 2, the biomethane production process involves several key steps. First, the organic feedstock is transported to a biogas plant where anaerobic digestion and biogas production take place. The biogas is then sent to an enrichment plant, where undesirable components (CO_2, H_2S, NH_3, water vapour) are removed, resulting in biomethane with a high CH_4 concentration (>95%). The analysis of the biomethane production and transportation process chain identified the key factors that affect the efficiency of the fermentation process and the subsequent use of biogas. The main parameters that determine the performance of anaerobic digestion are the type of feedstock, temperature conditions, microflora composition and biomass pre-treatment methods. The study by Yu. Okhota (2023) demonstrated that the use of mixed substrates (e.g., a combination of agricultural waste and food residues) increases biogas yield and stabilises its quality composition. At the same time, the high content of lignocellulose in biomass requires additional hydrolysis or mechanical grinding steps to increase the availability of organic compounds for microorganisms.

Temperature conditions are crucial in fermentation processes. The mesophilic regime (35-40°C) ensures a stable fermentation process with minimal energy consumption, while the thermophilic regime (50-60°C) increases the decomposition rate of organic raw materials, but requires careful control of conditions to maintain microflora activity. The optimal ratio of nitrogen to carbon in biomass is also a critical parameter that affects the quality of the final biogas.

The process of biogas enrichment to biomethane involves the removal of CO_2, H_2S, NH_3 and water vapour. As shown in Table 1, different purification technologies are used, including membrane separation, variable pressure adsorption, absorption (chemical, physical, aqueous) and cryogenic distillation. Membrane technology is the most common due to its efficiency and low operating costs, although variable pressure adsorption and cryogenic separation provide higher purity of the final product.

Table 1. Technical characteristics of the main technologies for biogas purification to biomethane

Cleaning technology	Degree of CH_4 purification (%)	Energy consumption (kWh/1000 m³)	Main impurities removed	Advantages	Limitations
Membrane separation	96-98	0.15-0.3	CO_2, H_2O	Low costs, compactness, simplicity	Does not completely remove H_2S and NH_3
Variable pressure adsorption	97-99	0.2-0.5	CO_2, partially H_2S	High product purity	High capital expenditures, moisture sensitivity
Chemical absorption	98-99.5	0.3-0.6	CO_2, partially H_2S	Extremely high CO_2 efficiency	Corrosion, reagent costs
Physical absorption	95-97	0.2-0.4	CO_2	Efficient at high pressure	Limited efficiency at low-pressure
Water absorption	90-96	0.25-0.4	CO_2, H_2S, NH_3, H_2O	Environmentally friendly, does not require chemicals	Low efficiency at low-pressure
Cryogenic distillation	98.5-99.9	0.5-0.8	CO_2, H_2S, H_2O, NH_3	Maximum purity of biomethane	High energy costs, the complexity of the process

Source: compiled by the authors based on Yu. Okhota (2023)

Following Table 1, each of the biogas treatment technologies has advantages and limitations that determine their feasibility depending on specific production conditions. Membrane separation demonstrates a balanced ratio between energy efficiency (0.15-0.3 kWh/1000 m³) and high CH4 removal (96-98%), making it the most popular for small and medium-sized plants. Variable pressure adsorption technology provides even higher purity (up to 99%) and better CO_2 removal but is sensitive to humidity and requires significant investment. Chemical absorption provides extremely high CO_2 removal efficiency but is accompanied by corrosive effects and reagent costs. Physical and aqueous absorption are inferior in terms of purification but remain simple and environmentally acceptable solutions for medium-sized facilities. Cryogenic distillation shows the highest quality of biomethane purification (up to 99.9%) and can remove all major impurities simultaneously, but requires the highest energy costs and complex infrastructure. Thus, the choice of a particular technology should be based on the optimal balance between the required biomethane quality, the investor's economic capacity and the technical conditions of the plant.

The biomethane produced can be used in various sectors of the economy. It is supplied to medium and low-pressure gas networks, transported to high-pressure gas pipelines, or used to fuel vehicles through automotive gas-filling compressor stations (Table 2). Depending on the scale of production and logistics, there are three possible approaches to creating biomethane complexes: centralised plants based on a single biogas plant; multi-level systems combining several sources of raw materials; and distributed biogas networks with biogas pipelines transporting raw materials to a single processing complex.

Table 2. Technical parameters of biomethane transportation and storage in the gas transmission system

Parameter	Values/units of measurement	Comment
Operating supply pressure in the gas transmission system	1.2-7.5 MPa	Depending on the category of the pipeline
Minimum CH_4 content	≥96%	Requirement for compliance with DSTU EN 16723-1:2023

Continued Table 1.

Parameter	Values/units of measurement	Comment
Maximum CO_2 content	≤2%	Ensuring the quality of gas for transportation
Biomethane temperature range	-5°C...+50°C	Safe transport temperature
Efficiency of the compressor station for supply	85-92%	Determines the energy loss on compression
Possibility of storage in UGS facilities	Yes	Technical compatibility of biomethane with underground natural gas storage facilities
Estimated losses during transport	0.1-0.5% per 100 km	Depending on the quality of the seals, the condition of the pipelines

Source: compiled by the authors based on Yu. Okhota (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

Table 2 highlights the key technical parameters that are crucial for the integration of biomethane into the Ukrainian gas transmission system and can be used for a preliminary engineering assessment of its compatibility with the existing infrastructure. In particular, the operating supply pressure in the range of 1.2-7.5 MPa indicates the need for compressor equipment capable of compressing gas to a level that corresponds to the category of the gas pipeline. This affects electrical calculations, in particular electricity consumption at compressor stations, where an efficiency of 85-92% can estimate energy losses during the supply process and justify the feasibility of using different types of compressors (turbo compressors, reciprocating, screw, etc.). The minimum CH_4 content of ≥96% and the maximum CO_2 content of ≤2% meet the requirements of DSTU EN 16723-1:2023, which ensures the appropriate calorific value of the gas and compatibility with combustion systems. This is critical for safety, and combustion efficiency in industrial and domestic installations, as well as for the accuracy of gas calorific value calculations in commercial metering. The range of permissible temperatures for biomethane (-5°C...+50°C) demonstrates its reliability in transportation in different climatic zones of Ukraine, which avoids thermal deformation or the risk of water vapour condensation in networks. Estimated transmission losses (0.1-0.5% per 100 km) are an indicator of the technical condition of gas pipelines and the quality of sealing joints, which determines the need for periodic maintenance and modernisation of the gas transmission system. Special attention should be paid to the technical feasibility of biomethane accumulation in underground gas storage facilities, which indicates its full interoperability with natural gas if it meets the standards. This opens up the prospects for balancing demand, creating strategic reserves, and using biomethane as an element of flexible energy supply.

An analysis of European practice demonstrated that the adaption of the infrastructure to receive biomethane requires the development of a system of guarantees of origin and the modernisation of compressor stations to stabilise gas pressure in the networks. The use of biomethane as a motor fuel is also actively developing, as evidenced by the growing number of automotive gas-filling compressor stations adapted to receive biomethane. The EU experience demonstrates the effectiveness of strategies to expand the use of biomethane. Table 3 demonstrates the dynamics of the biomethane industry in the EU in 2019-2024, reflecting the number of biomethane plants in the leading countries of the industry.

Table 3. EU countries with the largest number of biomethane plants

Country	2019	2020	2022	2023	2024
Germany	232	242	250	260	270
France	123	214	400	500	550
Great Britain	99	107	120	130	135
Sweden	70	70	75	78	80
Netherlands	51	60	68	72	75
Denmark	42	52	60	65	70
Switzerland	37	39	45	50	55
Italy	12	23	30	35	40
Finland	17	22	25	27	30
Austria	15	15	18	20	22
Norway	13	13	15	18	20
EU (total)	725	880	1400	1510	1600

Source: compiled by the authors based on Yu. Okhota (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

According to the European Biogas Association, at the end of 2023, there were 1510 biomethane plants in operation in Europe, which is 201 more than in 2022. In 2024, the total installed capacity of biomethane plants reached 6.4 billion m^3 per year. Table 3 shows the dynamics of growth in the number of biomethane plants in the EU in

2019-2024, which demonstrates the gradual but steady expansion of the renewable gas sector. Germany traditionally holds the lead in terms of the number of biomethane plants: from 232 in 2019, their number increased to 270 in 2024. However, it is France that is showing the highest growth rate, from 123 plants in 2019 to 550 in 2024, as a result of consistent government policy to support biomethane production and build the relevant infrastructure. The UK also demonstrates stable dynamics: the number of its biomethane plants has increased from 99 to 135 over the five years. The Nordic countries of Sweden, Denmark and Finland have shown gradual growth, which is in line with the strategic course of these countries towards decarbonisation and expansion of the renewable energy sector. In particular, the number of plants in Sweden increased from 70 to 80, in Denmark from 42 to 70, and in Finland from 17 to 30. Similar positive dynamics can be observed in the Netherlands (from 51 to 75), Switzerland (from 37 to 55) and Italy (from 12 to 40), which indicates the modernisation of bioenergy infrastructure and increased investment in the sector. Biomethane capacity developed at a more moderate pace in Austria (from 15 to 22) and Norway (from 13 to 20), which can be explained by the structure of their energy mix, particularly the high share of hydropower in Norway. Overall, in 2019-2024, the number of biomethane plants in the EU increased from 725 to 1600, which confirms the high interest in biomethane as a key component of the energy transition strategy and strengthening the region’s energy security.

Thus, these data confirm the positive dynamics of the biomethane industry in Europe, which is the result of active environmental policy, financial incentives and growing demand for renewable energy resources. The EU plans to significantly expand the production of renewable gases. In this context, the European Commission (2025) has developed the REPowerEU programme aimed at strengthening the resilience of the EU energy system. The strategy is based on two key pillars: diversification of gas supplies by increasing imports of liquefied natural gas and pipeline gas from alternative suppliers, and active development of biomethane and renewable hydrogen production and imports. The REPowerEU includes urgent measures to mitigate the effects of high energy prices, ensure the stability of gas supplies and accelerate the transition to clean energy sources. Figure 3 shows the projected growth of biogas and biomethane production in Europe in 2020-2050, in billion m^3. Production is projected to increase from around 15 billion cm^3 in 2020 to over 120 billion cm^3 in 2050.

