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Assessment of the energy and overall efficiency of the closed irrigation network of irrigation systems on the basis of the complex of resource-saving measures

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Abstract: The presence of water, food and energy crises, both at the global and regional levels, as well as their deterioration under conditions of climate change, with an insufficient level of technical condition of existing irrigation systems, increase the strategic importance of irrigation as the guarantor of the agricultural sector sustainable development.

This makes it necessary to increase, foremost, energy and overall (technical, technological, economic, and environmental) efficiency of the closed irrigation network of irrigation systems. In this regard, the complex that includes organisational-technological, technical, and resource-saving groups of measures was developed. Estimation of energy and overall efficiency of the closed irrigation network of irrigation systems at the implementation of developed complex were executed on the example of the agricultural enterprise located in the Petropavlovsk district of the Dnipropetrovsk region of Ukraine. For this purpose, machine experiment based on a use of the set of optimisation, forecasting and simulation models was implemented, including the model of climatic conditions, the model of water regime and water regulation technologies, as well as the model of crop yields on reclaimed lands.

According to the obtained results, established that implementation of the complex reduces the consumption of irrigation water by 2.2–30.7% and electricity consumption by 12.9–38.2%. The rate of specific costs decreases from 1.6 to 1.32–1.47, and the coefficient of environmental reliability increases by 5.6–16.7%. At the same time, the profitability index increases from 1.07 to 1.75–2.57, and the discounted payback period decreases from 18 to 8–5 years.

Keywords: assessment, closed irrigation network, closed irrigation system, complex of resource-saving measures, energy efficiency, overall efficiency

INTRODUCTION

The predominant part of Ukraine's territory is located in the zone, which is characterised by an insufficient level of natural moisture. For the period from 1990 to 2010 the total area of arid and very arid zones, where sustainable agriculture is impossible without irrigation, increased by eight mil ha. At the same time, less than 500 thous. ha have actually been irrigated recently, which is less than 20% of the available agricultural land. According to the adopted Strategy of irrigation and drainage in Ukraine for the period up to 2030, energy efficiency issues are crucial for the adoption of the direction of modernisation of existing irrigation systems [KMU 2020].

More than 700 pumping stations (PS) operate on closed irrigation systems (CIS) of Ukraine, which consume 500 mln kWh of electricity per y to ensure the process of water pumping.

Thus, about 220 PS operate alone on the on-farm closed irrigation network (CIN) of the Kakhovka irrigation system, which annually pumps 800–1040 mln m^3 of water and consumes 280–360 mln kWh of electricity. Under the conditions of long-term operation of irrigation systems, their technical condition has significantly deteriorated, the specific consumption of electricity for water pumping has increased, and the widely used manual control of water supply became outdated and does not meet modern requirements for the efficiency of irrigated agriculture.

The presence of water, food, and energy crises, both at the global and regional levels, as well as their deterioration under conditions of climate change, increase the strategic importance of irrigation as the guarantor of sustainable development of the agricultural sector of the country's economy [Kovalenko *et al.* 2019; Martyn *et al.* 2020; Openko *et al.* 2022; Shevchenko *et al.* 2017; Valipour 2017; van Maanen *et al.* 2021].

The integral part of the CIS functioning and in particular of the CIN, as one of the most important elements of the CIS, is the need to improve their energy efficiency [Dehtiar *et al.* 2019]. Traditionally, this is carried out through the implementation of organisational and technical measures for energy saving, primarily for the PS, as well as for individual technical elements of the CIN, or based on the results of their energy audit.

Significant factors influencing the energy efficiency of the CIN operation are changes in design modes of operation due to an increase in the number of water users who, under market conditions, prefer crops with the same irrigation time, as well as changes in climatic conditions [Kovalenko *et al.* 2021; Rokochynskiy *et al.* 2020b]. This leads to an increase in the water demand for cultivated crops [Rokochynskiy *et al.* 2020c], and to the associated additional spending on irrigation water and energy resources, which increases the overall burden on the CIS [Rokochynskiy *et al.* 2020a].

