

Increasing the energy efficiency of sprinkler irrigation systems by optimising hydraulic modes and pumping equipment parameters

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Abstract. The aim of the study was to determine the energy effect of adaptive regulation of water supply modes and control of pumping equipment in the irrigation process. The study used analytical and balance methods, instrumental measurements of pressure, flow, and electricity consumption. Energy costs for irrigation remained (1,288 kWh/ha) with an average pump operating time of 9.6 h/day, which indicated the complete dependence of the systems on pumping supply (100%). The spatial scale of irrigation was significantly reduced – to about 100 thousand ha in 2023 and 40.5 thousand ha in 2025, which corresponded to only 10-20% of the pre-war potential (approximately 600 thousand ha). This condition was accompanied by losses of water (32-35%), energy (at least 30%) and critical wear of networks (over 75%). Optimisation of hydraulic modes provided a significant reduction in the load on the system, which was manifested in a reduction in the operating pressure from 0.60 to 0.42 MPa, a decrease in the power consumption of pumps from 56 to 39 kW and a decrease in the specific energy intensity of pumping from 430 to 305 kWh/1,000 m³. The introduction of automated control using a sensor network (humidity and pressure sensors) increased the adaptability of irrigation, increasing the frequency of irrigation adjustments from 1 to 6 times/day. This allowed reducing water supply during rainy periods by 35%, reducing seasonal energy consumption from 210 to 150 MWh and identifying 6 hidden leaks, which together confirmed

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the effectiveness of the transition to managed energy-saving modes of operation. The practical value of the study lies in the possibility of its use by water management organisations, agricultural enterprises and designers of land reclamation systems to reduce energy consumption, optimise irrigation modes and increase the efficiency of operation of existing infrastructure

Keywords: soil moisture sensors; water consumption; loss reduction; irrigation adjustments; network wear

INTRODUCTION

The relevance of this study is due to the growing dependence of the efficiency of agricultural production on irrigation in conditions of increased variability of climatic factors and instability of water supply. Irrigation is increasingly considered as a technological tool for stabilising yields and optimising the use of water resources. At the same time, the importance of the energy component of pumping water is increasing, which forms a significant share of operating costs. At the current stage of the operation of irrigation systems, the issue of increasing the energy efficiency is gaining particular relevance due to the need for rational use of existing infrastructure and limited possibilities for its rapid modernisation. The issues of this study are due to the preservation of non-adaptive hydraulic operating modes of pumping stations, significant energy losses during water transportation and insufficient level of automation of irrigation network management. Operation of systems with fixed pressure-flow parameters makes it difficult to coordinate water supply with actual irrigation needs and leads to overconsumption of electricity. Limited implementation of sensor monitoring and adaptive control algorithms reduces the possibilities of operational optimisation of water supply modes. The combination of these factors forms systemic limitations of irrigation energy efficiency, which require targeted scientific analysis and substantiation of engineering solutions.

As part of the research on irrigation energy supply, O. Sadovoy *et al.* (2024) substantiated the possibility of using solar energy installations to power sprinkler systems. The proposed solutions outlined ways to increase the energy autonomy of pumped water supply. In the works on electrical support of irrigation systems, O. Sadovoy *et al.* (2023) calculated the optimal geometric parameters of electrical control devices. The analysis demonstrated the importance of coordinating the design characteristics of the equipment with the operating modes of irrigation networks. In the direction of engineering optimisation of technical systems, V. Hruban *et al.* (2025) used finite element methods to assess the stress-strain state of agricultural machinery. The modelling performed allowed determining approaches to increasing the operational reliability of

structural elements. Taking into account the development of measurement technologies, J. Liu *et al.* (2024) systematised modern sensor solutions for controlling the parameters of hydraulic valves and systems. The above generalisations formed the basis for increasing the accuracy of monitoring and controllability of hydraulic processes.

Within the framework of research on intelligent control of hydraulic systems, P.M. Bhagwat *et al.* (2024) considered the use of adaptive control algorithms to reduce energy costs. The proposed approaches indicated the possibility of increasing the efficiency of hydraulic systems by optimising control effects. In the field of electro-hydraulic drives, R. Jin *et al.* (2024) developed artificial intelligence (AI)-oriented variable speed and displacement drive modules. The results presented demonstrated the potential of intelligent control for energy saving in complex hydraulic systems. In the field of multi-criteria optimisation of pumping modes, B. Brentan *et al.* (2024) considered approaches to controlling pumping stations in water distribution networks, taking into account energy, quality and operational constraints. The proposed control model provided a balance between energy efficiency and system stability. Based on artificial intelligence methods, L.R. Salvino *et al.* (2022) developed a water distribution network control system using artificial neural networks. The applied approach allowed adapting pump operating modes to variable loads with an orientation towards reducing energy costs.

Within the framework of a general review, Y. Ji *et al.* (2023) systematised the directions for increasing the efficiency of hydraulic turbines in energy recovery processes. The analysis outlined the potential for energy recovery in hydraulic and water management systems. From the perspective of industrial digitalisation, K. Sumit *et al.* (2022) investigated the implementation of Industrial Internet of Things technologies in hydraulic presses for the purpose of energy saving. The proposed solutions were based on continuous data collection and adaptive adjustment of equipment operating modes. In the field of mobile hydraulic systems, P. Fressia *et al.* (2022) analysed combined drive speed control and centralised power supply as tools for increasing

energy efficiency. The considered concepts identified the possibilities of reducing energy losses through coordinated control of drive systems. At the level of digital hydraulics, I. Azzam *et al.* (2022) studied approaches to reducing energy consumption in hybrid hydraulic transmissions. The use of discrete flow control ensured an increase in the overall efficiency of systems without complicating the design scheme.

The quantitative assessment of the energy effect of the combination of hydraulic mode optimisation, inverter control and intelligent control in real irrigation networks remained insufficiently studied. The aim of the study was to quantitatively assess the impact of hydraulic mode optimisation, inverter control and automated control on the energy efficiency of pumping water in irrigation systems. The objectives of the study were to analyse the energy characteristics of pumped water supply, assess the effect of optimising hydraulic modes using inverter pumps, and determine the impact of automation and sensor monitoring on the energy consumption of irrigation systems.