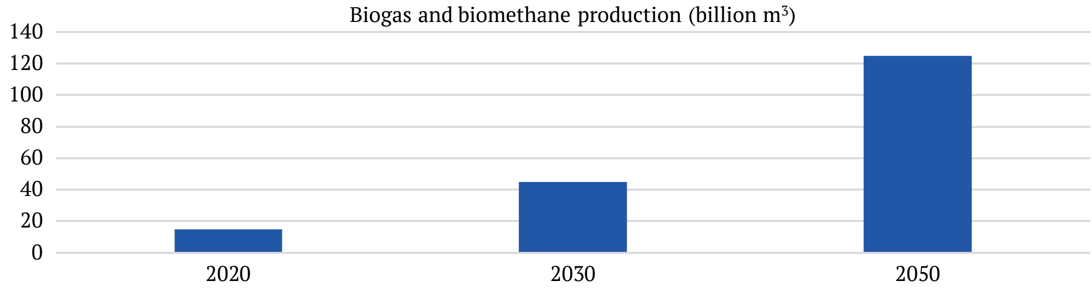

Figure 3. Forecast of biogas and biomethane production in Europe until 2050
Source: compiled by the authors based on Yu. Okhota (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

Data demonstrates a significant increase in production volumes: while in 2020 this number was relatively low, by 2030 it is expected to grow significantly, due to increased investment in the bioenergy sector and the active implementation of renewable technologies. By 2050, biogas and biomethane production is projected to reach its maximum levels, driven by the implementation of global decarbonisation initiatives, including the REPowerEU programme, which promotes the development of bioenergy and the integration of renewable sources into the overall energy balance. In the EU, the biomethane industry is regarded as one of the possible ways to achieve climate goals and reduce greenhouse gas emissions, which underlines its strategic importance in the transition to sustainable energy. Given these trends, biomethane is also a prominent way to ensure Ukrainian energy security, as it is a potential renewable energy source that can partially replace imported natural gas and help reduce dependence on fossil fuels. Its production is based on the use of local organic waste, which could theoretically reduce dependence on external energy suppliers and contribute to the development of the domestic energy sector. If the necessary economic and regulatory conditions are created in Ukraine, biomethane could be integrated into the national energy system, potentially stabilising gas supplies, especially in times of crisis when access to traditional energy resources is limited or unstable. Ukrainian current energy policy prioritises gradual diversification of energy sources, development of renewable resources and reduction of dependence on fossil fuels. Given global trends in decarbonisation, biomethane may become one of the most promising areas for improving national energy sustainability. European experience shows that political support, incentive mechanisms and regulatory frameworks are key to the development of the biomethane market. In Ukraine, these factors can also help accelerate the introduction of biogas enrichment technologies and their integration into the gas transmission network. In addition, biomethane may have export potential, which opens additional opportunities for the Ukrainian energy market, especially given the active development of renewable gases within the EU.

The potential for biomethane production in Ukraine largely depends on the availability of a feedstock base, which is formed from agricultural, industrial and household organic residues. An analysis of the resource potential demonstrated that the country has sufficient biomass to produce more than 10 billion cubic metres of biomethane per year, which is equivalent to approximately a third of current Ukrainian natural gas consumption. The main sources of biomass are agricultural waste, including cattle, pig and poultry manure, straw, corn stalks, silage and beet pulp. Industrial waste also has significant energy potential, especially residues from the food, sugar, brewing and dairy industries. An additional source of biomass is municipal organic waste, including solid household waste, catering residues and sewage sludge. According to analytical studies, the agricultural sector has the greatest potential for biomethane production, generating significant volumes of organic residues suitable for anaerobic digestion. Table 4 shows the potential of biomethane production based on different types of feedstocks.

Table 4. Potential for biomethane production from different types of feedstocks in Ukraine

Source of biomass	Potential biomethane yield (m^3/t)	Annual production potential (billion cm^3)
Cattle manure	55	2.5
Pig manure	60	1.8
Poultry manure	70	1.2
Corn silage	200	3.5
Wheat straw	120	2.0
Beet pulp	150	1.7
Remnants of the meat industry	800	0.9
Remnants of the dairy industry	500	0.8
Solid household waste	100	0.6
Wastewater	50	0.5

Source: compiled by the authors based on Yu. Okhota (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

The distribution of raw materials is a key factor in the formation of biogas clusters, which contribute to efficient logistics and optimisation of production processes. The greatest opportunities for biomethane production are concentrated in regions with a high concentration of agricultural production, which ensures a stable supply of organic waste for processing. Figure 4 illustrates the regional distribution of biomethane production potential in Ukraine, covering the availability of feedstock and the concentration of agricultural enterprises.

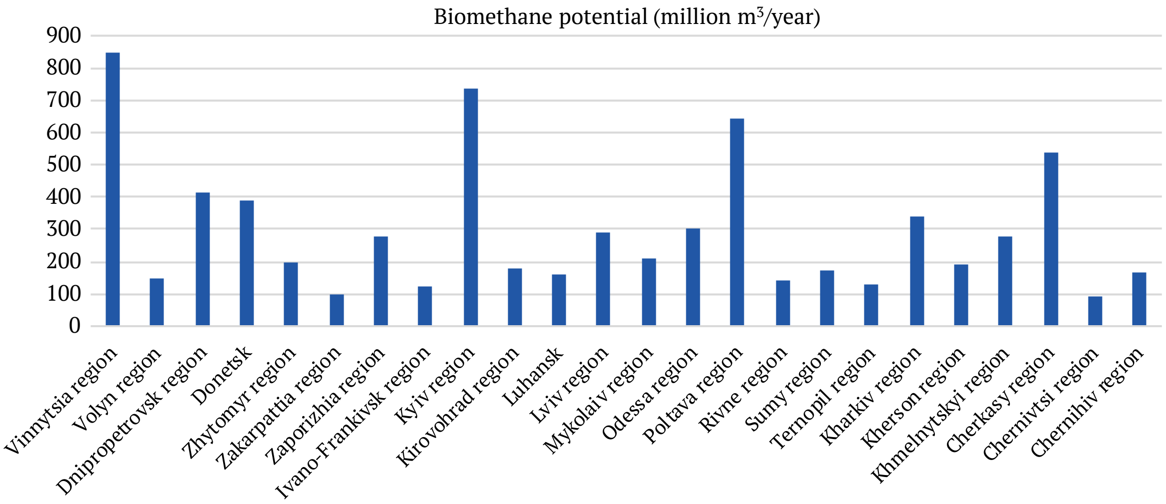

Figure 4. Regional distribution of biomethane production potential as of 2024
Source: I. Zamula *et al.* (2024)

The potential for biomethane production in Ukraine is estimated at 21.8 billion m^3 per year, which is higher than the country's natural gas production in 2023 (18.7 billion m^3). The most promising regions for biomethane production are Kyiv, Vinnytsia, Poltava and Cherkasy regions, which have a significant raw material base for processing organic waste. The regional distribution of biomethane production potential in Ukraine is uneven. The highest potential is in Vinnytsia, Kyiv, Cherkasy, Poltava, Dnipro and Donetsk regions, where the potential for CH_4 production ranges from 38 to 846 million m^3 per year.

These data demonstrated significant opportunities for the development of the biomethane industry in Ukraine, especially in regions with a developed agricultural sector and the availability of raw materials for biogas production. The economic feasibility of large-scale biomethane production largely depends on the cost of raw materials, the cost of biogas purification and enrichment processes, and the level of government support for the sector. Analysis of the European experience determined that countries with developed biogas infrastructure actively use subsidies, tax benefits and systems of guarantees of origin to stimulate biomethane production. In this context, Ukraine needs to develop and implement similar instruments that will help attract investment in the sector and create a stable biomethane market. From the perspective of energy security, biomethane is seen as a key element in the strategy of replacing imported natural gas. Biogas can diversify energy sources and reduce dependence on volatile international markets. In addition, the transportation of biomethane through existing gas networks makes it a beneficial option for ensuring the stability of energy supply in regions with access to an extensive gas transmission infrastructure.

The use of biomethane also reduces greenhouse gas emissions, as its production is based on a closed carbon cycle. The use of agricultural waste and industrial and household residues in biogas plants reduces CH_4 and CO_2 emissions generated by their uncontrolled decomposition. This is especially important in the context of European climate commitments and the gradual decarbonisation of the energy sector.

The potential of biomethane as a backup fuel for energy needs in times of crisis is notable. Military operations and the deliberate destruction of Ukrainian energy infrastructure create an urgent need to develop decentralised energy sources that can ensure uninterrupted gas and electricity supply independently of centralised systems. Biomethane has significant potential in this context, as it can be produced and used locally, reducing the vulnerability of regional energy systems to attacks on major gas pipelines and power generation facilities. Figure 5 demonstrates that biomethane is one of the most promising energy sources for ensuring energy security in times of crisis.

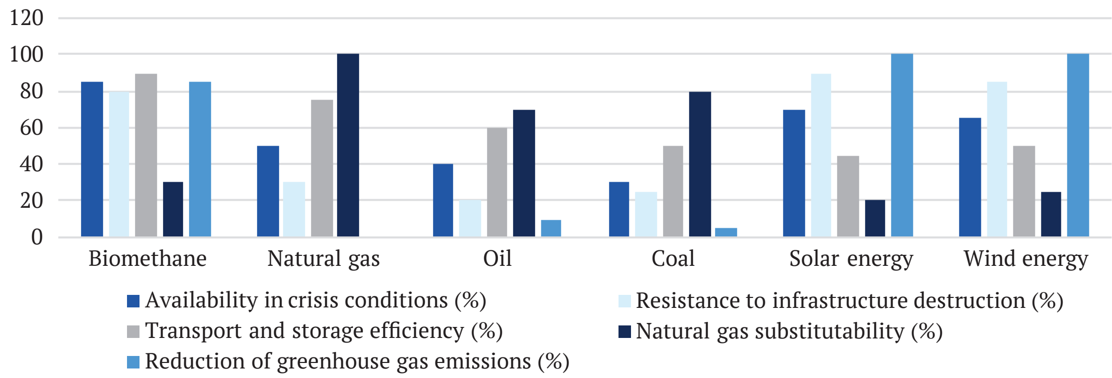

Figure 5. Comparative analysis of energy sources by energy security and environmental efficiency criteria
Source: compiled by the authors based on Law of Ukraine No. 1820-IX (2021)

Figure 5 demonstrates that biomethane has one of the highest availability rates in a crisis at around 85%, which is significantly higher than the respective rates for natural gas (50%) and oil (40%). This is determined by the decentralisation of biomethane production, and gas can be generated without being tied to imported supplies or main gas pipelines. Resilience to infrastructure destruction. In the event of targeted destruction, it is critical to maintain uninterrupted energy supply. Biomethane has 80% resilience, which means that even if the main gas transmission networks are damaged, its production and use can be carried out locally. This is a significant advantage compared to centralised gas systems, which have only 30% resilience as they are dependent on large trunk pipelines. Biomethane can be easily transported through existing gas networks and stored in storage facilities, with an efficiency of up to 90% in this regard. By comparison, storing electricity from solar and wind power plants is much less efficient, as they require battery storage or special energy conversion systems, making them only 45-50% efficient.

The diagram also demonstrated that biomethane can replace up to 30% of the total volume of natural gas in Ukraine, which is equivalent to about 9-10 billion m^3 per year. For comparison, imported natural gas covers about 40-50% of the country's total gas consumption. Thus, increasing biomethane production will significantly reduce dependence on imports. Biomethane has a significant positive environmental impact, reducing greenhouse gas emissions by around 85% compared to natural gas. While the combustion of coal, oil and conventional gas generates significant amounts of CO_2, biomethane has a near-neutral emissions balance due to the use of organic waste. Table 5 shows the projected volumes of biogas and biomethane production in Ukraine by 2050, considering the prospects for their use in various sectors of the economy.