Based on the design characteristics of the existing CIS and the conditions for their operation, such systems have a decrease in energy efficiency and irrigation water use efficiency, violations of optimal irrigation regimes, and a decrease in crop yields [Openko *et al.* 2017; Rokochynskiy *et al.* 2021a].

In accordance with the National energy efficiency action plan, for the period up to 2020, the goal was to reduce energy spending by 9% compared to the base period of 2005–2009 [KMU 2015].

Thus, the urgent and important task today is to increase energy efficiency and the overall efficiency of the CIN of the CIS in compliance with modern environmental and economic requirements [Clark (ed.) 2009; Greaves, Wang 2017; KMU 2020; Lankford 2006; Moreno *et al.* 2010; Openko *et al.* 2020; Rodriguez-Diaz *et al.* 2009; Tarjuelo *et al.* 2015]. In this regard, a complex of resource-saving measures was developed and proposed, aimed at improving the efficiency of the use of energy, water, and other resources in the CIS [Gerasimov *et al.* 2020].

Conventionally, these measures are divided into three groups, which include:

1) group of organisational and technological measures:
   – change in the direction and content of economic activities of land users (introduction of new varieties of agricultural crops, improvement of the structure of sowing crops and technologies for their growing on irrigated lands);
   – the use of low-pressure sprinkling equipment, in particular, circular-action equipment with automated irrigation of field corners, which increases the coefficient of agricultural use of irrigated lands;
   – complex automation of the CIS work;
2) group of technical measures:
   – reduction of pressure losses on the suction line of the PS;
   – optimisation of the parameters of the main pipeline and the distribution pipeline network of the PS to reduce the design pressure of the PS;
   – retrofitting of the PS with thruster speed controllers of pumping units to ensure a smooth start and stop of pumping and power equipment, reduce the number of accidents and extend the life of the equipment;
3) group of resource-saving measures:
   – reduction of unproductive use of irrigation water (bursts in pipelines, spending for replenishing the volume of water in the CIN by installing the necessary safety pipeline valves and substantiating energy-efficient modes of operation of the CIN;
   – reduction of pressure losses on the suction line of the PS (optimisation of the water intake process, improvement of the waste-retaining devices of the water intake structure, etc.);
   – substantiation of resource-saving modes of operation of the system PS – CIS – sprinkling machine (SM).

The above list of comprehensive measures to improve the energy efficiency of the CIS is not exhaustive, it depends on the design features of the system and can be changed or supplemented in each specific case.

The above measures can only be conditionally divided into three groups since the implementation of some of them has resulted in several groups at once. So, for example, the use of low-pressure sprinkling equipment not only reduces the design pressure of the PS but also increases the reliability of the existing pipeline network due to the reduction of pressure in the pipelines both during stationary operation of the CIS and during dynamic processes (start-stops of the PS and SM, the formation of hydraulic shock, etc.).

The purpose of this work is a comparative assessment of the energy and overall efficiency of the CIN based on the complex of resource-saving measures for organisational, technological, technical, and resource-saving improvement of the CIS.

MATERIALS AND METHODS

To determine the overall technological (resource), economic, environmental, and investment efficiency of the proposed complex of measures, the necessary materials were used in full regarding relevant indicators and their parameters characterising of technical condition and operating conditions of the object under study before and after its modernisation and reconstruction.

This assessment was carried out on the basis of a computer experiment based on the use of the set of optimisation, economic-mathematical, and predictive-simulation methods and models, including the model of climatic conditions of the area, the model of water regime and water regulation technologies, as well as the model of the yield of crops grown on reclaimed lands, for predictive assessment on the long-term basis of indicators and parameters of technological (resource), economic, environmental and investment efficiency of object's functioning [Frolenkova *et al.* 2007; 2020; Rokochynskiy 2010; Rokochynskiy *et al.* 2021b].