MATERIALS AND METHODS

Research conditions and objects of observation

The research was carried out in 2023-2025 on the basis of the scientific park of the Mykolaiv National Agrarian University "Agroperspectiva" with the involvement of a sample of typical operating sprinkler systems in southern Ukraine, which were operated exclusively with pumped water supply and functioned on centralised pressure networks. The sample included 8 pumping stations ($n = 8$) and 12 irrigation systems ($n = 12$) with centralised pumping stations and pressure-type distribution networks, focused on ensuring the operation of frontal action (linear move), circular action (centre pivot), drum sprinkler systems (hose reel irrigators), as well as on-farm hydrants. The study combined the generalisation of open statistical materials on the functioning of irrigation systems in Ukraine with an experimental and computational assessment of the effects of optimising hydraulic regimes. Initial data on energy consumption, water supply volumes and spatial scales of irrigation were used to form baseline levels of indicators and normalise results without interfering with the operational modes of the facilities. The research was carried out in compliance with the European Code of Conduct for Research Integrity (All European Academies, 2023), which regulated the ethics, transparency, and reproducibility of scientific research.

The analysis was carried out on existing sprinkler systems in southern Ukraine, which were operated with pumped water supply and were based on centrifugal pumping units of horizontal and vertical design

with a nominal flow of 80-150 m³/h and a head of 40-70 m. Such pumping equipment was selected due to its typical application in land reclamation networks, constructive versatility and technical suitability for the implementation of frequency control without replacing pumps. Pump operation modes were controlled using Danfoss VLT® AQUA Drive FC 202 (Danfoss, Denmark) and Schneider Electric Altivar Process ATV630 (Schneider Electric, France) inverter drives, focused on water supply and wastewater systems. The use of these drives was due to the support for pressure stabilisation, built-in energy optimisation functions, and compatibility with sensor networks of irrigation systems.

Power consumption parameters in pump irrigation systems

Total electricity consumption by pumping stations (million kWh) was formed on the basis of aggregated data for each studied pumping station, with subsequent statistical generalisation. The initial values of energy consumption were taken into account separately for each facility (n stations), after which descriptive statistics methods were applied – summation, calculation of average values and interval estimation of variation (standard deviation, coefficient of variation). The specific energy intensity of water pumping (kWh/1,000 m³) was determined on the basis of generalised official statistical materials of state water resources management bodies of Ukraine based on the results of the Irrigation season 2025 (2025). The data were formed by aggregating reporting information from pumping stations on actual electricity consumption and volumes of supplied water.

The specific energy consumption of water supply (kWh/m³) was calculated by formula:

$$E_v = \frac{E_{tot}}{V}, \quad (1)$$

where E_v – specific energy consumption of water supply, kWh/m³; E_{tot} – total electricity consumption by pumping units for the calculation period, kWh; V – actual volume of water supplied for the same period, m³. Electricity consumption per 1 ha of irrigation (kWh/ha) was determined by formula (1).

The maximum daily energy intensity of the supply was determined as the ratio of the maximum daily electricity consumption by pumps to the corresponding daily volume of supplied water according to the formula:

$$E_{max} = \frac{E_{d,max}}{V_d}, \quad (2)$$

where E_{max} – maximum daily energy intensity of water supply, kWh/m³/day; $E_{d,max}$ – maximum daily electricity

consumption by pumping units, kWh; V_d – daily volume of water supplied on the corresponding peak load day, m^3 . The average duration of pump operation per day was determined instrumentally, for this purpose the Fluke 1738 Power Logger electricity analyser (USA) was used.

Scale and structure of irrigation infrastructure operation

The actual area of irrigation in 2023 (thousand hectares) was determined based on analytical materials from agricultural information resources and industry reviews that summarised official data on the actual operation of irrigation systems after 2022 (In Ukraine, the area..., 2024).

The total area of irrigated land in 2025 (thousand hectares) and the number of regions with active irrigation were determined based on official information reports from central executive bodies and state information agencies that summarised the results of the functioning of the land reclamation infrastructure (In Ukraine, the total area..., 2025). The area with concluded water supply contracts (thousand hectares) was determined based on data from industry analytical reviews formed on the basis of information from irrigation system operators and water users (Ukraine is increasing the area..., 2025).

The average irrigation area per region (thousand hectares/region) was determined by the calculation method using the formula:

$$A_{avg} = \frac{A_{tot}}{N}, \quad (3)$$

where A_{avg} – average irrigated area per region, thousand ha/region; A_{tot} – total area of irrigated land, thousand ha; N – number of regions with active irrigation. The share of the pre-war irrigation level (%) was determined according to the source data containing an estimate of the pre-war base level and current areas (The first step..., 2026).

Operational condition and resource losses of water management networks

The pre-war potential of irrigated areas (thousand hectares) was determined based on generalised analytical materials of agricultural and water management surveys that characterised the design capacity of Ukraine's land reclamation infrastructure until 2022 (In Ukraine, the area..., 2024). Water losses during transportation (%) were determined by the balance method using the formula:

$$L_w = \frac{V_{in} - V_{out}}{V_{in}} \times 100, \quad (4)$$

where L_w – water losses during transportation, %; V_{in} – volume of water supplied by the pumping station to the network, m^3 ; V_{out} – volume of water recorded at the final water intake points, m^3 .

The share of energy losses in pumping systems (%) was determined based on the results of industry scientific research and generalised technical and economic assessments of the efficiency of pumping stations (Stashuk *et al.*, 2024). The degree of wear of irrigation networks since the beginning of 2022 (%) was determined in specialised industry analytical materials (Irrigation in Ukraine 2026..., n.d.). The share of systems without automated control (%) was determined by the inventory method based on the analysis of the presence of frequency converters and regulators in the pumping stations. Automated systems included stations equipped with frequency converters of the Danfoss VLT Aqua Drive FC 202 type (Denmark).

The impact of pressure regulation and frequency control of pumps

The comparison was performed between the operating modes of pumping stations before optimisation, which were characterised by fixed pressure-flow parameters, and after optimisation, in which the regulation of the operating pressure and flow was carried out by inverter drives taking into account the hydraulic conditions of the network. Monitoring in the “before optimisation” mode lasted 30 days, in the “after optimisation” mode – 30 days; the parameters were recorded in 5-minute increments, which formed 288 measurement intervals per day for each station. The analysis was performed for no less than 10 repetitions of stabilised operating cycles in each mode; the criterion for a stable hydraulic state was considered to be a deviation of the operating pressure of no more than $\pm 3\%$ and a flow of no more than $\pm 5\%$ for at least 20 minutes of continuous operation.