Table 5. Forecast of biogas and biomethane production in Ukraine until 2050

Years	Biogas for heat and power generation	Biomethane, total	Biomethane for thermal power plants	Biomethane for transport	Biomethane for heat production and industrial use	Biomethane for export
2020	0.13	0	0	0	0	0
2025	0.36	0.44	0.11	0.01	0.1	0.22
2030	0.6	1	0.23	0.08	0.2	0.5
2035	0.83	1.69	0.35	0.18	0.31	0.84
2040	1.06	2.5	0.49	0.34	0.43	1.25
2045	1.28	3.44	0.63	0.54	0.55	1.72
2050	1.5	4.5	0.79	0.79	0.68	2.25

Source: compiled by the authors based on Bioenergy in 2024: A global report is now available at SAF (2024)

According to forecasts, the total volume of biomethane could increase to 4.5 billion m^3 per year in 2050, while biogas for heat and power production could reach 1.5 billion m^3. The main growth in biomethane production is expected to come from exports, which could grow from 0.22 billion m^3 in 2025 to 2.25 billion m^3 in 2050. Domestic consumption of biomethane will also gradually increase, for thermal power plants, transport, industry and heat production. In 2030, 0.23 billion m^3 of biomethane is expected to be used for thermal power plants, which will account for approximately 23% of the total projected volume, and by 2050 this figure will increase to 0.79 billion m^3. The use of biomethane for transport will also have an upward trend: in 2030, the production of 0.08 billion m^3 is forecasted, and in 2050, 0.79 billion m^3. This indicates the prospect of widespread use of biomethane as an environmentally friendly motor fuel. In general, the projected increase in biomethane production in Ukraine could significantly reduce dependence on natural gas imports and promote the development of renewable energy.

The prospects for biomethane exports from Ukraine to the EU are an important area of development for the bioenergy industry, which is in line with the European goals of decarbonisation and energy security. Ukraine's integration into the European energy area requires that the national biomethane market comply with EU requirements, including certification mechanisms, a system of guarantees of origin and transportation standards. In 2019-2024, several measures were taken at the legislative level to promote the development of the biomethane market and its exports. In particular, the Law of Ukraine No. 1820-IX (2021) was adopted. The implementation of this mechanism will enable export of biomethane to Europe by Ukrainian producers, as the availability of a relevant certificate will confirm its compliance with environmental standards. In addition, the Procedure for the Functioning of the Biomethane Register was approved, which defines the procedures for registration, verification and accounting of the fuel produced.

An additional step was the adoption of the Law of Ukraine No. 2320-IX (2022), which promotes the use of organic waste as a feedstock for biomethane production. This correlates with European approaches to the circular economy and resource utilisation strategies. Another important achievement was the adoption of State Standard of Ukraine No. 16723-1:2023 (2023), which regulates the technical requirements for biomethane for injection into gas networks. This standard was developed following the European norms, which greatly simplifies the integration of Ukrainian biomethane into the EU gas supply system. Financial incentives are key in the development of the biomethane industry, as they ensure the economic attractiveness of production and help attract investment. As the experience of EU countries shows, government support in the form of biomethane tariffs and feed-in tariffs for biomethane electricity is an effective mechanism for stimulating this sector (Table 6).

Table 6. Financial support for biomethane in EU countries

Country	Biomethane tariff (EUR/m^3)	Green tariff for electricity (EUR/kWh)
Denmark	0.735	-
France	0.45-0.95 (municipal solid waste), 0.85-1.25 (agriculture)	0.15-0.175
Italy	0.796	-
Netherlands	0.483-1.035	-
Germany	-	0.134-0.237 (+0.03 bonus for biomethane)
Great Britain	-	0.1-0.116 (FIT scheme, RHI until 2021)
Switzerland	-	0.146-0.233 (depending on the source and power)
Sweden	-	No fixed tariffs; support through tax incentives
Finland	-	State investment grants, certificates of origin
Austria	-	Regional subsidies, tax instruments
Norway	-	Support through Enova SF, fiscal incentives, no fixed tariff

Source: compiled by the authors based on Ministry of Agrarian Policy and Food of Ukraine (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

As shown in Table 6, there are two main mechanisms of financial support for the biomethane sector in the EU and associated countries: direct tariffs for biomethane injected into the gas transmission network and feed-in tariffs for electricity produced from biomethane or biogas. Several countries (France, Denmark, Italy, and the Netherlands) have clearly defined tariff incentives for biomethane: for example, in Denmark, it is 0.735 EUR/m^3, in France 0.45-0.95 EUR/m^3 for biomethane from municipal solid waste and 0.85-1.25 EUR/m^3 for agricultural feedstock. In Italy, the tariff is fixed at 0.796 EUR/m^3, and in the Netherlands in the range of 0.483-1.035 EUR/m^3, which creates long-term financial attractiveness for investors. At the same time, in countries such as Germany, the UK, France, Switzerland and partially Austria, priority is given to tariffs for electricity produced from biomethane. In Germany, the tariff ranges from 0.134-0.237 EUR/kWh with an additional bonus of 0.03 EUR/kWh for the use of biomethane. In France, the tariff is 0.15-0.175 EUR/kWh, in the UK 0.1-0.116 EUR/kWh, and in Switzerland 0.146-0.233 EUR/kWh. In Sweden, Finland, Austria and Norway, fixed tariff rates are generally absent, but alternative support mechanisms are used: tax breaks, guarantees of origin, investment grants or support from government agencies, such as Enova SF in Norway. This diverse approach to financing reflects national energy strategies and market development in each country. At the same time, the availability of financial incentives in any form significantly enhances the economic feasibility of investing in the biomethane industry, ensuring its competitiveness against traditional energy resources.

Ukraine, which is developing the biomethane sector, can use the experience of EU countries to develop its financial support mechanisms. Even though the legal framework for biomethane production has already been established through the introduction of a register of guarantees of biomethane origin, it is necessary to create a system of economic incentives that will help attract investment and increase production. Possible support instruments include the introduction of a guaranteed tariff for biomethane, tax benefits, and a feed-in tariff for electricity produced from biomethane. Such measures could stimulate the construction of new biomethane plants and increase investor interest in the Ukrainian renewable gas market. Projected estimates show that by 2050, Ukraine could produce up to 4.5 billion m3 of biomethane per year, much of which could be exported. This will not only reduce dependence on fossil fuel imports but will also contribute to the decarbonisation of the economy, which is in line with the European trends of energy transformation. Ukraine is actively working to integrate the biomethane market into the European energy space, which requires harmonising its regulatory framework with EU legislation. The Law of Ukraine No. 1820-IX (2021) establishes the legal framework for biomethane certification and the functioning of an electronic register of guarantees of origin. The document provides a legal basis for the implementation of biomethane guarantees of origin that meet EU requirements. An important addition is the Law of Ukraine No. 2320-IX (2022), which defines the principles of organic residue management as a valuable raw material for bioenergy, for biomethane production. In the context of the technical integration of biomethane into the gas transmission system, the State Standard of Ukraine No. 16723-1:2023 (2023). In particular, the document regulates the permissible content of CH_4, CO_2, H_2S, NH_3 and water vapour, as well as pressure and temperature parameters. At the EU level, the regulation is based on the Directive of the European Parliament and of the Council No. 2018/2001 (2018), which defines mandatory shares of energy from renewable sources in final consumption, in particular in the transport sector, and provides for the use of a system of guarantees of origin for biomethane and other renewable gases. In addition, Regulation (EU) No. 2019/942 of the European Parliament and the Council Establishing a European Union Agency for the Cooperation of Energy Regulators (2019) defines the mechanisms for European monitoring and verification of renewable gas guarantees of origin, including carbon footprinting requirements, which is key for biomethane trade in the EU single market.

Despite the adoption of relevant legislative changes, Ukrainian biomethane exports require further development of certification mechanisms in line with EU standards and integration of the Ukrainian Register of Guarantees of Origin with the European Renewable Gas Registry. Despite its high export potential, the Ukrainian biomethane market faces several barriers. One of the key ones is customs and administrative restrictions: the lack of clear mechanisms for certification and confirmation of biomethane origin following EU standards makes it difficult for it to enter the European market. In addition, Ukraine currently has limited access to the European biomethane transportation infrastructure, as not all gas operators recognise the possibility of integrating Ukrainian biomethane into their gas transmission system. An additional barrier is the lack of long-term supply contracts, as European buyers require guarantees of stable production, which is not yet sufficiently supported by the state in Ukraine.

Calculations of biomethane production costs show a significant advantage for Ukraine due to the lower cost of raw materials. CAPEX (capital expenditures) in Ukraine is 900-1200 EUR/kW of installed capacity, which is lower than in the EU (1500-2000 EUR/kW). OPEX (operating costs) for Ukrainian biogas plants are estimated at 25-35 EUR/MWh, while in the EU this figure reaches 40-55 EUR/MWh due to higher labour and administrative costs (Geletukha *et al.*, 2022). Despite economic competitiveness, low levels of investment support and lack of government incentives remain key constraints to the development of the biomethane sector. The most effective support mechanisms that can be implemented in Ukraine are tax incentives for biomethane producers, feed-in tariffs similar to European programmes, and state subsidy programmes for the modernisation of biogas plants. In 2019-2024, biogas production in Ukraine grew at a steady pace. In 2024, about 1 billion m^3 of biogas was produced, although this is significantly lower than the projected growth rate of the sector. The main risks include the lack of government support in the form of a feed-in tariff for biomethane, the high cost of connecting to the gas transmission system, and military risks that limit investment activity in the sector. However, with proper support, the forecast for 2050 remains optimistic: 2 billion m^3/year in 2030, 6 billion m^3/year in 2040, and 10 billion m^3/year in 2050.

Comparison of biogas treatment methods shows that the most appropriate for Ukrainian biogas plants are variable pressure adsorption and membrane technology. The membrane technology is the most common in the EU due to its high efficiency but requires significant investment. Variable pressure adsorption is the best option for Ukraine due to lower implementation costs and easier operation. Cryogenic separation, although providing the highest level of purification, is too energy-intensive and expensive for Ukrainian producers. The logistical possibilities for transporting biomethane from Ukraine are currently limited, but there are two main export routes. Ukraine's gas transportation system, which is one of the largest in Europe, could theoretically be used to transport biomethane but needs to be adapted to accept this type of fuel. Liquefied natural gas exports are another promising option, enabling the transportation of biomethane in liquefied form to European terminals. Given the European experience, the most effective model would be to create biomethane hubs in Ukraine's border regions, which would simplify its further transportation to the EU.

The integration of Ukrainian biomethane into the European energy system requires further improvement of the regulatory framework, adaptation of infrastructure and introduction of support mechanisms, including tax benefits and feed-in tariffs. By actively attracting investment and implementing relevant reforms, Ukraine has every opportunity to become a key supplier of biomethane to the EU market. Given the strategic importance of biomethane for the country's energy security, the development of financial support mechanisms will be an important step towards creating a competitive biomethane market in Ukraine and its further integration into the European energy space.