These models, their methodological and information support for computer implementation were developed in the research laboratory "Optimisation and automation of control in water engineering and water technologies" (Ukr.: Optymizatsiia ta avtomatyzatsiia upravlinnia u vodnii inzhenerii ta vodnykh tekhnolohiiakh) at the Department of Water Engineering and Water Technologies of the National University of Water and Environmental Engineering (Ukr.: Kafedra vodnoi inzhenerii ta vodnykh tekhnolohii Natsionalnoho universytetu vodnoho hospodarstva ta pryrodokorystuvannia), Rivne, Ukraine. Their use is regulated by the relevant industry standards of the State Agency for Water Resources of Ukraine (Ukr.: Derzhavne ahenstvo vodnykh resursiv Ukrainy), Kyiv, Ukraine [DBN 2000; ROKOCHYNSKIY *et al.* 2010].

The object of research for implementation of machine experiment is the agricultural enterprise located in the Petropavlovsk district of the Dnipropetrovsk region of Ukraine, with the area of irrigated land of 614.7 ha (Fig. 1).

The main fund of the soil cover consists of ordinary chernozems with different depths of the humus layer and granulometric composition (from light loamy to light clayey soils). The level of groundwater in the floodplains does not exceed the depth of 3–4 m; in the watersheds, groundwater is at the depth of 20–30 m and does not take part in soil formation.

The main direction of economic activity of the agricultural enterprise is the cultivation of grain, including high-quality food grain, industrial and vegetable crops. According to production data, as of 2017, the average yield of winter wheat at the object was 3400 kg·ha^{-1}, winter barley – 2350 kg·ha^{-1}, winter rapeseed – 2430 kg·ha^{-1}, spring barley – 1850 kg·ha^{-1}, corn – 3000 kg·ha^{-1} and sunflower – 1700 kg·ha^{-1}.

For water supply to the system, the pumping station (PS) has equipped four pumps with a nominal speed of rotation of 1450 turns per min and a diameter of the impeller of 425 mm. Irrigation of cultivated crops is carried out by sprinkling with the use of sprinkling machines DMF (Ukr.: doshchuvalna mashyna fermena – truss sprinkling machine) "Frehat" with frame structure.

The main goal is the design of technical and technological complex of measures that on the same irrigated area, will increase the level of resource and energy effectiveness.

The following complex organisational, technological, and technical measures for the modernisation and reconstruction of the research object are envisaged for implementation:

- replacement of sprinkling machines "Frehat" of the DMU (Ukr.: doshchuvalna mashyna unifikovana – unified sprinkling machine) series, which are selected according to the configuration of the existing distribution network, modifications DMU-A362-50, DMU-B409-80, and DMU-B463-90 – before the reconstruction of the system, for modification DMU-Anm337-30-01, DMU-Bnm409-57-01, and DMU-Bnm463-57 – after reconstruction;
- installation of the new design filter (cone filter) on the suction pipeline of the PS to reduce pressure losses and increase its service life [GERASIMOV *et al.* 2015a];
- installation of thyristor speed controllers of pumping units to automate the operation of the PS, justification of energy-efficient modes of its operation;
- introduction of integrated automation operation of the system PS – distribution network – sprinkling machine (SM) [GERASIMOV *et al.* 2006];
- substantiation of parameters and retrofitting of the closed irrigation network (CIN) with new design means to prevent the formation of hydraulic shock [GERASIMOV *et al.* 2001a; GERASIMOV *et al.* 2001b; GERASIMOV *et al.* 2015b; GERASIMOV *et al.* 2015c];
- reduction of unproductive losses of irrigation water in case of accidents on the main and distribution pipelines, as well as spending of filling or replenishing the network due to ruptures and damage.

