UDC 622.271.4 DOI: https://doi.org/10.15407/geotm2022.163.033

COMPARATIVE ASSESSMENT OF ENERGY GENERATING TECHNOLOGIES BY THE PRINCIPLE OF FULL ENVIRONMENTAL RESOURCE INTENSITY

Kopach P.I., Yakubenko L.V., Mormul T.M., Danko T.T., Gorobets N.V., Halchenko Z.S.

Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine

Abstract. The proposed comparative assessment of energy generating technologies is executed according to a methodology of an assessment of technologies of nature management of full environmental resource intensity. The methodology is based on the application of the first developed integrated indicator of environmental impact. It is proved that reduction to this integrated indicator of all indicators of quality of environmental components according to the degree of their damage with taking into account the cost expenses provide almost complete restoration of natural components. The assessment of nature management technologies is carried out, which is based on the use of the methodology of full environmental resource intensity. The proposed methodology makes it possible to track changes in the consumption, damage and removal of natural resources. The problem of technology assessment and ways to solve it are considered. The scheme of calculation of the integrated indicator of ecological impact is developed. Indicator influence on the components of the environment is determined. The coefficients of reduction to the critical indicator according to the degree of damage of the natural component (earth, water, atmospheric air) are derived. The formulas of reduction to critical indicators for the components of the environment are derived. The system-forming component of the natural-technogenic system is determined. The calculation of the coefficients for reducing the indicators of the state of the environmental components to a single integral value is made. It is proved that the integrated indicator of environmental impact is a characteristic indicator, which in a single value form reproduces the man-made impacts on all natural components allowing to achieve significant efficiency in making optimal management decisions. The methodology for assessing environmental technologies was tested at major energy generating enterprises, which referred to the main environmentally cost-intensive areas of economy. A comparative assessment of energy generating technologies was performed on the example of hydroelectric power plant and thermal power plant (based on the indicators of Burshtyn thermal power plant and Kakhovka hydroelectric power plant). It is proved by calculation that the indicator of integrated ecological impact of a thermal power plant is technologically 32.3 times better than the indicator of integrated ecological impact of a hydroelectric power plant.

Keywords: integral ecological resources, energy-generating technologies, ecologically costly technologies of nature management.

1. Introduction

In modern conditions, life dictates new guidelines and directions for the development of industrial enterprises, which becomes an impetus for the introduction of new technological solutions and new trends in the interaction of production and nature. But it is possible to achieve this only if a system and mechanisms for managing ecological processes are built, if the management is focused not only on the improvement of technologies, but, first of all, on the greening of production.

There is a necessity to create a methodology for evaluating various economic spheres according to the indicator of ecological cost, taking into account energy and economic optimality, which should contribute to their further development.

One of the important stages of the study of natural and man-made systems is the research and assessment of technologies as objects affecting the natural environment of the territory. Considerable attention is devoted to this aspect in our research [1–5].

The problem of technology assessment and ways to solve it. Scientific and technical development, as well as solving structural issues that have not been solved for a long time, are possible only if a breakthrough is made in creating a system of technological innovations harmonized with the environment, where production is chosen as the basis. Based on this, we consider it is necessary to create a methodology for assessing various spheres of economy according to the indicator of environmental resource intensity with taking into account energy and economic optimality.

The ecological efficiency of nature management characterizes the relationship between the size of natural resource costs and the value of the useful product obtained as a result of these costs. The need to use an ecological criterion when making management decisions related to the ecological optimization of nature management needs to be considered in more detail. It is natural that the technical criteria most fully reflect engineering and technological features and the specifics of technological systems; economic criteria take into account only the actual efficiency that can be represented in value terms, while many environmental aspects are left out of consideration; social criteria consider only the status of technological processes in the context of meeting certain public needs; legal criteria correlate the process of functioning of the technology with the system of existing legislation; the existing ecological criteria (land intensity, specific emissions, volumes of discharges, etc.) also reflect only a separate, narrowly selected aspect and cannot be used for ecological optimization in the context of sustainable development. Therefore, it is obvious that there is a need to develop and introduce a new criterion that allows us to evaluate in a generalized form the ecological consequences of the functioning of one or another nature management technology. The main principle of developing such an aggregate criterion is the accounting of all resources involved in the production process (labor, material, energy, natural, which are used in this production both directly and indirectly) with their subsequent conversion to natural resources.