The operating pressure in the network (MPa) was determined by direct measurement using digital strain gauge pressure sensors WIKA A-10 (Germany) and Siemens SITRANS P320 (Germany), installed in the control nodes of the pressure pipelines. The obtained values were used as input parameters for calibrating the hydraulic model of the network in the Environmental Protection Agency Network Evaluation Tool (EPANET), which allowed specifying the spatial distribution of pressures and head losses.

The average water flow rate (m^3/h) was determined from the readings of electromagnetic flow meters Siemens MAG 5100W (Germany) or ultrasonic flow meters Endress+Hauser Prosonic Flow W (Switzerland), mounted on the pressure pipelines. The values were averaged

over stable hydraulic conditions, which ensured the representativeness of the data for further calculations. The power consumption of the pumps (kW) was determined from the instantaneous values of active power recorded by three-phase electrical energy analysers Fluke 435-II (USA) or stationary meters Schneider Electric PM8000 (France), with subsequent integration over time.

The specific energy intensity of pumping (kWh/1,000 m³) was determined by the formula:

$$E_s = \frac{E_{tot}}{V} \times 1,000, \quad (5)$$

where E_s – specific energy intensity of pumping, kWh/1,000 m³; E_{tot} – integrated electricity consumption by pumping units, kWh; V – total volume of pumped water, m³.

Hydraulic head losses (m) were determined as the difference between the total head at the outlet of the pumping station and the head at the control nodes of the network, taking into account the results of modeling in EPANET 2.2 (U.S. EPA), where the calculation in the Extended Period Simulation mode, actual lengths and diameters of pipelines, roughness coefficients for pipe material, nodal flows, specified boundary conditions based on measured pressure and flow values, as well as a simulation time step of 5-10 min were used. This approach allowed combining the results of field measurements with a computational analysis of the distribution of losses along the network.

Intelligent regulation of water supply under changing conditions

Comparisons were made between the operating modes of irrigation systems without automation, based on fixed water supply settings, and modes with automation, in which control was carried out on the basis of sensor monitoring and adaptive control algorithms. The input variables of the algorithm were the deviation of soil moisture from the established target range and the deviation of pressure in the network from the given setpoint, while the control effect was implemented by changing the frequency of rotation of pumps with inverter drives through the correction of the parameters p_{set} or Q_{set} . The fuzzy rule base was formed in the form of conditional dependencies of the type: if soil moisture decreased below the standard interval at an allowable pressure level, a moderate increase in supply was carried out; optimisation of solutions was carried out according to the criterion of minimising specific energy consumption while simultaneously observing the restrictions on the limit pressure and agrotechnically allowable humidity. The number of soil moisture sensors and wireless pressure sensors (units) was determined by the inventory method based on the actual

configuration of the sensor network of the irrigation system. The installed capacitive soil moisture sensors Decagon EC-5 (Meter Group, USA) and wireless strain-resistive pressure sensors WIKA A-10 (WIKA Alexander Wiegand SE, Germany), integrated into the network control nodes and pump groups, were taken into account.

The frequency of irrigation mode correction (times/day) was determined by the calculation method as the number of changes in the water supply control parameters during the daily interval. The calculation was performed according to the formula:

$$f_c = \frac{n_c}{t}, \quad (6)$$

where f_c – frequency of correction of irrigation modes, times/day; n_c – number of corrections of control parameters during the observation period; t – duration of the observation period, day. Corrections were initiated by rule-based and adaptive control algorithms that combined rule-based control and fuzzy logic control. Threshold conditions were formed based on the deviation of soil moisture from the target interval and exceeding the permissible pressure limits in the network, while the fuzzy algorithm ensured a smooth change in pump flow and head in transient modes.

The change in water supply on rainy days (%) was determined by analytical method as the relative difference between the average daily water flow in the absence of precipitation and on days with precipitation ≥ 5 mm/day, which were classified as rainy according to the established threshold criterion. The water supply volumes were determined by the readings of electromagnetic flowmeters Siemens SITRANS MAG 5100W (Siemens AG, Germany) installed on pressure pipelines. The seasonal energy consumption of the system (MWh) was determined by integrating the instantaneous values of the active electric power of the pumping units for the entire growing season. The generalised calculation was carried out by formula:

$$E_{season} = \int_0^T P(t) dt, \quad (7)$$

where E_{season} – seasonal energy consumption of the system, MWh; $P(t)$ – instantaneous active power of pumping equipment, kW; T – duration of the growing season, h. Power measurements were performed using three-phase PowerLogic PM8000 electricity analysers (Schneider Electric, France).

The detected pipeline leaks (units/season) were determined by the hydraulic method, based on the analysis of the discrepancy between the calculated and measured parameters of pressure and water flow. For this purpose, a comparison of the results of network

modelling in the EPANET 2.2 software environment (U.S. EPA) with the actual data of pressure sensors and flow meters was used, with local anomalies being considered as indicators of possible leaks. The given indicators were given as average values for intervals of stable hydraulic regime, and the variability of the results was assessed by the range of fluctuations and, by the standard deviation, which ensured the correct statistical representation of numerical data.

RESULTS

Energy consumption assessment of water pumping transportation

The analysis of energy consumption within the studied systems allowed forming a quantitative characteristic of the functioning. The total energy consumption by pumps was 51.5 million kWh. The obtained value indicated the energy costs for supporting the water supply system throughout the entire growing season. The value of energy consumption showed a low correlation between the actually irrigated area and its physical characteristics. At the same time, the obtained indicator was consistent with the fact that the inertia of the operating modes of pumping stations, in which a decrease in water supply was not accompanied by a proportional change in pump power or operating time, led to an increase in the energy intensity of the irrigation process in the studied irrigation system. Thus, the energy consumed by pumps did not correspond consistently to the actual load of the system. The specific energy intensity of the water pumping process was 393.7 kWh/1,000 m³, which reflected the energy costs for water transportation under the established hydraulic conditions. The obtained values confirmed the influence of all factors that formed energy costs in the studied area. Energy costs were based on

pressure losses in pumping stations, on the lack of correlation of pump operating modes and on the technical condition of the system pipelines. Therefore, in this form, this analysis of the indicator confirmed that the cause of energy costs was mainly associated with the hydraulic mismatch of the irrigation system, and not with an increase in the need for water supply for irrigation. This level of specific energy intensity indicated the possibility of reducing electricity costs without reducing irrigation volumes in this case. The specific energy consumption of water supply was 0.394 kWh/m³, which determined the energy costs for transporting a unit of water. The obtained value reflected the average value of all elements of the system, from pumps to the final water distribution nodes. Thus, the analysis of this indicator confirmed that the established operating mode of the pumps achieved stability of water supply. In this case, the pumps exceeded the optimal pressure parameters, which indicated a non-adaptive approach to resource optimisation during the operation of pumping stations.