Thus, the proposed complex of measures increases the energy and resource effectiveness of the CIN on each of the

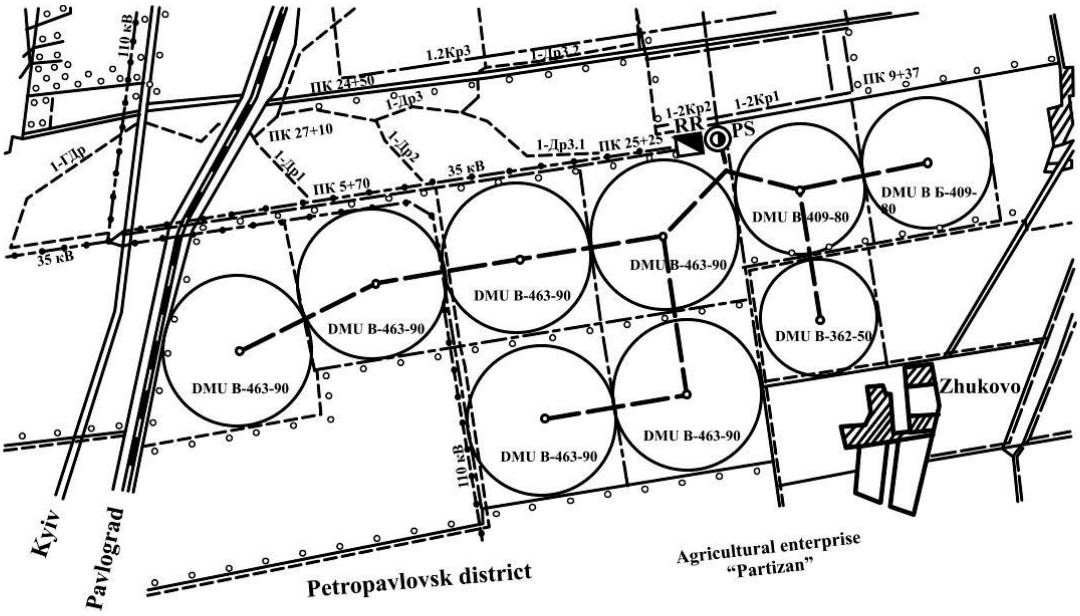

Fig. 1. Scheme of irrigation system's site on lands of the agricultural enterprise of the Petropavlovsk district of the Dnipropetrovsk region of Ukraine; source: Regional office of water resources in Dnipropetrovsk region (Ukr.: Rehionalnyi ofis vodnykh resursiv u Dnipropetrovskii oblasti)

technical and technological levels of CIN operating with the goals of minimising costs and unproductive water losses, by reducing pressure and pressure loss, respectively, reducing electricity costs.

According to the researchers [FROLENKOVA *et al.* 2007; 2020; ROKOCHYNSKIY *et al.* 2021b; STASHUK *et al.* (eds.) 2020; TURCHENIUK, ROKOCHYNSKIY 2020], comparative assessment of the effectiveness of project option (PO) for modernisation and reconstruction of water management and reclamation facilities based on the complex of diverse resource-saving measures by assessing the overall technical, technological (resource), economic and environmental efficiency of its functioning can be performed according to such complex optimisation model:

$$\begin{cases} ZP^0 = \min\limits_{\{i\}} \sum_{p=1}^{n_p} \frac{\left[\left(C_{pi}+E_n K_i\right)+R_{pi}\right]\alpha_p}{W_{pi}}; i=\overline{1,n_i}; \\ R_j^0 = \min\limits_{\{i\}} \sum_{p=1}^{n_p} \left|R_{jpi} - \hat{R}_j\right|\alpha_p;\ j=\overline{1,n_j};\ i=\overline{1,n_i} \end{cases} \quad (1)$$