The general structure of the environmental assessment of production technology includes the following directions: assessment of technology (technological uniqueness according to existing analogues in the world, including the best available technologies; environmental friendliness of production methods, technical means, technological parameters of the main redistributions, product safety, safety of waste use and storage); compliance with existing standards (technologies of raw material extraction, use of territory, resources, emissions and discharges, sanitary and hygienic standards); compliance with restrictions and tolerances; determination of exceeding standards; establishing the degree of environmental danger (risk).

The process of resource consumption during the functioning of any enterprise is generally characterized by full resource intensity, which includes the total amount of resources used to produce a unit of production.

The criterion for evaluating the efficiency of economic activity is the end-to-end full resource intensity of a specific type of activity, reduced to natural resources, and we refer to it as "integral environmental resource intensity", which takes into account both direct and indirect resource costs (equipment, buildings, structures, social infrastructure, etc.).

The assessment of nature management technologies is based on the application of the methodology of full environmental resource intensity. The proposed methodology makes it possible to monitor changes in consumption, damage and extraction of natural resources.

The degree of environmental impact of the technologies of business entities is determined by a certain list of quantitative and qualitative indicators that act as criteria for assessing the functioning of an industrial enterprise. This is the basis for using a complex and systematic approach to the formation of a system of indicators.

The ecological assessment of technologies is carried out for the ecological justification of the selected production method and technologies, taking into account all of the ecological consequences of this technology. In a comprehensive environmental assessment of technologies, the degree of environmental friendliness of production methods and technological changes is determined, the exits of the technology into the natural environment are assessed, the environmental hazard of the obtained products, their use and storage is assessed, and the hazard of storage and use of the generated waste is assessed.

Approaches to the assessment of production, taking into account environmental aspects, determine the need to clarify the system of the following principles: systematicity, complexity, periodicity, specificity, scientific content, effectiveness, objectivity, efficiency. The use of these principles makes it possible to evaluate and take into account the ecological and social consequences of the "enterprise-environment" relationship, to form a system of ecological and economic indicators of a modern enterprise.

To justify the indicator of the effectiveness of environmental protection technologies, in the conditions of open technological systems, for example, mining productions, energy-generating enterprises, etc., it is necessary to develop a methodology that would allow, due to the use of special assessment criteria, to obtain unambiguous numerical values of assessment indicators that are maximally adequate for real ecological and technological processes.

For these purposes, the method of environmental assessments is most suitable. We have developed a system of environmental assessments using the criterion of integrated environmental resource intensity.

The calculation of the integral indicator of environmental impact implements the process of reducing the indicators of various components of the natural environment to a single integral indicator. Such reduction must be carried out on the basis of a scientifically based methodological principle based on a deep analysis of the interaction of technological processes and components of the natural environment of the territory where nature management is carried out.

The structure of technological influences shown in Figure 1 refers to the man-made component of the natural and man-made system, which is any industrial enterprise. To ensure the possibility of managing natural and man-made systems in the process of their transition to the regime of sustainable functioning, an integral indicator of ecological impact on the environment I_{IEI} is developed.