The integral value of electricity consumption per unit area was 1.288 kWh/ha, which quantitatively reflected the energy costs of irrigation per unit of production. The obtained value reflected the integral impact of the duration of operation of pumping stations, pumping modes and irrigated areas. Analysis of the value of the obtained indicator showed that electricity consumption bypassed the issue of resource improvement of the irrigation system in favour of ensuring its economic benefit. At the same time, even with minimal deviations from the pump operation settings, an increase in electricity consumption per hectare of production was observed in the study area, which negatively affected the sustainability of the irrigation system in terms of changes in its consumption (Table 1).

Table 1. Energy characteristics of pumped water supply in irrigation systems of Ukraine (2025)

Indicator (unit)	Value	Note
Total electricity consumption by pumping stations (million kWh)	51.5	Generalised operational data of pumping stations that provided water supply in functioning irrigation systems during the 2025 growing season
Specific energy consumption of pumping (kWh/1,000 m ³)	393.7	The value is given in terms of the volume of water actually supplied and reflects the relationship between energy consumption and water flow in pumping networks
Specific energy consumption of water supply (kWh/m ³)	0.394	Normalised energy characteristic of pump flow, used to compare operating modes of systems regardless of the spatial and production scales
Electricity consumption per 1 ha of irrigation (kWh/ha)	1288	Given in relation to the area of land in 2025 actually involved in irrigation during the period under study
Average pump operation time per day (hours)	9.6	Average value obtained during the period of active operation of pumping equipment during the growing season
Maximum daily energy consumption of supply (kWh/m ³ /day)	0.47	Characteristics of system operating modes under conditions of increased daily water supply intensity
Share of pump supply in irrigation (%)	100	Reflects the structure of water supply within the studied irrigation systems in the absence of alternative water supply sources

Source: compiled by the authors based on *Irrigation season 2025: Over 40 thousand hectares of Ukrainian lands provided with water (2025)*

The generalisation of the obtained results allowed establishing that the energy characteristics of the pumped water supply were determined by a combination of high total energy consumption, increased specific energy intensity of pumping and significant electricity consumption per irrigation area. The set of numerical values obtained indicated that the existing hydraulic modes were not optimised in terms of energy efficiency and did not take into account the real needs of irrigation. The results of this section confirmed the feasibility of further analysis of the impact of pressure optimisation, modernisation of pumping equipment and the introduction of automated control as tools for reducing energy consumption.

Spatial characteristics and management organisation of irrigation

The actual irrigation area in 2023 was approximately 100,000 hectares. This indicator reflected the physical scale of operating irrigation systems in the post-crisis period and characterised the level of use of the existing infrastructure. The result obtained indicated that irrigation was carried out in limited and heterogeneous areas, which made it difficult to establish stable hydraulic regimes. In this situation, pumping stations operated at sub-maximum capacity, and water supply regimes were often determined by the local needs of individual areas, rather than by agreed management schemes. The established scale of irrigation confirmed the existence of a gap between the potential of irrigation infrastructure and the level of its use. In 2025, the total area of irrigation decreased to 40.5 thousand hectares, which reflected a further narrowing of the spatial coverage of irrigation. This indicator characterised the transition of the system to a localised mode of operation, in which irrigation was carried out in limited areas without the possibility of uniform load distribution between

network elements. Such a concentration of irrigation in limited areas led to an increase in the uneven operation of pumping stations and complicated the application of centralised approaches to optimising water supply. The result showed that the spatial narrowing of irrigation was accompanied by a loss of flexibility in the management of hydraulic regimes.

The area of land with formalised water supply contracts was about 40,000 hectares, which reflects the organisational level of readiness of irrigation systems for operation. This indicator characterised the volume of areas for which formalised water use conditions were organised and which had access to pumped water supply. The result showed that the majority of actually irrigated areas operated within the framework of formalised contractual relations. However, the spatial boundaries remained narrow. As a result, the organisational structure of water supply was aimed at supporting a minimally sufficient irrigation infrastructure, rather than at fully utilising the capabilities provided by existing networks. This approach created conditions under which pumping stations operated in modes that did not allow for optimal distribution of flows in space. The share of actual irrigation from the pre-war level was 10-20%, which was explained by the use of different bases of comparison – the design potential of the systems or the actually operated areas in previous years. The obtained indicator indicated the loss of most of the pre-war irrigation potential and a sharp reduction in the scale of infrastructure use. Under these conditions, spatial planning of irrigation lost its systematicity, and pumping stations were operated under conditions of uneven and limited load. The analysis confirmed that the current scale of irrigation does not allow realising the design advantages of centralised water supply networks and does not significantly reduce specific energy costs (Table 2).

Table 2. Spatial and organisational scale of irrigation operation in Ukraine (2023-2025)

Indicator (unit)	Value	Note
Actual irrigation area in 2023 (thousand hectares)	~100	The indicator reflected a sharp reduction in irrigation after 2022. The area limitation reduced the efficiency of using existing infrastructure
Total area of irrigated land in 2025 (thousand hectares)	40.5	The value characterised the current level of irrigation restoration. It remained significantly lower than the pre-war potential
Number of areas with active irrigation (units)	4	The indicator showed a high regional concentration of irrigation in Zaporizhia, Kirovohrad, Mykolaiv and Odesa regions. The main load fell on a limited number of regions
Area with concluded water supply contracts (thousand hectares)	~40	The indicator reflected the real volume of functioning systems. It testified to organisational readiness for irrigation
Share of pre-war irrigation level (%)	10-20	The value indicated the loss of a significant part of the potential. This necessitated the modernisation of existing systems
Average irrigated area per region (thousand hectares/region)	~10	The indicator was used to assess the scale of the load on regional systems. It was applied in modelling pumping modes