where: ZP^0 = minimum value of the indicator of reduced costs according to the accepted condition of the selected criterion of economic optimality, which corresponds to the optimal PO from the totality of possible options $I = \{i\}$, $i=\overline{1,n_i}$, C_{pi} = current costs for obtaining cultivated agricultural products according to the PO, including agricultural costs C^a, reclamation costs C^r, and irrigation water costs C^{iw}, E_n = normative coefficient of economic efficiency of capital investments K_i for the PO relevant options, R_{pi} = weather and climate risk according to the relevant PO, a_p = known (set or specified) values of frequency or proportions of typical meteorological regimes possible state in the estimated periods of vegetation of the totality $\{p\}$, $p=\overline{1,n_p}$, within the design period of the facility operation $\sum_{p=1}^{n_p} \alpha_p = 1$; W_{pi} = volume (cost) of agricultural products received according to the relevant options for regime, technological and technical solutions of the totality $\{i\}$, $i=\overline{1,n_i}$; $R^0{}_j$ = minimum values of actual volumes deviations of physical indicators of used resources R_{jpi} of the totality $\{j\}$, $j=\overline{1,n_j}$, in relation to their corresponding scientifically substantiated (rational) values $\hat{R}_j$.

According to the researchers [STASHUK *et al.* (eds.) 2016; 2020; TURCHENIUK, ROKOCHYNSKIY 2020], the assessment of environmental efficiency of the proposed complex of resource-saving measures implementation is carried out on the basis of calculating the environmental reliability coefficient (k_{er}) of the closed irrigation system (CIS) operation based on the totality of relevant physical indicators of environmental efficiency (indicators of water regime, salt regime and productivity of irrigated lands).

Such a coefficient gives an approximate assessment of the environmental sustainability of the project and the degree of consideration of environmental reliability factors of its operation, primarily from the point of view of maintaining favourable natural and reclamation soil regimes within the project period. The environmentally optimal variant of the PO is one for which the condition is met, and that the coefficient of environmental reliability is in the range of 0.5 to 1.0.

Forecast calculations to determine the overall technological (resource), economic, environmental, and investment efficiency of proposed complex measures were performed according to the following initial conditions: region – Dnepropetrovsk (Ukraine); natural-climatic zone – steppe; vegetation periods calculated according to conditions of heat and moisture supply: very wet – p = 10%, wet – p = 30%, medium – p = 50%, dry – p = 70%, very dry – p = 10%; calculated parameters of main meteorological characteristics of vegetation period from April to October: total precipitation – 293 mm; average air temperature – 17.4°C; average relative humidity – 63%; sum of air humidity deficit – 1247 mm; soils: ordinary chernozems, light loams and light clays predominate in granulometric composition.

As main options for the study were considered options for the object operation before and after reconstruction, including taking into account possible changes in the direction and content of the economic activity of land users:
– B1 – the cultivation of the set of agricultural crops (winter wheat with the share of sown area of 0.25; winter barley – 0.20; winter rapeseed – 0.05; spring barley – 0.10; corn – 0.15; sunflower – 0.25) before the system reconstruction;
– B2 – the cultivation of the set of agricultural crops (winter wheat – 0.25; corn – 0.25; soybeans – 0.25; sunflower – 0.25) after the system reconstruction;
– B3 – the cultivation of winter wheat monoculture after the system reconstruction;
– B4 – the cultivation of corn monoculture after the system reconstruction;
– B5 – the cultivation of soybean monoculture after the system reconstruction;
– B6 – the cultivation of sunflower monoculture after the system reconstruction.

RESULTS AND DISCUSSION

The important issue in evaluating the effectiveness of the closed irrigation system (CIS) operation is the choice and justification of criteria that would be the set of indicators that reflect versatile aspects of such objects operation. In this regard, we performed multi-criteria regression analysis, which allows us to establish the degree of relationship closeness between studied indicators and exclude those that have the smallest share of influence, thereby confirming the feasibility of using certain indicators as criteria for assessing the effectiveness of the CIS operation.

The final results of performed multi-criteria regression analysis are presented in tabular form (Tab. 1) as the list of indicators of technological (resource), economic and environmental efficiency of the CIS operation and their pair correlation coefficients.