DISCUSSION

The results of the study confirm the significant potential of biomethane production in Ukraine as a strategic resource for energy security and economic development. According to the study by G. Geletukha & Y. Matveev (2021), the use of local agricultural and industrial waste can produce more than 10 billion m^3 of biomethane per year, which can replace a significant share of imported natural gas. The study results correlated with the findings of M. Zupančič *et al.* (2022), who analysed waste to biogas technologies in European countries, proving that decentralised biomethane production contributes to increased energy independence and reduced fossil fuel use. The introduction of modern biogas to biomethane technologies is crucial to ensure that the product meets EU technical standards (Kucher *et al.*, 2022). An important stage of this study was the comparison of biogas purification technologies for its enrichment to biomethane. The analysis of different purification methods demonstrated that variable pressure adsorption and membrane separation are the most efficient and economically feasible for Ukrainian production conditions, which is confirmed by similar studies by B. de Souza Moraes *et al.* (2022) and M. Gustafsson *et al.* (2024). Variable pressure adsorption technology ensures high biomethane purity by efficiently removing CO_2, H_2S and other impurities, while membrane separation is less energy-intensive and reduces operating costs. Studies also indicate that cryogenic distillation has the highest level of purification but is less accessible due to high capital and operating costs. The results of this study confirm the significant potential of biomethane production in Ukraine as a strategic resource for energy security and economic development. Analysis of the Ukrainian market has shown that the use of local agricultural and industrial waste can produce more than 10 billion m^3 of biomethane per year, which can replace a significant share of imported natural gas. The regional analysis confirmed that the most promising regions for the development of biomethane clusters are Vinnytsia, Kyiv, Poltava, Khmelnytskyi, Cherkasy, and Lviv regions, which is consistent with the findings of G. Trypolska (2023a; 2023b).

An analysis of the costs of biomethane production in Ukraine has demonstrated the competitiveness of the industry compared to the EU. CAPEX for Ukrainian biogas plants is 900-1200 EUR/kW, which is significantly lower than the European figures (1500-2000 EUR/kW). OPEX is estimated at 25-35 EUR/MWh, while in the EU this figure reaches 40-55 EUR/MWh due to higher labour and administrative costs. This is in line with the findings of N.P. Reznik *et al.* (2024), emphasise the impact of financial incentive mechanisms on the development of the biomethane industry.

From an environmental point of view, the use of biomethane can reduce CO_2 emissions by 85% compared to natural gas, as confirmed by the study by S. Belinska *et al.* (2024). In addition, biomethane is in line with the European Green Deal strategy, which defines it as a key resource for decarbonising the economy, as noted by M. Zablodskiy *et al.* (2024). The analysis of the export potential of Ukrainian biomethane has revealed several barriers, including customs and administrative restrictions, lack of clear certification mechanisms, and limited access to the European gas transmission infrastructure. At the same time, this study demonstrated that the introduction of mechanisms of origin and the adaptation of the regulatory framework to EU standards could significantly improve the export potential of Ukrainian biomethane, which is supported by the findings of B. Cahill & L. Palti-Guzman (2023).

A separate aspect of this study was an assessment of the stability of biomethane as an energy source in crises. Our analysis has shown that decentralised biomethane production can minimise the risks of gas supply disruptions, which is consistent with the findings of M. Farghali *et al.* (2022) and O. Kucher *et al.* (2024). An important factor was the study of biomethane's resistance to attacks on energy infrastructure, which is critical in times of war and unstable geopolitical situations. The agricultural sector, which generates large volumes of organic waste suitable for anaerobic digestion, has significant potential for biomethane production (Golub *et al*., 2018). This was confirmed by Y. Chernysh *et al.* (2022), who identified agricultural waste as the main source of raw materials for the development of the biomethane industry in Ukraine. In addition, the analysis of G. Ahamer (2021) confirmed that the use of agricultural residues is a key factor in ensuring the country's energy independence.

The assessment of the logistical possibilities for biomethane exports from Ukraine showed that there are two main routes of transportation the Ukrainian gas transmission system and the export of liquefied natural gas. Transportation through the gas transmission system is the most obvious and potentially cost-effective option, as Ukraine has one of the most extensive gas networks in Europe (Danylyshyn & Koval, 2023). However, this requires infrastructure upgrades, including the adaptation of compressor stations, the introduction of biomethane quality control systems, and the integration of the Ukrainian certification system for guarantees of origin with European standards of the European Renewable Gas Registry. In addition, one of the key challenges is the lack of a regulatory framework for the commercial transportation of biomethane through the gas transmission system, which requires harmonisation with EU legislation.

The second promising route is the export of liquefied natural gas, which enables transportation of biomethane in liquefied form through specialised terminals (Lisovyk *et al*., 2024). This option is particularly relevant for entering the global market and supplying biomethane to countries that do not have direct gas connections with Ukraine. However, the export of liquefied natural gas requires significant investments in the creation of relevant infrastructure, including liquefied biomethane plants, terminals for loading it, and logistics chains for transportation. Despite the high initial costs, LNG exports could become a strategic area of development, especially in the context of the growing demand for renewable gases in Europe.

To implement the export potential, it is necessary to modernise gas networks, which was confirmed by Y. Furdas *et al.* (2024) and E. Shahini *et al.* (2024). The authors emphasised that the adaptation of the gas transmission system for biomethane includes both technical improvements (installation of purification systems, control of biomethane mixing with natural gas) and regulatory changes (harmonisation of certification rules, harmonisation of transportation tariffs). International cooperation is also an important aspect of Ukraine's integration into the European biomethane market, which involves synchronising standards, mutual recognition of guarantees of origin and harmonisation of export procedures (Andreitsev *et al*., 2024). Given the successful experience of Germany, Denmark and France in expanding the biomethane sector, Ukraine has the potential to become a significant supplier of renewable gas to the European market, but this requires a clear strategy for developing logistics infrastructure and overcoming existing regulatory barriers.

In summary, it is worth noting that the results of this study are closely intertwined with the work of other authors, confirming the complex nature of the topic of biomethane development in Ukraine. This applies to both the assessment of the technical potential of production and the analysis of the economic feasibility, technological efficiency and environmental significance of biomethane. The research results demonstrate a common vision of the need for a transition to decentralised energy, where biomethane plays a key role in ensuring energy sustainability and independence. There is also a common perception that the development of the biomethane sector requires simultaneous modernisation of infrastructure, adaptation of the regulatory framework to EU standards, introduction of financial support mechanisms, and integration into the European renewable gas certification and metering system. The importance of cross-sectoral cooperation between agriculture, energy, environmental policy and international trade is also confirmed.

CONCLUSIONS

The study confirmed that the Ukrainian biogas and biomethane industries are important components of energy independence and decarbonisation of the country's economy. An analysis of the Ukrainian regulatory framework shows the gradual implementation of EU standards, through the adoption of Law of Ukraine No. 1820-IX on the development of biomethane production and the creation of an electronic register of guarantees of its origin. This creates the preconditions for biomethane exports to the EU. However, further alignment with the RED II Directive and the Gas Guarantees Regulation is required for full integration. The production potential of biomethane in Ukraine is estimated at over 10 billion m^3 per year, which can replace a significant portion of imported gas, ensuring energy stability. The results obtained demonstrate that biogas production from agricultural, industrial and municipal waste is a promising area that not only reduces dependence on natural gas imports but also contributes to environmentally sound waste management.

The introduction of modern purification technologies, such as membrane separation, variable pressure adsorption and cryogenic distillation, ensures the production of high-quality biomethane that meets EU requirements and can be integrated into gas transmission networks. A comparison of biomethane production costs (CAPEX, OPEX) in Ukraine and the EU showed the competitiveness of domestic products due to the lower cost of raw materials. CAPEX for Ukrainian biogas plants is estimated at 900-1200 EUR/kW, which is significantly lower than in the EU (1500-2000 EUR/kW). OPEX is estimated at 25-35 EUR/MWh, which is also more favourable compared to Europe (40-55 EUR/MWh). However, the development of the biomethane industry is hampered by the lack of financial support mechanisms. The most effective incentives that can be introduced in Ukraine are tax benefits for biomethane producers, "green" tariffs and government subsidies for the modernisation of biogas plants. An analysis of the EU's competitive environment has shown that the most dynamically developing biomethane market is in France, Germany and Denmark, where favourable financial support mechanisms are in place.

Ukraine has the potential to integrate into this market but faces logistical challenges. The main barriers to exports include customs and administrative restrictions, lack of clear certification mechanisms, and limited access to the European biomethane transport infrastructure. An estimate of real biomethane production in Ukraine for 2019-2024 shows slow growth in the industry. In 2023, about 300 million m^3 of biogas was produced, which is only 3% of the potential volume. The main factors limiting production are the lack of government support in the form of a feed-in tariff for biomethane, the high cost of connecting to the gas transmission system, and military risks. The resilience of biomethane to crises and the possibility of its local production minimises the risks associated with gas supply interruptions, which is especially important in times of energy instability. Biomethane can ensure a stable supply of energy even in the event of the destruction of the main infrastructure, making it a strategically important resource for Ukraine.

Further research should address the improvement of biomethane purification and transportation technologies, developing a regulatory framework for its certification following EU standards, and creating favourable economic conditions for attracting investment in the renewable gas sector. Ukrainian integration into the European biomethane market opens additional opportunities for the development of this industry, which will contribute to economic growth and increase national energy security.

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CONFLICT OF INTEREST

None.

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Біогазова та біометанова промисловість України як основа енергетичної незалежності країни

Анотація. Метою дослідження було провести оцінку потенціалу біометанової промисловості України, аналіз технологій виробництва та очищення біогазу, економічних та нормативно-правових аспектів, а також можливостей інтеграції у ринок ЄС. Дослідження підтвердило, що Україна має ресурсний потенціал для виробництва понад 10 млрд м^3 біометану на рік завдяки використанню відходів агропромисловості, тваринництва, харчової промисловості та побутових органічних залишків. Проаналізовано технологічні процеси виробництва, включаючи анаеробне зброджування, очищення та збагачення біогазу, а також ефективність методів очищення, таких як мембранна сепарація, адсорбція при змінному тиску та кріогенна дистиляція. Досліджено нормативно-правову базу України щодо біометану та її гармонізацію зі стандартами ЄС. Прийняття Закону № 1820-IX та ДСТУ EN 16723-1:2023 спрощує сертифікацію, однак потребує подальшого удосконалення для повної відповідності європейським вимогам. Порівняльний аналіз витрат на виробництво біометану в Україні та ЄС показав конкурентоспроможність української продукції через нижчу вартість сировини, проте обмежену доступність фінансових стимулів. Виявлено ключові інвестиційні бар'єри, серед яких нестача державних субсидій, відсутність гарантованих тарифів та складність сертифікації. Результати дослідження підтверджують, що біометан сприяє скороченню викидів вуглекислого газу (CO_2) на 85 % порівняно з природним газом та відіграє ключову роль у циркулярній економіці. Проаналізовано реальні показники виробництва біометану в Україні за 2019-2024 роки, що демонструють поступове зростання, але значне відставання від країн ЄС. Оцінено перспективи експорту українського біометану до ЄС, конкурентне середовище, логістичні виклики, необхідність модернізації газотранспортної системи та гармонізації стандартів. Практичне значення проведеного дослідження полягає у наданні комплексної аналітичної бази для формування ефективної державної політики у сфері розвитку біометанової промисловості України

Ключові слова: відновлювана енергетика; декарбонізація; газифікація біомаси; циркулярна економіка; енергетична стабільність

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Electricity generation from biogas: Modern technologies and prospects for Ukraine's energy independence

Abstract. Electricity production from biogas and biomethane is a promising area of renewable energy development that can substantially reduce Ukraine's dependence on fossil fuels, reduce greenhouse gas emissions, and increase energy security. The purpose of the present study was to analyse modern technologies for electricity production from biogas and biomethane, assess their efficiency, technical advantages, disadvantages, and opportunities for integration into the overall energy system of Ukraine. The research methodology included a comparative analysis of cogeneration plants, internal combustion engines, and gas turbines used to generate electricity from biogas, as well as methods of biogas purification to the level of biomethane. The analysis was performed considering technical efficiency, economic feasibility, and environmental safety. The findings of the study revealed that cogeneration units demonstrate the highest efficiency, which ranges from 80-90%, due to the simultaneous production of heat and electricity. Gas turbines provide an efficiency of 30-40%, and internal combustion engines – 25-45%. A comparative analysis of biogas purification methods showed that membrane technologies are the most promising due to their high purification efficiency (95-98%) and economic feasibility. Other methods, such as absorption, cryogenic, and adsorption, have limitations in application due to elevated energy costs or low purification efficiency. It was found that biogas purification to biomethane enables its use for electricity generation, transportation by gas pipelines, and ensuring the stability of power grids, especially during peak load periods.