Source: compiled by the authors based on *In Ukraine, the area of irrigated land has decreased sixfold (2024)*, *In Ukraine, the total area of irrigated land exceeded 40 thousand hectares (2025)*, *Ukraine is increasing the area of irrigated land: Contracts for 40 thousand hectares have been signed in four regions (2025)*, *The first step: The irrigation market in Ukraine has begun to recover (2026)*

The summary of the results allowed establishing that the spatial and organisational scales of the irrigation system during the studied period were distinguished by a significant reduction in area, localised water supply and limited integration of areas into a single system. The combination of small actual irrigation areas with narrow but formalised water use zones created conditions under which pumping stations operated outside the optimal operating modes. The numerical values obtained as a result of the analysis indicate that spatial restrictions and the organisational structure of the irrigation system had a significant impact on the operation of pumping equipment and contributed to an increase in specific resource consumption.

Network wear and loss of water and energy resources

The level of water losses during transportation was 32-35%, which characterises the scale of the discrepancy between the volume of water supplied by pumping stations and the amount of water actually used for irrigation. This indicator was formed as a result of the cumulative effect of long open channels, worn pipelines and leakage of network elements. Under such conditions, water transportation was associated with a systematic decrease in its useful flow along the entire length of the irrigation system. The established level of water losses meant that a significant part of the pumped water supply did not participate in irrigation, which led to an increase in the total volume of water supply and a corresponding increase in the load on the pumping equipment. The physical condition of the networks was characterised by a degree of wear of $\geq 75\%$. This indicator reflected the degree of degradation of the main structural elements of the irrigation infrastructure, including pipelines, channels, valves and connecting nodes. Under such conditions, the network operated mainly outside its design parameters, which determined the instability of hydraulic conditions. The

wear of the infrastructure was accompanied by an increase in the roughness of the internal surfaces, local deformations and a partial loss of throughput in some areas. As a result, water was supplied under conditions of increased head losses, which required maintaining increased operating parameters of the pumping units.

The share of energy losses in pumping systems was $\geq 30\%$, which reflected the ratio between the total electricity consumption and its useful part spent directly on water supply, and included the costs of overcoming the hydraulic resistance of the network, pressure losses in pipelines, pump operation beyond the optimal efficiency coefficient, and additional energy costs associated with the instability of the modes. This indicator was formed under conditions of inconsistency of the operation of pumps with the actual hydraulic characteristics of the network, as well as the need to compensate for pressure losses in worn sections of the network. Under such conditions, part of the electricity was spent on supporting operating modes not related to the useful transportation of water, which increased the total energy consumption of irrigation. The established share of energy losses reflected the structural inefficiency of the system due to the combination of the technical condition of the network and the operating modes of pumping units. A comprehensive analysis of the obtained indicators allowed outlining the nature of the relationship between the technical condition of irrigation networks and resource losses. High levels of water losses generated increased pumping costs, which were accompanied by increased energy consumption to support such losses. The high degree of infrastructure deterioration determined the instability of hydraulic regimes and limited the precise regulation. The share of energy losses in pumping systems reflected the consequences of such operation, when the efficiency of electricity use decreased due to compensation for technical and hydraulic deficiencies (Table 3).

Table 3. Technical condition and resource losses of irrigation networks in Ukraine

Indicator (unit)	Value	Note
Pre-war potential of irrigated areas (thousand hectares)	~600	The indicator characterised the design capacity of the systems. The difference with the actual areas indicated the degradation of the infrastructure
Water loss during transportation (%)	32-35	The value reflected physical losses in channels and pipelines. These were associated with filtration and excess pressure
Share of energy losses in pumping systems (%)	≥ 30	The indicator indicated inefficient operation of pumping equipment. Its decrease was expected with optimisation of operating modes
Degree of wear of irrigation networks at the beginning of 2022 (%)	≥ 75	The value indicated a critical technical condition of the networks, which led to an increase in hydraulic and energy losses
Share of systems without automated control (%)	>85	The value indicated the predominance of manual control. This reduced the adaptability of the systems to weather conditions

Source: compiled by the authors based on *In Ukraine, the area of irrigated land has decreased sixfold (2024)*, V.A. Stashuk et al. (2024), *Irrigation in Ukraine 2026: Prices, competition for water, state support and new irrigation technologies (n.d.)*

Thus, the results of the study reflected the set of technical and operational characteristics of irrigation networks, within which water and energy losses were formed during water pumping. The established values of water losses, the degree of physical wear of the infrastructure and the share of energy losses outlined the real parameters of the networks' functioning in the studied period and determined the nature of the interaction between the technical condition of the system and its operating modes. The results obtained recorded the existing limitations of the functioning of irrigation networks, which affected the level of resource load and operating conditions of pumping equipment.

Adjustable pumping modes and reduction of hydraulic losses

After the formation of optimised hydraulic operating modes, the operating pressure in the irrigation network was set at 0.42 MPa. This parameter indicated the adjustment of the pump operating modes using frequency modulation, which allowed stabilising the hydraulic conditions in the network. The irrigation network operated at this pressure level without loss of fluid flow, and the load on its elements was uniform along the supply path. The operation of the network in such conditions of reduced pressure was associated with a decrease in local head losses and stabilisation of flow patterns. The formation of this operating pressure demonstrated the possibility of irrigation systems operating without the use of redistributed head reserves characteristic of standard operating modes. The electrical load on the pumping system in conditions of optimised hydraulic operating modes was 39 kW. This value reflected the stability of the pumps during the water supply process in the absence of peak overload. The pumping system operated with soft frequency modulation without sharp fluctuations in electricity consumption. Compliance of the pump operating modes with the actual needs of water supply ensured the stability of energy consumption during the water supply process. The recorded electricity consumption was manifested as a transformation of the energy consumption pattern from pulsed to uniform, which had a positive effect on the energy balance of irrigation.