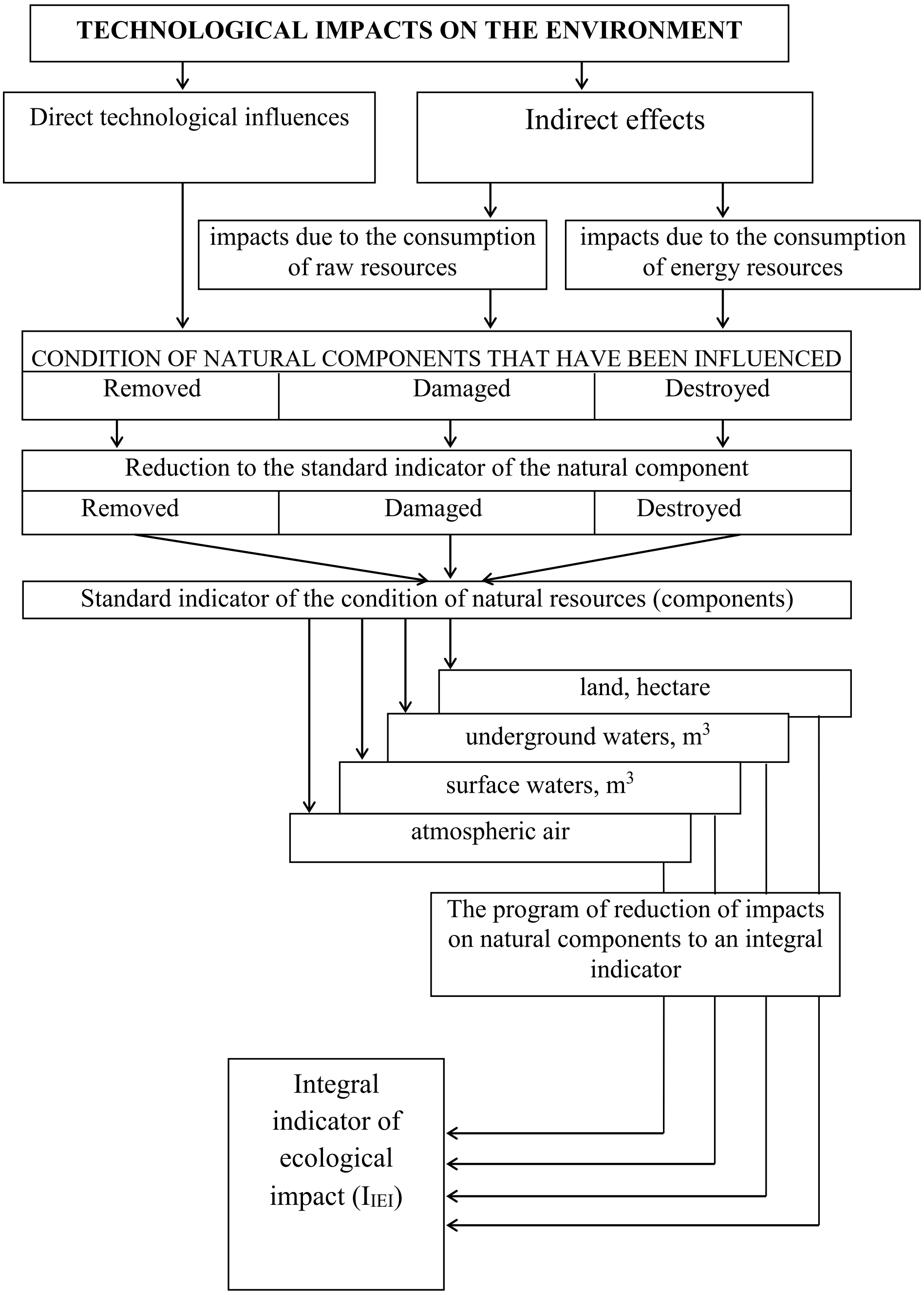

Figure 1 – Calculation scheme of the integral indicator of ecological impact

2. Methods

Basic provisions of the method of assessment of nature management technologies

Determination of indicators of influence on environmental components

Any arbitrary technology of nature management affects the components of the environment: atmosphere – A; land – Z; hydrosphere – W. Impacts on natural components differ among themselves by their intensity and character.

The atmosphere is characterized by pollution with various gaseous chemical compounds and solid (suspended) particles.

For lands – non-traditional use, mechanical damage to the fertile layer and contamination with various substances that negatively affect soil productivity.

For the hydrosphere – pollution (chemical, sanitary-toxicological, biological, etc.), damage or change in the hydrological or hydrogeological regime of the system.