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The developed recommendations included improving biogas purification technologies, creating infrastructure for its transportation and storage, and designing mechanisms for government incentives for bioenergy development. The use of bioenergy technologies can ensure the stability of Ukraine's energy system, increase its efficiency, and reduce dependence on conventional energy sources

Keywords: renewable energy; biomethane; cogeneration units; gas turbines; internal combustion engines; gas transmission systems

INTRODUCTION

Electricity production from biogas and biomethane is a promising area of renewable energy development that can greatly reduce Ukraine's dependence on fossil fuels and ensure its energy independence. In the context of growing energy instability and rising costs of conventional energy sources, the use of biogas and biomethane is becoming particularly relevant. Biogas is produced through the anaerobic fermentation of organic materials, which allows converting agricultural, food, and livestock waste into a valuable energy resource. After purification, biogas is converted into biomethane, which can be used as a fuel for generating electricity, heat, or energy storage to stabilise energy networks.

Modern scientific research on the use of biogas for electricity generation shows the immense potential of this technology in the context of energy transformation. Considerable attention has been paid to increasing the efficiency of cogeneration plants by improving combustion processes. O. Kolbasenko *et al.* (2023) demonstrated the possibility of improving heat transfer in power systems through a vibratory combustion mode of a water-fuel emulsion, which reduces fuel consumption and simultaneously increases the overall energy efficiency of plants.

In the field of advanced technologies for generating electricity from biogas, a valuable contribution was made by S.N.K. Syahri *et al.* (2022), who analysed the challenges of converting biogas to electricity using cogeneration technologies. The researchers emphasise the need to improve gas turbines and optimise thermal schemes to increase efficiency. In their global review, B.C.G. Rodrigues *et al.* (2025) outlined the most efficient technologies for anaerobic digestion, multi-stage biogas purification, and standardisation of biomethane production processes, which enables increased stability of generation parameters.

Ł. Mamica *et al.* (2022) analysed the prospects for biogas plants in Poland, focusing on the role of a favourable regulatory framework and investment attractiveness for market expansion. The researchers' conclusions may be relevant to the Ukrainian context, where the issue of incentivising investors and developing infrastructure for biomethane generation and transportation is also relevant. In the same context, it is worth mentioning the study by G. Gadirli *et al.* (2024), which comprehensively overviewed biogas plant technologies and emphasised the significance of biomethane as a tool for stabilising power grids and energy storage. The researchers emphasised the role of gas purification and the development of storage systems to ensure continuity of energy supply.

In terms of biogas purification, the findings of J. Das *et al.* (2022) are notable, as they focused on biological purification methods that reduce costs and improve the environmental safety of the process. The researchers discussed the advantages of biofiltration, photosynthetic, and microbial methods that can be used as an alternative to conventional chemical treatment. In biogas production optimisation, N.I. Madondo *et al.* (2022) compared the efficiency of electromagnetic, microbial, and conventional anaerobic systems. Their findings proved that the use of external electromagnetic fields can increase biogas yields by accelerating methanogenesis, which opened prospects for increasing the productivity of biogas plants.

S. Abanades *et al.* (2022a) conducted an in-depth analysis of global biogas practices, supported by a comparison of legal frameworks in different countries. The study outlined the barriers to technology adoption in countries with low regulatory support and emphasises the need for political will for the successful development of the biogas sector. Special attention should be paid to the study by J. Wang *et al.* (2023), which focused on increasing the efficiency of biogas generation through the pretreatment of agricultural residues, specifically straw. The researchers proved the effectiveness of such methods as steam operation, alkaline activation, and ultrasonic digestion, which improve the bioavailability of raw materials.

A.I. Amhamed *et al.* (2024) analysed the possibilities of using alternative fuels, including biomethane, in the aviation and energy sectors. The modelling showed that biomethane can be successfully integrated into high-temperature generation systems and used in hybrid energy systems that combine cogeneration and energy storage.

Thus, the analysis of scientific sources showed that the development of biogas technologies is focused on three key vectors: gas purification to the level of biomethane, improvement of cogeneration and automated power generation systems, and integration into flexible energy systems with energy storage capabilities. These areas form the scientific basis for enhancing the energy security of countries, including Ukraine, and contribute to strengthening its energy independence in the face of constant external challenges.

The purpose of the present study was to perform a theoretical analysis of existing technologies for electricity production from biogas and biomethane, compare their efficiency, identify shortcomings and prospects for implementation in Ukraine to improve energy security.

MATERIALS AND METHODS

The research methodology included a theoretical analysis of existing technologies for electricity production from biogas and biomethane (Madondo *et al.*, 2022; Wang *et al.*, 2023; Amhamed *et al.*, 2024). The first stage of the study examined the methods of anaerobic digestion of organic materials, such as agricultural, food, and municipal waste. The principal focus was on the conditions under which anaerobic fermentation takes place, including temperature, humidity, pH, microflora composition, and quality of raw materials. Furthermore, the study analysed the technological advancement of converting biogas into electricity using cogeneration units, gas turbines, and internal combustion engines. The influence of technological parameters on the efficiency of electricity generation and the possibilities of their optimisation were recognised. Particular attention was paid to the examination of the efficiency of biogas plants in industrial conditions and the possibility of their improvement.

The second stage of the study was aimed at exploring methods of biogas purification to produce biomethane, which is a high-quality energy carrier that can be used for electricity generation or transportation through gas pipelines. The study considered membrane, absorption, cryogenic, adsorption, and biological purification methods. The analysis was based on their efficiency in removing the major impurities (methane (H_2S), carbon dioxide (CO_2), energy costs, economic feasibility, and the possibility of industrial application in Ukraine. Special attention was paid to the technologies of biogas enrichment to the level of biomethane, including membrane, absorption, cryogenic, and adsorption methods. Their advantages and disadvantages, efficiency in industrial conditions, environmental safety, and economic feasibility were investigated. The possibilities of using purified biomethane to stabilise energy networks and ensure reliable energy supply were also covered.

The third stage of the study involved a comparative analysis of electricity generation technologies from biogas and biomethane. Methods such as cogeneration plants, gas turbines, and internal combustion engines used to convert biogas into electricity are considered. The efficiency of these technologies, their environmental performance, technical advantages and disadvantages, as well as the economic feasibility of their application in various industrial production conditions were assessed in detail. The study employed comparative analysis methods based on the generalisation of data from scientific publications and technical documentation (Mamica *et al.,* 2022; Das *et al.,* 2022; Gadirli *et al.,* 2024). The key indicators of efficiency were as follows: efficiency, emissions of harmful substances, energy costs per unit of treated biogas, specific capital, and operating costs. The assessment was based on a comparison of typical indicators presented by S.N.K. Syahri *et al.* (2022), O. Kolbasenko *et al*. (2023), and B.C.G. Rodrigues *et al.* (2025), as well as generalised data on the practical application of biogas plants in industrial conditions. The research tools included tabular analysis, construction of comparative diagrams, and systematisation of efficiency parameters in the form of analytical ones, which helped to establish optimised technological solutions for the conditions of Ukraine. The study investigated the prospects for the integration of biogas plants into the overall energy system of Ukraine, the possibility of using biomethane for energy storage and stabilisation of power grids, especially in conditions of uneven load and peak consumption periods (Madondo *et al.,* 2022; Abanades *et al.,* 2022a; Amhamed *et al.,* 2024). Possible schemes for the use of biomethane in gas transmission systems, their economic efficiency, and potential ways to increase efficiency by modernising existing technological processes were analysed (Wang *et al.,* 2023).

The final stage of the study focused on the development of theoretical recommendations for improving existing technologies for electricity production from biogas and biomethane. The study considered the possibilities of optimising biogas purification processes, improving electricity generation technologies, and their integration into the Ukrainian energy system. Particular attention was paid to creating conditions for increasing the efficiency of renewable energy sources, improving infrastructure, and developing mechanisms to stimulate the development of bioenergy at the state level.

RESULTS AND DISCUSSION

Analysis of biogas and biomethane production technologies

Biogas is a gas mixture, the principal components of which are CH_4 and CO_2, produced as a result of the anaerobic decomposition of organic matter in specialised plants known as biogas generators or methane tanks. Their design and operation are aimed at maximising methane production. Biogas combustion can recover 60-90% of the energy contained in the original dry feedstock. The biogas production process is based on the anaerobic digestion of organic materials such as agricultural waste, food waste, and municipal waste. The key conditions for anaerobic fermentation include controlled temperature, humidity, pH, microbial composition, and quality of the feedstock. Optimum temperature conditions for anaerobic digestion are divided into mesophilic (30-40°C) and thermophilic (50-60°C). The mesophilic mode requires lower energy consumption, but the fermentation process is slower than in the thermophilic mode. At the same time, thermophilic fermentation ensures faster decomposition of organic matter but requires greater energy consumption and more complex process control.

The moisture content of the feedstock should be maintained at 80-90% to ensure optimum conditions for the microorganisms involved in the fermentation process. The pH value is a critical parameter, as anaerobic microorganisms function best at pH values between 6.5 and 8. The microflora composition includes methanogenic bacteria and enzymatic microorganisms, which ensure a full cycle of conversion of organic matter into biogas.

The quality of the feedstock directly affects the biogas yield, which necessitates preliminary waste preparation, such as shredding, moistening, or adding catalysts (Golub *et al.*, 2018).

The effectiveness of anaerobic digestion for various types of organic waste depends largely on its chemical composition, specifically the content of carbohydrates, proteins, and lipids. Waste with an elevated content of carbohydrates and lipids provides a greater biogas yield compared to materials that contain a considerable amount of cellulose or lignin.