The specific energy consumption for water transportation under conditions of optimised hydraulic operating modes was 305 kWh/1,000 m³. This parameter indicated the ratio of energy consumption to the supplied volume, which was maintained within the established hydraulic operating modes. The achieved level of this parameter became possible due to the correlation between the reduced operating pressure and the operation of pumping equipment within the parameters close to its design capacity. Water transportation under these conditions had a reduced level of unproductive energy consumption associated with the overcompensation of head reserves. The achieved level of specific energy consumption demonstrated a new level of energy efficiency in the process of water supply for the needs of existing irrigation networks. Based on these indicators, it was possible to characterise changes in the energy properties of pumping irrigation networks under optimised hydraulic operating modes. Reducing the operating pressure created conditions for reducing electrical loads directed at pumping systems, which is manifested in reducing the values of electricity consumption. Stabilising the operating modes of pumping equipment simultaneously ensured the creation of a uniform picture of energy consumption and reducing energy losses associated with the use of incongruent operating modes. The recorded level of specific energy consumption included both changes in relative units, which improves the understanding of the efficiency of water supply regardless of the scale of the network. The presented numerical indicators characterised the increased energy efficiency of irrigation network by adjusting the operating modes without changing the physical parameters of the pumps of irrigation networks. The operation of pumping systems under optimised pressure and inverter control ensured a better match between the hydraulic properties of irrigation infrastructures and the ratio of head and flow of pumps. The operation of irrigation infrastructures under these conditions-maintained modes as close as possible to the design ones, minimising the energy requirements for irrigation caused by technical shortcomings of drainage infrastructures (Table 4).

Table 4. Effect of pressure optimisation and use of inverter pumps

Indicator (unit)	Before optimisation	After optimisation	Note
Working pressure in the network (MPa)	0.60	0.42	Pressure reduction eliminated excess hydraulic losses. Optimisation was achieved through modelling in EPANET
Average water flow (m ³ /h)	120	92	The indicator reflected the transition to the optimal supply mode. This prevented excessive water and energy consumption
Hydraulic head loss (m)	19	11	The reduction in losses indicated an increase in network efficiency. This had a positive effect on pump efficiency

Table 4, Continued

Indicator (unit)	Before optimisation	After optimisation	Note
Pump power consumption (kW)	56	39	The indicator reflected the direct energy effect of the optimisation. The reduction corresponded to a level of 20-30%
Specific energy consumption of pumping (kWh/1,000 m ³)	430	305	The indicator was used to compare system operation scenarios. It confirmed the effectiveness of the optimisation

Source: compiled by the authors

Thus, the results of the study outlined the quantitative parameters of the energy effect achieved as a result of optimising hydraulic modes and using inverter control of pumping equipment. The established values of operating pressure, consumed electric power and specific energy intensity of pumping determined new operational limits of pumping water supply within the existing irrigation systems under adjusted operating modes. The set of the above parameters reflected the change in the nature of the system's energy consumption and formed a quantitative basis for further assessment of the impact of automated control, sensor monitoring and intelligent regulation algorithms on irrigation modes and total energy costs in the conditions of the actual technical condition of the networks.

Sensor monitoring as the basis of dynamic irrigation modes

The number of soil moisture sensors in the system was 24 units, which provided spatially detailed tracking of the state of moisture within the irrigated areas. This distribution of the sensor network created a continuous array of data on spatial and temporal changes in moisture detected and distributed in the air to adjust irrigation modes. The established density of sensors compensated for the uneven moisture state in soil conditions and microrelief of the irrigated area, thereby minimising the need for irrigation according to averaged schemes. Adaptive irrigation schemes and the amount of water supplied to plants corresponded to the needs. Under these conditions, the risk of over-watering reduced the unproductive energy consumption associated with the operation of the pumping station. The irrigation system for supporting and monitoring hydraulic parameters included 18 wireless pressure sensors distributed in a spatially distributed network along the supply and

distribution sections. This configuration allowed for real-time control of the pressure supply rate throughout the network, which allowed for dynamic regulation of the pump and equipment. Stable hydraulic conditions created under these conditions reduced the need to maintain an excess supply of hydraulic pressure. This constant and stable configuration of the pressure sensor network created uniform water transport conditions that evenly distributed energy consumption to the pumping station, instead of concentrating unproductive electricity consumption.

The number of irrigation mode adjustments per day was 6, which characterised the high level of adaptability of the AI-based control system. These changes occurred in response to soil moisture sensors and weather sensors connected through AI-driven algorithms. Under these conditions, the water supply management was adjusted to provide reduced irrigation according to strict schedules. Regular irrigation mode adjustments up to six times a day allowed the pumps to operate as needed. Given this practice, electricity consumption was levelled without the peak loads that are usually caused by traditional control systems. The seasonal electricity consumption for this automated irrigation management system was 150 MWh. This figure represented the total electricity consumption calculated during the growing season. This value stabilised at a fixed level after the conditions of energy supply to the irrigated plants stabilised. This new seasonal energy consumption curve stabilised as a result of adapted pumping stations and pumps, dynamic pressure correction and non-invasive control of irrigation modes based on artificial intelligence. Such seasonal energy consumption with automation minimised electricity consumption peaks and evenly distributed consumption patterns over time (Table 5).

Table 5. The impact of automation, sensors, and AI control on irrigation modes

Indicator (unit)	Without automation (traditional control without adaptive algorithm)	With automation	Note
Number of soil moisture sensors (units)	0	24	The use of sensors ensured that irrigation was adapted to the plants' needs, reducing water overspending
Number of wireless pressure sensors (units)	2	18	Increasing the number of sensors allowed the system to be monitored in real time, which reduced energy losses

Table 5, Continued

Indicator (unit)	Without automation (traditional control without adaptive algorithm)	With automation	Note
Frequency of irrigation mode correction (times/day)	1	6	The indicator reflected the flexibility of management. Frequent corrections increased the accuracy of water supply
Change in water supply on rainy days (%)	0	- 35	Automation allowed the water supply to be reduced during favourable weather conditions, which had a direct energy-saving effect
Seasonal energy consumption of the system (MWh)	210	150	The indicator characterised the total effect of automation and AI management. Its decrease indicated an increase in efficiency
Pipeline leaks detected (units/season)	0	6	The use of thermography allowed detecting hidden leaks, which reduced unproductive water and energy losses

Source: compiled by the authors

Thus, the results of the study outlined the quantitative parameters of the impact of automation, sensor monitoring and AI-control on the energy consumption of irrigation systems within the studied period. A combined consideration of the above parameters made it possible to characterise the change in the system operating modes under the conditions of applying adaptive control schemes based on continuous collection and processing of operational data. Spatially detailed sensor monitoring formed the information basis for regulating water supply in accordance with the current soil condition and hydraulic conditions of the network, while AI-control algorithms provided for prompt correction of the operating modes of pumping equipment. The established values of the number of sensors, the frequency of mode correction and seasonal electricity consumption determined new operating conditions for the functioning of irrigation systems under intelligent control schemes. The frequency of corrections determined the dynamics of the operation of pumping units and the nature of the energy load during the day, while seasonal energy consumption reflected the integrated result of the action of automation and intelligent control within one vegetation cycle.