According to the presented data, it was revealed that the closest relationship in terms of pair correlation coefficients value takes place between water consumption for irrigation ($m^3 \cdot ha^{-1}$) and electricity consumption for its pumping ($kWh \cdot ha^{-1}$) – 0.92; cost of electricity for water pumping ($USD \cdot ha^{-1}$) and cost of water for irrigation ($USD \cdot ha^{-1}$) – 0.98; net profit ($USD \cdot ha^{-1}$) and total capital investments ($USD \cdot ha^{-1}$), current costs ($USD \cdot ha^{-1}$), as well as the cost of gross production ($USD \cdot ha^{-1}$) – 0.93, 0.93 and 0.94, respectively.

The main generalised results of technological, economic, and investment indicators and parameters of the object operation before and after reconstruction according to relevant options are presented in Figure 2 and Tables 2–5.

The investment evaluation of the optimal PO is performed by the main indicators used in the calculation of investment attractiveness of land reclamation project: net present value

Table 1. Matrix of pair correlation coefficients between indicators of the closed irrigation systems operation effectiveness (R = 0.91)

Indicators	Water consumption for irrigation ($m^3 \cdot ha^{-1}$)	Cost of water for irrigation ($USD \cdot ha^{-1}$)	Electricity consumption for water pumping ($kWh \cdot ha^{-1}$)	Cost of electricity for water pumping	Total capital investments	Current costs	Cost of gross production	Net profit	Coefficient of environmental reliability
				USD·ha^{-1}					
Water consumption for irrigation ($m^3 \cdot ha^{-1}$)	1.00	0.33	0.92	0.45	–0.64	–0.82	–0.82	–0.75	–0.34
Cost of water for irrigation ($USD \cdot ha^{-1}$)	0.33	1.00	0.44	0.98	–0.64	–0.52	–0.62	–0.39	–0.60
Electricity consumption for water pumping ($kWh \cdot ha^{-1}$)	0.92	0.44	1.00	0.58	–0.69	–0.78	–0.81	–0.77	–0.43
Cost of electricity for water pumping ($USD \cdot ha^{-1}$)	0.45	0.98	0.58	1.00	–0.78	–0.65	–0.75	–0.56	–0.69
Total capital investments ($USD \cdot ha^{-1}$)	–0.64	–0.64	–0.69	–0.78	1.00	0.87	0.93	0.93	0.76
Current costs ($USD \cdot ha^{-1}$)	–0.82	–0.52	–0.78	–0.65	0.87	1.00	0.97	0.93	0.76
Cost of gross production ($USD \cdot ha^{-1}$)	–0.82	–0.52	–0.81	–0.75	0.93	0.97	1.00	0.94	0.73
Net profit ($USD \cdot ha^{-1}$)	–0.78	–0.39	–0.77	–0.57	0.93	0.93	0.94	1.00	0.68
Coefficient of environmental reliability	–0.34	–0.60	–0.42	–0.68	0.76	0.76	0.73	0.68	1.00

Source: own study.