Cogeneration plants, gas turbines, and internal combustion engines are used to convert biogas into electricity. Cogeneration plants are the most widespread due to their superior efficiency, which can reach 80%–90% when electricity and heat are produced simultaneously. Gas turbines are mainly used for large industrial facilities and have an efficiency of 30-40% when generating electricity only. Internal combustion engines are effective for small biogas plants with efficiencies of 25% to 45%, depending on the type and operating conditions. Table 1 summarises the key parameters of these technologies and their efficiencies.

Table 1. Key parameters of biogas production technologies and their efficiency

Technology	Temperature conditions (°C)	Efficiency (%)	Key advantages	Key disadvantages
Cogeneration plants	30-40 (mesophilic), 50-60 (thermophilic)	80-90	High efficiency, simultaneous generation of heat and electricity	Extensive capital expenditure
Gas turbines	50-60 (thermophilic)	30-40	High power, high reliability	Low efficiency without heat generation
Internal combustion engines	30-40 (mesophilic)	25-45	Effective for small plants	Emissions of harmful substances

Source: compiled by the authors based on J. Wang *et al.* (2023)

As can Table 1 demonstrates, the highest efficiency is achieved with cogeneration plants (80-90%) that combine heat and electricity generation. Gas turbines are highly efficient and reliable, but their efficiency is much lower (30-40%) when heat is not used. Internal combustion engines are characterised by relatively low efficiency (25-45%) and are only suitable for small installations.

Analysis of process parameters, such as temperature and biogas treatment methods, can determine the optimum conditions for increasing the efficiency of electricity generation. Furthermore, an essential aspect is the possibility of improving existing technologies through the introduction of new purification systems, the use of biomethane, and its integration into the overall energy system of Ukraine. The analysis of technological parameters shows that an increase in the efficiency of electricity generation is possible through optimisation of the anaerobic digestion process, use of high-quality raw materials, and improvement of biogas purification technologies. A prominent aspect is to ensure the stability of the process by maintaining the optimum temperature and controlling the pH level. In industrial environments, biogas plants provide stable electricity and heat production, but their efficiency can be increased by modernising gas purification technologies, improving the fermentation process and using hybrid plants that combine several energy sources. Figure 1 presents a schematic of the anaerobic digestion process, highlighting the key steps.

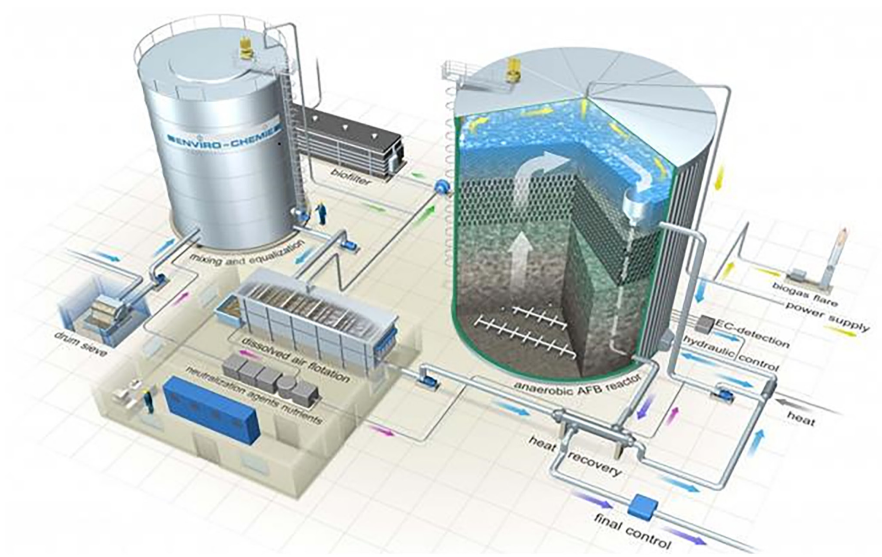

Figure 1. Schematic of the anaerobic digestion process

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

As shown in Figure 1, the biogas production process involves several key steps to ensure efficient generation and optimum use of the energy produced. First, the feedstock is pre-treated, which includes shredding, mixing, and emulsification to achieve a homogeneous consistency. The prepared feedstock is then fed to the Anaerobic AFB Reactor, where the fermentation process takes place in the absence of oxygen. Essential parameters controlled at this stage include temperature, humidity, pH, and microflora composition, which affect the efficiency of organic matter decomposition and methane production. After the fermentation process is complete, the biogas produced is purified from unwanted impurities such as hydrogen sulphide, ammonia, and carbon dioxide to produce high-purity biomethane. The process waste that is left after biogas separation is converted into recyclable materials that can be used in agriculture as fertilisers. Furthermore, the system includes temperature and energy control mechanisms that ensure optimum conditions for fermentation and increase the productivity of the biogas generator. This multi-level control system ensures stable biogas production and high efficiency of the production process.

Biogas purification and biomethane production

Biogas purification is a crucial step in the production process, as raw biogas contains impurities that can greatly reduce its energy value and cause technical problems during use. The key undesirable impurities are hydrogen sulphide (H_2S), ammonia (NH_3), CO_2, water vapour, and other volatile compounds. To produce high-quality biomethane that can be used for power generation or transported through gas pipelines, biogas must be thoroughly purified. Biogas treatment methods are divided into chemical, physical, and biological. Chemical methods involve the use of chemical absorbents such as sodium or calcium hydroxide, which effectively remove hydrogen sulphide and ammonia. Physical methods involve the use of technologies such as membrane separation, absorption, cryogenic separation, and adsorption. Membrane technologies provide a strong level of purification by separating methane from carbon dioxide using semi-permeable membranes.

Cryogenic separation is used to liquefy and further separate the gas mixture into its constituent components, which ensures biomethane purity of up to 98%. Adsorption methods involve the use of activated carbon or zeolites to remove impurities through a physical adsorption process. Biological purification methods involve the use of biofilters or bioreactors that remove hydrogen sulphide by oxidising it to elemental sulphur. A comparative analysis of biogas purification methods is presented in Table 2.

Table 2. Comparative analysis of biogas treatment methods by efficiency and economic feasibility

Purification method	H_2S removal efficiency (%)	CO_2 removal efficiency (%)	Economic feasibility	Key disadvantages
Membrane	95-98	85-95	High	High costs for membranes
Absorption	90-95	80-90	Medium	Requires chemical solvents
Cryogenic	98-99	98-99	Low	High energy costs
Adsorption	80-90	70-80	High	Low efficiency for high volumes
Biological	70-85	None	Medium	Process duration

Source: compiled by the authors based on AC Group (n.d.), V. Pérez *et al.* (2021)

As presented in Table 2, the cryogenic method provides the greatest treatment efficiency, but is also characterised by extensive energy costs, which makes it economically unfeasible for industrial use. Membrane and adsorption methods are the most promising due to their high treatment efficiency and relatively low implementation costs. Biological methods demonstrate average efficiency but have notable potential for improvement through improved designs of biofilters and bioreactors.

Purified biomethane can be used to generate electricity using cogeneration plants, gas turbines, and internal combustion engines. It can also be transported through gas transmission systems, ensuring the stability of energy networks. The stability of biomethane supply can be increased by storing it in backup storage facilities or integrating it with other renewable energy sources (Shram & Kachan, 2023).

The level of biogas purification from impurities determines the areas of its use. This can include biogas combustion for electricity production (generation and cogeneration – simultaneous production of electricity and heat), heat production (in boilers with corresponding burners), purification to biomethane and subsequent injection into the gas network, and biofuel production (bioLNG). Figure 2 presents the process of cooling and purification of biogas to biomethane, including the principal stages of removing unwanted impurities and improving gas quality.

The process consists of two principal stages: cooling and purification of biogas, and biogas upgrading to biomethane. The first stage involves gas dehydration, primary desulphurisation, H_2S separation, and filtration. The second stage involves the removal of other impurities, separation of CO_2, and gas dehydration to produce high-quality biomethane.

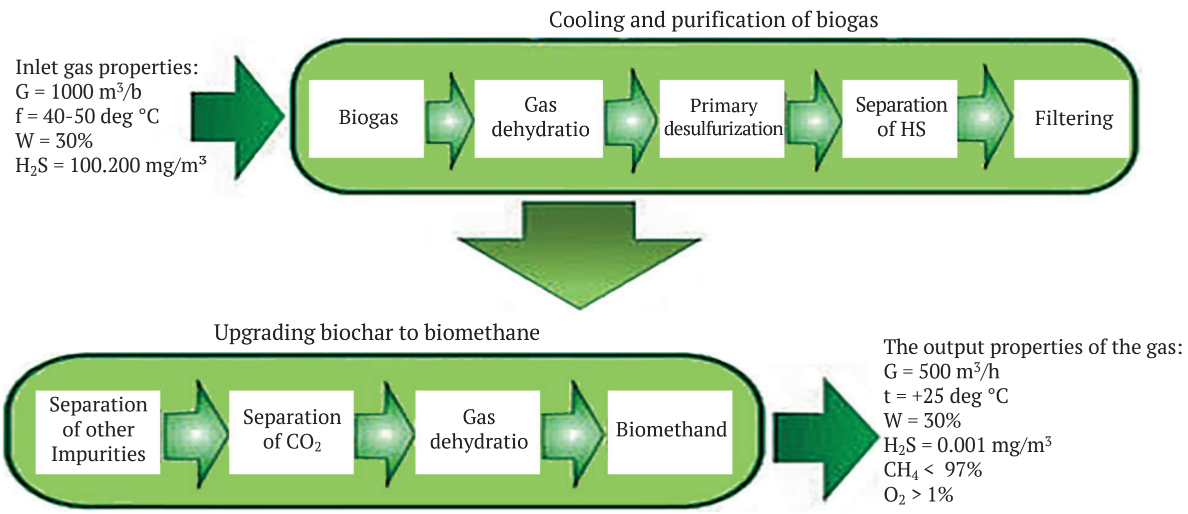

Figure 2. Schematic of the biogas cooling and purification process
Source: compiled by the authors based on AC Group (n.d.)

As Figure 2 demonstrates, the output is high-quality biomethane with a CH_4 content of over 97% and minimal impurities, making it suitable for electricity generation or transportation through gas pipelines. The use of such technologies helps to ensure the stability of energy grids and use biomethane as an alternative fuel, which helps to reduce greenhouse gas emissions and improve energy security.

Comparative analysis of electricity generation technologies

Electricity is produced from biogas and biomethane using a variety of technologies, including cogeneration plants, gas turbines, and internal combustion engines. The choice of a particular technology depends on a series of factors, including technical characteristics, environmental performance, economic feasibility, and integration into the overall energy system. Cogeneration plants are used to produce electricity and heat simultaneously. They demonstrate prominent efficiency, which varies between 80-90% due to the utilisation of heat released during the generation process. The principal advantages of cogeneration plants include high efficiency, economic feasibility for small and medium-sized plants, and the ability to provide continuous power generation. The disadvantages are extensive capital costs for the construction and operation of plants, as well as dependence on a stable supply of biogas. Gas turbines are an efficient way to generate electricity from biogas on an industrial scale. They provide high power and reliability, but their efficiency is still lower than that of cogeneration plants, typically by 30-40%. The principal advantage is the ability to operate at hot temperatures, which yields more energy per unit of fuel. At the same time, gas turbines are economically viable only for large-scale plants operating with pure biomethane. Internal combustion engines are efficient for small and medium-sized plants, providing an efficiency of 25-45%. These plants are well-suited for local power systems where electricity generation from biogas can be carried out autonomously. The key disadvantages of internal combustion engines include emissions and relatively low efficiency compared to other technologies (Gutarevych *et al.*, 2020). Table 3 compares the key technologies for generating electricity from biogas and biomethane in terms of technical characteristics, economic feasibility, and environmental performance.