DISCUSSION

The results obtained showed that the optimisation of hydraulic modes in combination with inverter control of pumping equipment contributed to a significant change in the energy properties of pumped water supply. Stabilisation of the operating pressure in the network created conditions for the rejection of excess pressure reserves inherent in traditional operation schemes without violating the stability of hydraulic modes. This approach was consistent with modern ideas about energy-saving management of irrigation systems, where maintaining coordinated pressure-flow parameters is considered a key factor in reducing pressure losses and mechanical loads on network elements. Changing the

nature of the operation of pumping equipment from discrete to adaptive ensured the alignment of the energy profile of water supply. Inverter control made it possible to coordinate the operating modes of pumps with actual hydraulic conditions, which reduced unproductive electricity consumption and increased operational stability. The generalisation of energy characteristics in relative indicators reflected an increase in the efficiency of water transportation within the existing infrastructure without the need for its structural modernisation. In the context of energy efficiency analysis of hydraulic systems, the works of R. Dindorf *et al.* (2023) and Y. Ebada *et al.* (2025) considered individual technical aspects of optimisation. R. Dindorf *et al.* generalised models of hydropneumatic accumulators as a tool for reducing energy losses, however, the study was of a survey nature and did not cover the operating modes of pumping networks with variable loads. Y. Ebada *et al.* focused on increasing the efficiency of centrifugal pumps and reducing cavitation in laboratory conditions, but the analysis was limited to a single unit without taking into account network hydraulics. In contrast to these approaches, in this study, energy parameters were estimated for the entire water supply system, which made it possible to trace the relationship between optimised pressure, flow stabilisation and reduction of unproductive losses in real irrigation conditions.

From the perspective of optimising water supply modes, G. Tardy *et al.* (2024) and Y. Pang *et al.* (2024) analysed the possibilities of reducing energy consumption in technical systems with controlled hydraulic parameters. G. Tardy *et al.* applied optimisation approaches to the design of energy-efficient power transmissions of mobile equipment, however, the study was limited to closed loops with regulated operating cycles. Y. Pang *et al.* simulated irrigation planning scenarios to reduce energy costs, however, the emphasis was on the calendar and agrotechnical irrigation schedule without a detailed analysis of the hydraulic behaviour of the

network. In this study, the optimisation was performed for an open pumping system with variable flow rates and pressure modes, which allowed combining pressure regulation, inverter control and sensor monitoring and evaluating the combined effect in real conditions of long-term seasonal operation. In the field of intelligent control of hydraulic systems, I. Azzam *et al.* (2023) and L. Li *et al.* (2025) developed algorithmic approaches to optimisation. I. Azzam *et al.* proposed automated selection of pump operating modes, but the control was based mainly on the internal parameters of the equipment. L. Li *et al.* increased energy efficiency by optimising flows in manipulators, without taking into account external natural factors. In this study, intelligent control was integrated with spatially distributed soil moisture and pressure sensors, which ensured the adaptation of water supply modes to real irrigation needs and formed a systemic approach that was not implemented in the above works.

In the field of experimental evaluation of pumping equipment, the works of L. Manservigi *et al.* (2023) and M. Yanikören (2025) analysed local ways to increase energy efficiency. M. Yanikören investigated the energy consumption of gear pumps using the Taguchi method, focusing on the influence of design parameters on the efficiency of a single unit, but without taking into account the interaction of the pump with an extended pipeline network. L. Manservigi *et al.* considered the use of the pump as a turbine to reduce pressure losses, but the approach was focused on reducing local leaks and did not cover variable water supply modes. In this study, the optimisation was carried out at the level of the entire irrigation system, which allowed evaluating the integrated energy effect of pressure regulation and inverter control under real operating conditions.

In the context of hybrid hydraulic drives, F. Khajvand *et al.* (2023) and V.H. Nguyen *et al.* (2025) focused on increasing energy efficiency through energy recovery in mobile equipment. F. Khajvand *et al.* implemented a serial hybrid hydraulic drive scheme aimed at accumulating and reusing braking energy, however, the analysis remained limited by the conditions of repeated motion cycles and did not take into account the variability of the hydraulic load in space. V.H. Nguyen *et al.* investigated the concept of double energy recovery in hydraulic cylinders of working bodies, paying primary attention to the kinematic and power characteristics of individual nodes, while spatially distributed pressure losses and the features of the operation of extended networks were not analysed. Unlike the above approaches, in this study, energy efficiency was increased without the use of recuperation circuits, through adaptive control of water supply modes, which allowed reducing energy

costs without complicating the structural scheme of the system. From the perspective of intelligent control and optimisation, M. Bhola *et al.* (2023) and S. Iyer *et al.* (2025) applied algorithmic methods to improve the efficiency of hydraulic systems. S. Iyer *et al.* optimised the geometric parameters of the impellers of pumps for thermal plants, focusing on improving the aerohydrodynamic characteristics of the units, however, variable network operating modes and the impact on total energy consumption were not considered. M. Bhola *et al.* used machine learning methods to control the hydrostatic transmission of a loading machine, but the object of the study remained a closed system with predefined operating scenarios. In the presented study, intelligent control algorithms were integrated with spatially detailed sensor monitoring of soil moisture and pressure in the network, which ensured the adaptation of water supply modes to external natural and operational factors and formed a more universal and scalable approach to increasing the energy efficiency of irrigation systems.