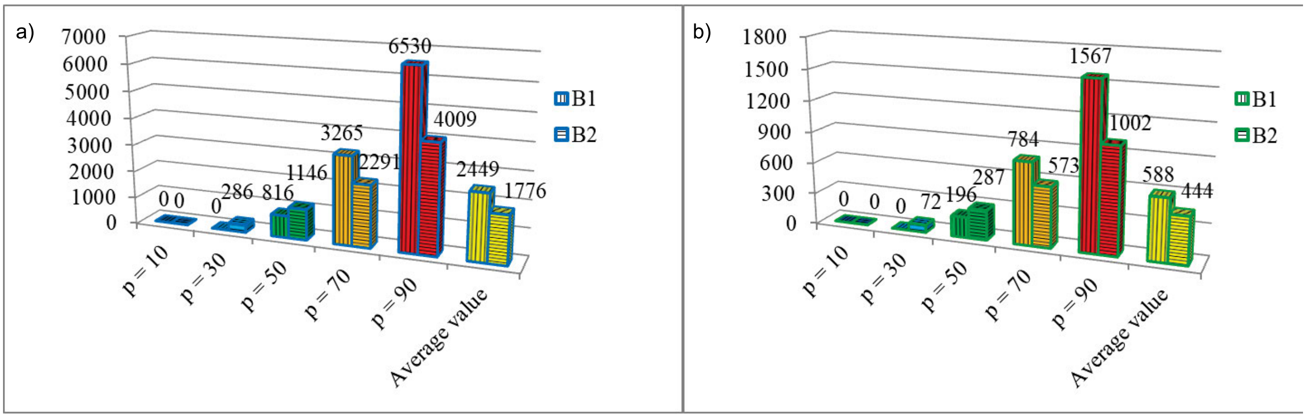

Fig. 2. Water consumption for irrigation – $m^3 \cdot ha^{-1}$ (a) and electricity consumption – $kWh \cdot ha^{-1}$ (b) for its pumping on the example of corn irrigation as the most water- and energy-intensive crop according to study options; B1 = before the system reconstruction, B2 = after the system reconstruction; source: own study

(NPV), profitability index (PI), discounted payback period (DPP) internal rate of return (IRR) of investments [Frolenkova *et al.* 2007; 2020; Kovalenko *et al.* 2021; Rokochynskiy *et al.* 2021b].

In this case, must be satisfied the condition that,

$$\begin{cases} NPV_i \geq 0 \\ IRR_i \geq d_i \\ DPP_i \leq T \end{cases} \tag{2}$$

where: d_i = discount rate for the project; T = discounted investment payback period acceptable for the investor.

Thus, the introduction of the complex of interrelated resource-saving measures in natural-agro-meliorative conditions of the real object according to considered options provides a reduction of irrigation water consumption from 2.2 to 30.7% and electricity consumption from 12.9 to 38.2%. The rate of specific costs decreases from 1.6 to 1.32–1.47, and the coefficient of environmental reliability increases by 5.6–16.7%. At the same time, the profitability index increases from 1.07 to 1.75–2.57, and the discounted payback period decreases from 18 to 8–5 years.

It should be noted that since not all possible factors that form the overall efficiency are taken into account when performing forecasting and optimisation calculations, and the results obtained from them are of pronounced relative nature, the final decision on choosing the best project option remains with investors or the customer farmers.

Table 2. Indicators of technological (resource) efficiency by research options

Estimated vegetation periods (p, %)	Indicators of technological (resource) efficiency by research options											
	B1		B2		B3		B4		B5		B6	
	water consumption for irrigation ($m^3 \cdot ha^{-1}$)	electricity consumption for water pumping ($kWh \cdot ha^{-1}$)	water consumption for irrigation ($m^3 \cdot ha^{-1}$)	electricity consumption for water pumping ($kWh \cdot ha^{-1}$)	water consumption for irrigation ($m^3 \cdot ha^{-1}$)	electricity consumption for water pumping ($kWh \cdot ha^{-1}$)	water consumption for irrigation ($m^3 \cdot ha^{-1}$)	electricity consumption for water pumping ($kWh \cdot ha^{-1}$)	water consumption for irrigation ($m^3 \cdot ha^{-1}$)	electricity consumption for water pumping ($kWh \cdot ha^{-1}$)	water consumption for irrigation ($m^3 \cdot ha^{-1}$)	electricity consumption for water pumping ($kWh \cdot ha^{-1}$)
10	–	–	–	–	–	–	–	–	–	–	–	–
30	–	–	243	61	573	143	286	72	–	–	–	–
50	816	228	888	222	859	215	1146	287	859	215	528	132
70	2531	709	1947	487	1718	430	2291	573	2004	501	1718	430
90	4490	1257	3107	777	2291	573	4009	1002	3150	788	3150	788
Average weighted value	1820	510	1432	358	1260	315	1776	444	1403	351	1248	312

Explanations: B1, B2, B3, B4, B5, B6 as p. 18
Source: own study.