The methodology assumes reducing the indicators of technogenic influence on each of the components to a single value with taking into account their ecological state (relative to pre-technogenic). To reduce to a single indicator, normalizing coefficients K_A^N, K_Z^N, K_W^N are used, and, to simplify calculations, it is proposed to systematize the degree of damage to natural components into three categories.

The state of a natural component that corresponds to the complete loss of its natural functions, i.e. its destruction, is taken as a *critical indicator* of technogenic impact. An indicator of the diametrically opposite state is the removal of a natural component from the system of traditional nature management without changes (loss) in quality state. The intermediate state of the natural component is classified as *damaged*.

The conversion coefficients given in tables 1–3 were derived and structured by the authors of this article based on the analysis of numerous literary sources, legislative and regulatory documents on nature management laws, statistical materials on various types of nature management, scientific publications by many authors, and scientific research works.

Land is considered as a natural resource, which is used in one way or another in any production technology. Therefore, the systematization of lands according to the nature of their use is carried out according to table 1:

- I category – use of land without deterioration of its quality;
- II category – damage with the possibility of restoration for traditional land use;
- III category – complete impossibility of traditional use and restoration.

Coefficients of reduction to a critical indicator by the degree of damage to land resources K_{ci}^Z are tentatively determined taking into account the energy consumption for their revitalization.

Table1 – Coefficients of reduction to the critical indicator by the degree of damage to the natural component (land)

Condition of the given components	Category by degree of damage	The coefficient of reduction to the critical indicator K_{ci}^Z
Removal	I category	0.01
Damage	II category	0.1
Destruction	III category	1.0

For discharges, the main factor that characterizes the degree of negative impact is the mineralization of the used natural waters. Therefore, the limit states for discharges are the following parameters (table 2).

The main indicator of the negative impact of production for emissions is the indicator of the relative toxicity of pollutants entering the natural environment. The determination of the coefficients of reduction to the same denominator for different pollutants is carried out taking into account the indicator of relative toxicity. The ideology of assessment requires the use of a single approach when aggregating components with different states of violation of the natural component to normalizing (critical) indicators.

Table 2 – Coefficients of reduction to the critical indicator by the degree of damage to the natural component (water)

Condition of the given components	Category by degree of damage	Mineralization of used waters	The coefficient of reduction to the critical indicator K_{ci}^{W}
Removal	I category	1.0 – 25.0	0.01
Damage	II category	25.1 – 50.0	0.1
Destruction	III category	> 50.0	1.0

We take nitrogen dioxide as a critical indicator of atmospheric air pollution, MPC_{NO_2} – 0.04 mg/m^3 (MPC – maximum permissible concentration).The 1st category of atmospheric air pollution includes pollutants of the 4th danger class, the 2nd category – substances of the 3rd danger class, the 3rd category – the 1st and 2nd danger classes. The indicator of relative toxicity of emissions is determined by the formula $K_t^I = \frac{MPC_{NO_2}}{MPC_i}$ [6]. In this case, the coefficients of relative toxicity will be correlated with the coefficients of reduction to the critical indicator (table 3).

For indicators of atmospheric air pollution, with accurate calculation, the conversion coefficients K_{ci} correspond to the relative toxicity coefficients K_t^i. For approximate calculations, it is possible to use the coefficients of reduction to the critical indicator of atmospheric air pollution (K_{ci}), given in Table 3.

Table 3 – Coefficients of reduction to the critical indicator by the degree of damage to the natural component (atmospheric air)

Condition of the given components	Category by degree of damage	Coefficient of relative toxicity of pollutants, K_t^i	The coefficient of reduction to the critical indicator K_{ci}
Removal	I category	< 0.2	0.01
Damage	II category	0.2 – 4.0	0.1
Destruction	III category	>4.0	1.0