In the field of water transportation optimisation and network management, M. Bayatloo *et al.* (2023) and J. Jafari-Asl *et al.* (2024) examined approaches to reducing energy and resource losses. J. Jafari-Asl *et al.* used an extended optimisation framework to reduce the ecological footprint of water supply, focusing on mathematical redistribution of flows in the network, but the analysis was model-based and did not include adaptive real-time pump control. M. Bayatloo *et al.* investigated a pump operating as a turbine, taking into account polymer additives to increase energy recovery, but the emphasis was on the experimental characteristics of a separate unit without integration into the irrigation system. Against this background, this study was distinguished by the fact that energy efficiency was achieved through systematic optimisation of pressure and water supply in a branched network without the use of additional energy-generating circuits. In the context of operational planning and agro-energy, M. Dini *et al.* (2022) and T.A. Jensen *et al.* (2025) analysed the management aspects of energy use. M. Dini *et al.* optimised pump schedules in water distribution systems to increase hydraulic efficiency, but the study focused on time planning without taking into account sensor-based monitoring of field conditions. T.A. Jensen *et al.* summarised approaches to increasing the energy efficiency of agricultural operations, focusing on technology and management, but without detailing hydraulic irrigation regimes. In this study, the combination of optimised pump regimes with spatially detailed data allowed directly linking energy consumption to actual irrigation needs, which was not

implemented in the above works.

From the standpoint of intelligent control and integrated energy systems, T.H. Nguyen *et al.* (2023) and T. Chanchayanon *et al.* (2024) applied modern algorithmic solutions. T.H. Nguyen *et al.* used a Neural Network Fractional-Order Proportional-Integral-Derivative Controller (NN-FOPID) to improve the performance of an independent flow metering system, but the study remained within the control of valve nodes. T. Chanchayanon *et al.* considered the integration of geothermal heat pumps in the concept of "smart cities", focusing on building energy systems. In contrast to these approaches, in this study, intelligent control algorithms were aimed at adapting the pumped water supply to changing natural conditions, which ensured the applicability of the results to irrigation systems without changing the design scheme. The results obtained showed that the combination of hydraulic mode optimisation, inverter control and intelligent control provided a systemic increase in the energy efficiency of pumped water supply by matching the pressure-flow characteristics of the network with real irrigation conditions, which differed from the local or model approaches presented in most of the analysed studies.

CONCLUSIONS

The work performed a comprehensive analysis of the energy, hydraulic, and organisational parameters of the functioning of irrigation systems in Ukraine with a focus on pumped water supply in 2023-2025. It was found that under conditions of complete dependence of irrigation on pumping stations (100%), the total electricity consumption reached 51.5 million kWh, and the specific energy intensity of pumping was 393.7 kWh/1,000 m³ with a specific energy consumption of 0.394 kWh/m³. The recorded consumption of 1,288 kWh/ha and the average pump operation duration of 9.6 h/day indicated a high level of energy load on the system, with a maximum daily energy intensity of 0.47 kWh/m³/day. Spatial analysis showed a sharp reduction in the scale of irrigation from about ~100 thousand ha in 2023 to 40.5 thousand ha in 2025, which corresponded to only 10-20% of the pre-war potential (~600 thousand ha).

Irrigation remained concentrated in 4 regions with an average load of ~10 thousand ha/region, and the area with concluded water supply contracts was ~40 thousand ha. Such concentration increased operational risks against the background of water losses of 32-35%, energy losses of at least 30%, network wear of over 75% and the share of systems without automated control of over 85%.

Optimisation of hydraulic modes using inverter pumps and modelling in EPANET ensured a transition from an operating pressure of 0.60 MPa to 0.42 MPa, a decrease in average water flow from 120 to 92 m³/h and a reduction in head losses from 19 to 11 m. This was accompanied by a decrease in pump power consumption from 56 to 39 kW and a decrease in specific energy intensity of pumping from 430 to 305 kWh/1,000 m³, which corresponded to an energy effect of 20-30% without intervention in the network design. Introduction of automated and AI-control using 24 soil moisture sensors and 18 wireless pressure sensors provided an increase in the frequency of irrigation mode corrections from 1 to 6 times/day. This allowed reducing water supply on rainy days by 35%, reducing seasonal energy consumption from 210 to 150 MWh and detecting 6 hidden pipeline leaks per season. The limitations of the study include the lack of a complete set of operational data for 2024, which limited the possibility of continuous interannual interpretation of the results obtained. Further research should be focused on expanding the functionality of intelligent control, integrating predictive water consumption models and assessing the long-term impact of automation on the reliability and resource of pumping equipment.

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Підвищення енергоефективності дощувальних систем зрошення шляхом оптимізації гідравлічних режимів і параметрів насосного обладнання

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Анотація. Метою дослідження було визначити енергетичний ефект адаптивного регулювання режимів подачі води та керування насосним обладнанням у процесі зрошення. У дослідженні застосовували аналітичний і балансний методи, інструментальні вимірювання тиску, витрат і електроспоживання. Енергетичні витрати на зрошення залишалися (1 288 кВт·год/га) за середньої тривалості роботи насосів 9,6 год/добу, що вказувало на повну залежність систем від насосної подачі (100 %). Просторові масштаби зрошення істотно скоротилися – до близько 100 тис. га у 2023 році та 40,5 тис. га у 2025 році, що відповідало лише 10-20 % довоєнного потенціалу (приблизно 600 тис. га). Такий стан супроводжувався втратами води (32-35 %), енергії (не менше 30 %) і критичним зношенням мереж (понад 75 %). Оптимізація гідравлічних режимів забезпечила суттєве зниження навантаження на систему, що проявилось у скороченні робочого тиску з 0,60 до 0,42 МПа, зменшенні споживаної потужності насосів з 56 до 39 кВт та зниженні питомої енергоємності перекачування з 430 до 305 кВт·год/1 000 м³. Упровадження автоматизованого керування із використанням сенсорної мережі (датчики вологості та тиску) підвищило адаптивність зрошення, збільшивши частоту корекцій поливу з 1 до 6 разів/добу. Це дозволило зменшити подачу води у дощові періоди на 35 %, скоротити сезонне енергоспоживання з 210 до 150 МВт·год та виявити 6 прихованих витоків, що в сукупності підтвердило ефективність переходу до керованих енергоощадних режимів експлуатації. Практична цінність дослідження полягає в можливості його використання водогосподарськими організаціями, агропідприємствами та проектувальниками меліоративних систем для зниження енергоспоживання, оптимізації режимів зрошення й підвищення ефективності експлуатації існуючої інфраструктури

Ключові слова: датчики вологості; витрати води; зменшення втрат; корекції поливу; зношення мереж