Table 3. Indicators of economic and environmental efficiency by research options

Economic and environmental efficiency	Research options					
	before reconstruction	after reconstruction				
	residual book value of the object (K_o = 95.60, $USD \cdot ha^{-1}$)	total capital investments after reconstruction (K = 1338.43, $USD \cdot ha^{-1}$)				
	B1	B2	B3	B4	B5	B6
Cost of water for irrigation ($USD \cdot ha^{-1}$)	69.60	54.75	48.18	67.91	53.66	47.74
Cost of electricity for water pumping ($USD \cdot ha^{-1}$)	48.73	34.23	30.11	42.45	33.52	29.83
Current costs ($USD \cdot ha^{-1}$)	550.89	1051.12	1137.03	1005.32	930.72	831.33
Share of water cost from current costs (%)	12.6	5.2	4.2	5.8	6.8	5.8
Share of electricity cost from current costs (%)	8.8	3.3	2.6	3.6	4.2	3.6
Cost of gross production ($USD \cdot ha^{-1}$)	552.52	1242.16	1386.81	1195.63	1227.31	1060.04
Net profit ($USD \cdot ha^{-1}$)	6.41	257.97	268.51	189.36	309.88	247.45
Specific cost indicator	1.631	1.382	1.322	1.445	1.471	1.392
Coefficient of environmental reliability	0.36	0.42	0.40	0.40	0.39	0.38

Explanations: B1, B2, B3, B4, B5, B6 as p. 18
Source: own study.

Table 4. Comparative characteristics of changes in indicators of technological (resource), economic and environmental efficiency before and after reconstruction according to relevant options

Changes in indicators of technological (resource), economic and environmental efficiency	Research options				
	B2	B3	B4	B5	B6
Reducing of water consumption after reconstruction (%)	21.3	30.8	2.2	22.9	30.7
Reducing of electricity consumption after reconstruction (%)	29.8	38.2	12.9	31.2	38.2
Increase of current costs (UAH·ha^{-1})	500.22	586.14	454.43	379.83	280.43
Reducing of water cost share from current costs (%)	58.7	66.7	54.0	46.0	54.0
Reducing of electricity cost share from current costs (%)	62.5	70.5	59.1	52.3	59.1
Increase of cost of gross production (USD·ha^{-1})	689.64	834.29	643.12	674.79	507.52
Increase of net profit (USD·ha^{-1})	251.56	262.11	182.95	303.47	241.05
Increase of coefficient of environmental reliability (%)	16.7	11.1	11.1	8.3	5.6

Explanations: B2, B3, B4, B5, B6 as p. 18
Source: own study.

Table 5. Indicators of investment efficiency by research options

Indicators of investment efficiency	Research options					
	B1	B2	B3	B4	B5	B6
Profitability index	1.07	2.22	2.29	1.75	2.57	2.14
Net discounted value (USD·ha^{-1})	115.30	1627.34	1723.71	1000.86	2101.08	1531.26
Discounted payback period (y)	18	6	6	8	5	6

Explanations: B1, B2, B3, B4, B5, B6 as p. 18
Source: own study.

CONCLUSIONS

The results of research on improving the energy efficiency of the closed irrigation network (CIN) of the closed irrigation system (CIS) on the basis of interrelated resource-saving measures for their technical, technological, and resource-saving improvement convincingly indicate that, firstly, energy efficiency parameters decisively depend, foremost, on the amount and efficiency of the use of irrigation water, design, technological and regime parameters of the pressure pipeline network, as well as multiple variables of natural-agro-reclamation conditions of the real object operation.

Secondly, the modernisation and reconstruction of existing irrigation systems with sprinkling irrigation in the steppe zone of Ukraine based on the implementation of the complex of resource-saving measures across the entire spectrum of organisational, technical, regime-technological, and resource-saving solutions ensure the energy-efficient use of irrigation water and electricity, increase the economic and environmental efficiency of irrigated land use, as well as investment attractiveness of irrigation generally and in variable modern conditions.

Our proposed solutions and obtained results correspond to the existing concepts and strategies of irrigation development in Ukraine and are aimed at achieving these goals, namely improving energy efficiency and the overall efficiency of irrigation systems.

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