In general, the formulas for reduction to critical indicators for environmental components will have the following form:

$$A^{cr} = (\sum A_i^I \cdot K_t^i) \cdot K_{ci}^{AI} + (\sum A_i^{II} \cdot K_t^i) \cdot K_{ci}^{AII} + (\sum A_i^{III} \cdot K_t^i) \cdot K_{ci}^{AIII}, \quad (1)$$

$$Z^{cr} = Z_I \cdot k^{ZI} + Z_{II} \cdot k^{ZII} + Z_{III} \cdot k^{ZIII}, \quad (2)$$

$$W^{cr} = W_I \cdot k^{WI} + W_{II} \cdot k^{WII} + W_{III} \cdot k^{WIII}, \quad (3)$$

where A_i^I, A_i^{II}, A_i^{III} – reduced to the critical mass of pollutant emissions, cond. t.; Z_I, Z_{II}, Z_{III} – the area of damaged land is brought to a critical level, cond. Ar; W_I, W_{II}, W_{III} – the volume of polluted waters reduced to a critical level, cond. m^3.

Determination of the system-forming component of the natural-technogenic system

The hierarchy of natural components of the territory is established by identifying the component most important for ensuring self-regulation of relationships in the natural system and its less important components. For example, for the techno-ecosystem "oasis in the desert", the system-forming component is the resources of the hydrosphere.

With taking into account the established hierarchy of natural components of the techno-ecosystem of the mining complex and the purpose of evaluating technological processes, the priority of measures and the use of resources to harmonize them with the natural environment is determined.

Let's suppose that some hypothetical enterprise functions in harmony with the natural environment. This means that its emissions do not spoil the atmospheric air in any way, its discharges are within the limits of fishery standards, the land within its land allocation is in a state that corresponds to pre-technogenic parameters, and its activity provides jobs and fills the budgets of various levels. Under such conditions, this enterprise can be considered perfectly ecologically clean and socially positive, which can serve as a reference point (unit of measurement) of the degree of achievement of an ecologically acceptable state of the environment. When assessing any other specific enterprise, it is necessary to determine the "conditional distance" that separates it from the exemplary one. Overcoming this distance is carried out through the introduction of environmental protection technologies.

Calculation of the coefficients of reducing indicators of the condition of environmental components to a single integral value

The idea and conditions for determining ideal industrial production are given above. It is noted that it can serve as a reference point (unit of measurement) of the degree of reachability of the existing production to its ecologically acceptable state (Figure 1). In the same figure, the parameter symbolizing the "conditional distance" that separates the production from the exemplary one is marked. Overcoming this distance is carried out through the introduction of environmental protection technologies. As a measure of such "distance", we will take the value of the costs C_Z, C_W, C_A, which would have be incurred by this enterprise for environmental protection measures in order to achieve the same environmentally safe state.

With taking into account the amount of these costs, on the basis of the analysis of statistical data, based on the value of the costs that must be incurred in the implementation of full rehabilitation, the coefficients of reducing the components of the environment to I_{IEI} are justified. Therefore, for the complete restoration of one hectare of destroyed and unusable land, it is necessary to spend conditional value units C_Z (cond.u). Costs for complete cleaning of polluted water discharges and reduction them to fishery quality is – C_W, cond. u. Costs for complete cleaning of emissions into the atmospheric air from dust and gas pollution are – C_A, cond. u.

Summary of pre-determined critical indicators of impact on the components of the natural environment is carried out in accordance with the assessment tasks, with taking into account the system-forming component.

When assessing technologies for which damage to land resources is the main and essential factor, the unit of area of land resources (Ar or hectare) is accepted as the unit of measurement of ecological equivalent.

The coefficients of integral reducing (ecological equivalent – land resources) are calculated according to the formulas:

$$K^A = \frac{C_A}{C_Z}, \quad K^L = \frac{C_Z}{C_Z}, \quad K^W = \frac{C_W}{C_Z}, \tag{4}$$

where K^A, K^L, K^W – coefficient of integral reducing, respectively, for the atmosphere, land and hydrosphere.

The integral indicator of environmental impact is determined by the formula:

$$I_{IEI} = A^{cr} \cdot K^A + Z^{cr} \cdot K^L + W^{cr} \cdot K^W. \tag{5}$$

Thus, the integral indicator of environmental impact is a characteristic indicator that reproduces man-made effects on all natural components in a single value form, which allows to achieve significant efficiency in making optimal management decisions.