Table 3. Comparative analysis of electricity generation technologies from biogas and biomethane

Technology	Efficiency (%)	Key advantages	Key disadvantages	Application area
Cogeneration plants	80-90	High efficiency, simultaneous heat and power generation	Extensive capital expenditure	Small and medium-sized plants
Gas turbines	30-40	High power, high reliability	Low efficiency without heat generation	Large industrial plants
Internal combustion engines	25-45	Effective for small plants	Emissions of harmful substances	Local power systems

Source: compiled by the authors based on V. Pérez *et al.* (2021), M.J.B. Kabeyi & O.A. Olanrewaju (2022a)

As Table 3 shows, cogeneration plants demonstrate the greatest efficiency (80-90%) due to the possibility of simultaneous production of heat and electricity. They are most suitable for small and medium-sized installations, although extensive capital costs are a major disadvantage. Gas turbines provide high power and reliability, but their efficiency without heat production stays relatively low (30-40%). Although internal combustion engines have a lower efficiency (25-45%), they are well-suited for local power systems, but the problem of harmful emissions continues to be relevant.

Apart from technical indicators, a valuable part of the analysis was the cost-effectiveness of different technologies. Research suggests that cogeneration units are the best option for integration into industrial and municipal systems where a constant supply of heat and electricity is required. Gas turbines and internal combustion engines are more suitable for large industrial plants or local power systems with limited access to centralised energy sources. The investigation of the prospects for integrating biogas plants into the overall energy system of Ukraine shows the possibility of efficient use of biomethane both for electricity generation and for its transportation through gas pipelines. Purified biomethane can be used as a backup energy source to ensure the stability of power grids in conditions of uneven load or peak consumption periods.

Figure 3 presents the scheme of integration of biogas plants into the overall energy system of Ukraine, including the possibility of using biomethane to stabilise the grid and provide backup power supply.

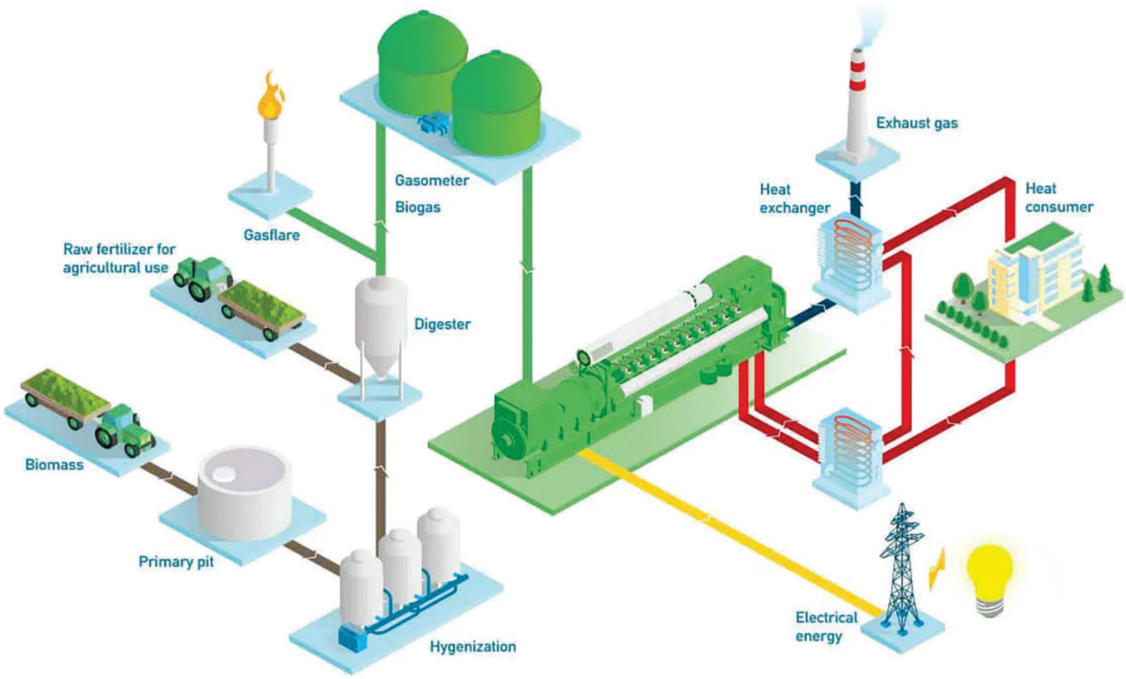

Figure 3. Scheme of integration of biogas plants into the general energy system of Ukraine
Source: compiled by the authors based on KTS Engineering (n.d.)

As Figure 3 shows, the key steps in the integration of biogas plants into the overall energy system of Ukraine include several key processes. First, the organic material is collected in a special pit where it is sterilised to remove harmful microbes. The processed material is then transferred to a bioreactor where it undergoes an anaerobic digestion process, resulting in the production of biogas. The generated biogas is stored in a storage tank to ensure a continuous supply of gas regardless of changes in production processes. Then, the biogas is treated to remove impurities and improve its quality to the level of biomethane. Finally, the purified biomethane is fed to a gas turbine plant that generates electricity and heat. Furthermore, biomethane can be transported through gas pipelines to stabilise the grid and provide backup power supply.

Development of recommendations for the integration of bioenergy technologies

Development of recommendations for the integration of bioenergy technologies into the energy system of Ukraine requires a detailed analysis of existing technological processes and development of effective approaches to their optimisation. The primary areas of improvement include increasing the efficiency of biogas purification processes, developing technical and organisational solutions to ensure the stability of energy supply and creating favourable conditions for the development of bioenergy industry at the state level.

Improvement of the efficiency of electricity generation technologies largely depends on the quality of biogas purification (Danylyshyn & Koval, 2023). According to the results of the comparative analysis, membrane technologies and cryogenic methods provide the greatest level of biogas purification, but they require extensive capital expenditures. Absorption and adsorption methods are more affordable, but less effective in removing carbon dioxide and other undesirable impurities. Optimisation of the biogas treatment process may involve combining multiple methods to achieve maximum efficiency at minimum cost. Particular attention is paid to improving pre-filtration systems and reducing the hydrogen sulphide content before feeding to the major treatment systems. To improve the efficiency of bioenergy plants, it is proposed to develop standardised technological processes that factor in the characteristics of distinct types of feedstock and industrial conditions. Specifically, it is vital to improve cogeneration units that simultaneously produce heat and electricity, which enables the most efficient use of biogas energy potential. Furthermore, it is necessary to develop methods for adapting gas turbines and internal combustion engines to work with purified biomethane, which will reduce emissions of harmful substances and increase the efficiency of energy conversion.

Ukraine's current energy infrastructure must be modernised to ensure the integration of biogas plants into the overall energy system. This includes the creation of new connections to gas transmission systems and the modernisation of existing networks for biomethane transportation. Proposed measures include the construction of special gas pipelines for transporting purified biomethane and the creation of backup energy storage systems to ensure the stability of energy supply. It is also essential to create a centralised system for monitoring and controlling biogas plants, which will allow for real-time monitoring of their performance (Atamanyuk *et al.,* 2015).

To accelerate the development of bioenergy in Ukraine, it is necessary to develop state support programmes, including financial incentives, tax benefits, and simplified licensing procedures. It is proposed to create a system of "green" tariffs for electricity generation from biomethane, as well as to establish preferential conditions for enterprises that purify biogas to the level of biomethane. Particular attention should be paid to the development of legislation regulating the use of biomethane in gas transmission systems and energy networks. Legislative initiatives adopted in Ukraine are directly aimed at integrating bioenergy technologies into the country's overall energy system, specifically for the production of electricity from biogas and biomethane. The adoption of the Law of Ukraine No. 1820-IX "On Amendments to Certain Laws of Ukraine Regarding the Development of Biomethane Production" (2021) creates a legal framework for the functioning of the biomethane market, particularly through the introduction of an electronic register of guarantees of origin of biomethane. This mechanism not only facilitates the export of biogas and biomethane to EU countries but also ensures that it can be used within Ukraine to generate electricity and stabilise energy networks. Thanks to the certification of biomethane and its compliance with environmental standards, Ukrainian energy companies will be able to use it as an alternative fuel, which helps to reduce dependence on traditional fossil energy sources (Kalinichenko *et al.,* 2019).

Furthermore, the adoption of the Law of Ukraine No. 2320-IX "On Waste Management" (2024) stimulates the use of organic waste for biomethane production, which is a crucial step towards expanding the resource base of renewable energy. This approach is in line with the European principles of the circular economy and creates conditions for improving the energy efficiency of industrial and utility companies through biogas plants. This is crucial for Ukraine, which is striving to achieve energy independence and stability of its energy system. The adoption of DSTU EN 16723-1:2023 (2023), which regulates the technical requirements for biomethane for injection into gas transmission networks, also considerably influences the integration of biogas plants into the Ukrainian energy system. The compliance of Ukrainian technologies with European standards will not only facilitate the export of biomethane but also increase the efficiency of its domestic use in the country's energy system. This includes the possibility of using purified biomethane both to generate electricity and to provide backup capacity at critical times. Thus, the adopted laws and standards create conditions for the effective integration of biogas plants into the overall energy system of Ukraine, which will not only increase the stability of electricity supply but also reduce dependence on fossil fuels, ensuring the country's environmental and energy security.

Integration of biogas into Ukraine's energy system is a major step towards improving energy efficiency and ensuring stable energy supply. The use of biogas in industrial and municipal facilities requires the improvement of biogas treatment, generation, and storage technologies. This involves the creation of special infrastructure facilities, including biogas plants and storage systems, which will help stabilise the power grid during peak loads or crisis situations. Furthermore, it is vital to ensure the integration of biogas technologies into the overall energy system by developing technical standards that regulate the quality of biogas for use in electricity and heat generation. The compatibility of biogas plants with existing energy networks is a critical aspect that requires the development of methods for power balancing and adaptation of equipment to the conditions of centralised energy supply (Sirko *et al*., 2023). Table 4 presents the key recommendations for optimising technological processes to integrate bioenergy plants into the Ukrainian energy system.