3. Results and discussion

Comparative assessment of energy-generating technologies

A comparative assessment of various types of energy-generating technologies was performed on the example of a hydroelectric power plant and a thermal power plant. We accept the indicators of the Burshtyn TPP and the Kakhovka HPP as the initial assessed data of the impact on the environment.

The choice of Burshtyn TPP is due to the fact that it includes an isolated lake for cooling water, while at other TPPs (Zaporizhzhia, Prydniprovska) water from the Dnipro River is used for this purpose, which does not allow taking into account the volume of water used for electricity generation.

The choice of the Kakhovka HPP is due to the fact that it is a typical power plant on a flat river, which is mostly characteristic for the geographical conditions of Ukraine.

Burshtyn TPP. The capacity of Burshtyn TPP is 2334 MW, 12 power units with a capacity of 200 MW each.

According to the indicators of mineralization, TPP discharges refer to the 1st category according to the degree of damage.

In terms of tons of conventional fuel (heat of combustion of coal – 7700 kcal/kg, fuel oil – 9350 kcal/kg, natural gas – 8555 kcal/m^3), fuel consumption amounts to 329280 t.c.f. With such fuel consumption (2002), 5.8 billion kW·h of electricity were generated.

Fuel consumption at Burshtyn TPP is the annual output of a large coal mine, such as the mines of «Pokrovske» Mine Administration. Therefore, man-made effects on natural components during the production of 3.3 million t.c.f. should be considered as indirect and be taken into account during the environmental assessment of TPPs.

Parameters of the Burshtyn TPP impact on the environment

Man-made impacts of the mine on atmospheric air are: mediscountthane emissions – 70.9 thousand tons/year; sulfur anhydride – 134 t/year; carbon dioxide – 1370 t/year; solid particles – 126.6 t/year; nitrogen oxide – 43.7 t/year.

Discharges of mine waters with mineralization up to 26.0 g/dm^3 are carried out into the storage pond with an area of 83.5 hectares. During the year, the inflow of mine waters is 3.0 million m^3/year. These discharges refer to II category (damage). The coefficient of reduction to the critical indicator is $K_{ci}^{W} = 0.1$.

The production of 1 million tons of coal leads to the loss of 4 hectares of land (for the entire period of operation of the mine – 83 hectares). Regarding the amount of coal consumed by the TPP (5 million tons), 20 hectares of land are lost in the area of coal mining. These expenses refer to the III category of damage, $K_{ci}^{Z} = 1.0$.

Taking into account the impact on fuel production, the environmental impacts of the Burshtyn TPP are: for the atmosphere (in terms of NO_2 equivalent) A^{cr} – 142198.9 T (NO_2-equiv.); for land resources: ash and slag dumps (category III) – 149.74 ha; reservoir (category III) – 1260 hectares; indirect effects (coal) (category III) – 20 ha. Together, in terms of Z^{cr} (ha-equiv.) – 1436.24 ha-equiv.; for the hydrosphere: discharges into the river (Cat I) – 2110 thousand m^3; indirect discharges (Cat. I) – 3000 thousand m^3. Total, in terms of (thousand m^3-equiv.) – 51.1 thousand m^3-equiv.

Reduction of the calculated above critical indicators of the impact of the Burshtyn TPP on the natural components of the environment to the I_{IEI} indicator is carried out according to the formula (5):

$$I_{IEI} = 142198.9\text{t - equiv.} \cdot 17.3 + 143624\text{ Ar - equiv.} \cdot 1.0 +$$
$$+ 51100.0\text{m}^3\text{ - equiv.} \cdot 2.1 = 2603772.2\text{ Ar - equiv.} (\text{I}_{\text{IEI}}\text{ units}) \cdot$$

The indicator of environmental impact on the production of one million kilowatt-hours of electricity is:

$$\frac{2603772.2}{5.8\text{ billion kW} \cdot \text{h}} = 448.92624\text{ Ar - equiv./million kW} \cdot \text{h } (\text{I}_{\text{IEI}}\text{ units}).$$

Kakhovka HPP. Performing similar calculations for the conditions of the Kakhovka HPP is carried out on the basis of the following indicators of the impact on the components of the natural environment.