Table 4. Recommendations on optimisation of technological processes to integrate bioenergy plants into the energy system of Ukraine

Optimisation area	Proposed measures	Expected outcomes
Biogas treatment	Combination of purification methods to maximise efficiency	Reduced impurities, improved biogas quality
Improvement of technological processes	Modernisation of cogeneration units, adaptation of gas turbines and internal combustion engines	Improved energy efficiency and environmental friendliness
Infrastructure solutions	Construction of gas pipelines, creation of backup energy storage systems	Stability of supply and flexibility of energy networks
Government support	Financial incentives, tax breaks, "green" tariffs	Increased investment in bioenergy

Source: compiled by the authors

As Table 4 shows, the principal recommendations for optimising technological processes include improving biogas purification methods, creating special systems for biogas transportation, and designing a legislative framework to stimulate bioenergy development. Thus, the integration of biogas into Ukraine's energy systems will help reduce dependence on fossil fuels, increase energy security, and create conditions for sustainable development of renewable energy.

The study of the possibilities of using purified biogas to stabilise energy networks confirmed its potential as a reliable backup energy resource capable of ensuring uninterrupted power supply during peak loads or crisis situations. The integration of biogas plants into the overall energy system of Ukraine involves the introduction of government incentive mechanisms, the creation of specialised infrastructures for the transportation and storage of biomethane, and the optimisation of technological processes for electricity generation (Kucher *et al*., 2022). The recommendations include improving biogas purification methods, modernising power generation facilities, integrating biogas plants into gas transmission systems, and creating state programmes to support bioenergy development. The proposed measures can greatly improve the energy efficiency of biogas and biomethane use in Ukraine, ensure reliable electricity supply, and contribute to reducing dependence on fossil fuels and improving the environmental situation in the country.

The findings of the present study proved the prospects of integrating biogas technologies into Ukraine's energy system as one of the key areas of renewable energy development. The research suggests that the use of biogas and biomethane for electricity generation is technically efficient and can help reduce dependence on fossil fuels and improve the environmental situation. A comparison with current international research revealed that the findings of the present study correlated with global trends in bioenergy. A. Ilari *et al.* (2022) confirmed that the use of agricultural and forest residues in bioenergy can greatly reduce the carbon footprint of power plants, but the efficiency of such plants is highly dependent on the quality of raw materials and the stability of supply. This is in line with the conclusions of the present study on the need for preliminary preparation of feedstock and control of technological parameters of anaerobic digestion.

O. Awogbemi *et al.* (2024) focused on the transformation of agricultural waste into highly efficient biofuels using combined pretreatment methods, which fully coincided with the conclusions of the present study on the feasibility of thermochemical and enzymatic treatment to increase biogas yields. Z. Xie *et al.* (2025) proposed an innovative approach to biogas utilisation by converting it into carbon nanomaterials. Although this technology is not yet widely used in industry, it demonstrates the potential for multifunctional use of biogas and emphasises the significance of its high-quality treatment, which was also confirmed in the present study. R. Stavinskiy *et al.* (2021) investigated the issue of improving energy efficiency through the improvement of transformer systems, but their study was indirectly related to the subject under study, as it concerned the technical improvement of power plants. M.U.B. Khawer *et al.* (2022) focused on the production of biogas and biohydrogen through anaerobic digestion of wastewater. Their findings confirmed that the use of food waste and domestic wastewater can be an effective source for biogas production. The data are consistent with the findings of the present study regarding the possibility of using various types of organic materials for biogas generation. S. Abanades *et al.* (2022b) provided a conceptual overview of sustainable electricity production from biogas. Their study confirmed that current technologies for biogas purification to biomethane are effective in ensuring its suitability for transportation through gas networks, which correlated with the findings obtained for membrane and adsorption purification methods. A.M. Shinde *et al.* (2021) assessed the life cycle of biogas and biomethane production for electricity generation. The researchers addressed the economic feasibility of electricity production from biogas on an industrial scale, which coincided with the conclusions about the prospects for the use of cogeneration plants and internal combustion engines.

U. Brémond *et al.* (2021) analysed the prospects for the development of the European biogas market until 2030, pointing out the need to improve biogas treatment and storage technologies to ensure a stable energy supply. Their conclusions were consistent with the present study's recommendations for improving biogas treatment processes. M.J.B. Kabeyi & O.A. Olanrewaju (2022b) detailed the technologies for converting biogas to electricity, emphasising the role of cogeneration systems as the most efficient solution for generating electricity from biogas. Their study confirmed the present findings obtained on the high efficiency of cogeneration plants and the prospects for their integration into the Ukrainian energy system. A. Admasu *et al.* (2022) described experimental and simulation studies of biogas production from industrial wastewater. Their findings demonstrate the effectiveness of using waste of various origins for biogas production, which was consistent with studies on the possibility of increasing the efficiency of anaerobic digestion through the improvement of technological processes.

M.P.C. Volpi *et al.* (2023) analysed the economic aspects of biogas production from waste using co-digestion technology in bioenergy sugar biorefineries. This study confirmed that biomethane production is more cost-effective than electricity production, considering the possibility of transporting it through existing gas networks. This conclusion coincided with the presented recommendations for the integration of biomethane into Ukraine's gas transmission systems to ensure energy security. R. Bedoić *et al.* (2021) examined the synergies between feedstock fees and Power-to-Gas technology, which can increase the economic viability of biomethane production. The researchers highlighted that the use of energy storage technologies and hybrid systems can markedly improve the efficiency of electricity generation from biogas. This is in line with the findings of the current study regarding the need to introduce energy storage systems and modernise existing biogas plants to optimise the use of the energy produced. B. Stürmer *et al.* (2021) conducted a regional comparative analysis of agricultural biogas production, emphasising that the efficiency of technologies depends heavily on the type of feedstock and regional conditions. The researchers confirmed the significance of developing specialised approaches to biogas production in Ukraine, considering local specifics. These data are consistent with the findings of the present study, which indicated the need to adapt anaerobic digestion technologies to the specifics of Ukrainian regions.

G. Geletukha *et al.* (2022) investigated ways to replace Russian natural gas through biogas and biomethane production in Ukraine. Their conclusions emphasised the role of developing a regulatory framework and creating infrastructure for transporting biomethane through existing gas networks, which was fully consistent with the presented recommendations to integrate biogas plants into the overall energy system of Ukraine to ensure energy independence. K. Redko *et al.* (2022) analysed the development of green energy as a way to ensure Ukraine's energy independence. The researchers emphasised the significance of state support and promotion of renewable energy sources, including biogas technologies. These conclusions fully coincided with the study's recommendations to develop mechanisms to stimulate the development of bioenergy at the state level. D. Thiruselvi *et al.* (2021) and A. Veeramuthu *et al.* (2025) provided a critical overview of global trends in biogas technologies, including methods for improving them for use in fuel cells and energy networks. Their study focused on the need to improve biogas purification technologies, which is consistent with the findings on the significance of optimising biogas purification processes to increase the efficiency of electricity generation and biomethane use in industrial settings.

Thus, the analysis of sources confirmed that the development of biogas technologies in Ukraine requires a comprehensive approach, including the improvement of biogas purification methods, creation of infrastructure for its transportation and storage, as well as the introduction of mechanisms for government incentives for bioenergy development. The integration of biomethane into Ukraine's gas transmission systems can substantially increase the efficiency of renewable energy sources and ensure the country's energy security.

CONCLUSIONS

The study confirmed that electricity production from biogas and biomethane is a promising area for ensuring Ukraine's energy independence. The analysis of modern biogas production technologies revealed the significance of optimising anaerobic digestion processes, improving biogas purification methods and integrating biomethane plants into the overall energy system. The findings showed that cogeneration technologies provide the greatest efficiency of 80-90% due to the possibility of simultaneous production of heat and electricity. Gas turbines, which provide power and reliability, have an efficiency of 30-40%. Internal combustion engines are characterised by relatively low efficiency (25-45%) but are well suited for local systems with limited access to centralised energy sources. At the same time, emissions of harmful substances are still a major disadvantage of these plants.

Purification of biogas to the level of biomethane is a critical step for its further use in energy systems. Membrane technologies provide a purification efficiency of up to 95-98%, which makes them the most promising due to their high economic feasibility. Cryogenic separation demonstrates the highest purification efficiency (98-99%) but requires extensive energy costs. Absorption and adsorption methods are more affordable but less efficient for large volumes of biogas. Biological methods, specifically biofilters, have the potential for further improvement.

The findings also confirmed the significance of creating an efficient infrastructure for transporting and storing biomethane, as well as developing technical standards to regulate its quality. A prominent aspect is to ensure the compatibility of biomethane technologies with existing gas networks and the introduction of government support programmes, including tax benefits and "green" tariffs. The proposed measures will contribute to the development of the national energy system, increase its sustainability and environmental safety. The use of purified biomethane can substantially improve the efficiency of energy networks and reduce dependence on fossil energy sources. Specifically, the use of cogeneration units, gas turbines, and internal combustion engines can ensure the stability of energy supply even in crises or under conditions of uneven load.

Thus, the findings of the present study confirmed that electricity production from biogas and biomethane is a promising area for ensuring Ukraine's energy independence. Further research should be aimed at improving biogas purification methods, creating efficient technologies for its use, and expanding the infrastructure for biomethane transportation, which will ensure the stability of energy supply and improve the country's energy security.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Виробництво електроенергії з біогазу: сучасні технології та перспективи для енергетичної незалежності України

Анотація. Виробництво електроенергії з біогазу та біометану є перспективним напрямом розвитку відновлюваної енергетики, який може суттєво зменшити залежність України від викопного палива, скоротити обсяги викидів парникових газів та підвищити рівень енергетичної безпеки. Метою дослідження був аналіз сучасних технологій виробництва електроенергії з біогазу та біометану, оцінка їхньої ефективності, технічних переваг, недоліків та можливостей інтеграції у загальну енергетичну систему України. Методологія дослідження включає порівняльний аналіз когенераційних установок, двигунів внутрішнього згоряння та газових турбін, які використовуються для генерації електроенергії з біогазу, а також методів очищення біогазу до рівня біометану. Аналіз проводився з урахуванням технічної ефективності, економічної доцільності та екологічної безпеки. Результати дослідження показали, що когенераційні установки демонструють найвищий коефіцієнт корисної дії, який коливається в межах 80-90 %, завдяки одночасному виробництву теплової та електричної енергії. Газові турбіни забезпечують коефіцієнт корисної дії на рівні 30-40 %, а двигуни внутрішнього згоряння – 25-45 %. Порівняльний аналіз методів очищення біогазу виявив, що мембранні технології є найбільш перспективними завдяки високій ефективності очищення (95-98 %) та економічній доцільності. Інші методи, такі як абсорбційні, кріогенні та адсорбційні, мають обмеження у застосуванні через високі енергетичні витрати або низьку ефективність очищення. Встановлено, що очищення біогазу до біометану дозволяє використовувати його для генерації електроенергії, транспортування газопроводами та забезпечення стабільності енергомереж, особливо у періоди пікового навантаження. Розроблені рекомендації включають вдосконалення технологій очищення біогазу, створення інфраструктури для його транспортування та зберігання, а також розробку механізмів державного стимулювання розвитку біоенергетики. Використання біоенергетичних технологій може забезпечити стабільність енергетичної системи України, підвищити її ефективність та знизити залежність від традиційних джерел енергії

Ключові слова: відновлювана енергетика; біометан; когенераційні установки; газові турбіни; двигуни внутрішнього згоряння; газотранспортні системи

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