The Kakhovka Reservoir, the sixth step of the Dnipro Cascade, carries out seasonal and partly multi-year flow regulation.

The water intakes of the Dnipro-Kryvyi Rih, Verkhno-Rohachinsky, Kakhovka and North-Crimean canals with a total water consumption of about 900 m^3/s, as well as water intakes of the Zaporizhzhya HPP and NPP are located on the Kakhov Reservoir.

The width of the zone of influence of the Kakhovka Reservoir on the groundwater level is 1.0–1.5 km in the upper part, 3.5–4.0 km in the middle, and 20–25 km in the lower part.

One of the large-scale problems of the Kakhovka Reservoir is the destruction of its banks. Of the 800 km of the entire coastline, 369 km were destroyed, 30 km of which were caused by landslides. Due to these processes, as well as due to the constant washing of soil from arable land, 82% of the water area of the reservoir is silted (the average layer is 0.19 m, the water area is from 0.1 to 1 m).

The total capacity of the Kakhovka hydroelectric power station is established 351 MW (6×58.5 MW). Average annual electricity generation is 1489 million kW·h.

Currently, the Kakhovka HPP-2 project has been developed. The total capacity of Kakhovka HPP-2 is provided at the level of 250 MW, which is 1.25% of the total capacity of operating power plants in Ukraine. The economic efficiency of the Kakhovka HPP-2 was compared with a power plant of the same capacity that operates on natural gas. The cost of electricity from the Kakhovka HPP-2 will be $264.1 MW·h, and the natural gas plant will cost $140.8 MW·h.

The assessed flow rate of the Kakhovka HPP is 4962 m^3/s, the spillway dam – 15438 m^3/s; assessed maximum discharge flow through structures (P = 0.1%) – 20468 m^3/s. The average long-term flow of the Dnipro at the hydroelectric junction reaches 52.2 km^3, the catchment area is 482 thousand km^2.

The structure of the hydroelectric power station includes the building of the hydropower plant with the installed capacity of six hydrounits N = 351 MW and the average annual energy production E = 1489 million kW·h.

The environmental impacts of the Kakhovka HPP include:

- direct impacts due to flooding of lands, destruction of shoreline lands, flooded lands, loss of water resources due to filtration through dams;
- indirect impacts due to the use of electricity when pumping water through the dam (water from rivers that are "supported" by dams and water that has filtered through embankment dams).

Indirect impacts amount to:

$$429.37 \text{Ar - equiv.} \cdot 47.6 = 20438.0 \text{Ar - equiv.},$$

where 429.37 Ar-equivalent is an indicator of the influence of the Kakhovka HPP during production 1 million kW·h. electricity; 47.6 million kW·h – electricity consumption for reverse pumping of filtration losses from the reservoir, million kW·h.

Filtration water, which caused flooding of the territory due to raising the level of the reservoir, amounts to 1409400 thousand m^3 (2.7% of the annual costs of the water balance, or 3.2% of the volume of water that passed through the turbines and produced 1489 million kW·h of electricity; 3.2% corresponds to 47.6 million kW·h of generated electricity).

Calculation of land losses flooded by the HPP reservoir and flooded territories: flooded (category III) – 2155 km^2 = 21550000 Ar-equivalent; destroyed by landslides – 7500 Ar-equivalent; flooded (Cat. II) – 14600 Ar·0.1 = 1460 Ar-equiv. Together, in terms of ar-equiv. – 21558960 ar-equiv.

Results of a comparative assessment of energy-generating technologies.

The obtained results of indicators of comprehensive technologies assessment of energy-generating industries are shown in Table 7.

Table 7 – Indicators of comprehensive assessment of energy-generating production technologies

Technological parameters	Indicators	Burshtyn TPP	Kakhovka HPP
The power of the station	P_{gen}	5800.0 million kW·h	1489.0 million kW·h
Number of power units (power)	$N(P_n)$	12 (200 MW)	6 (58.5 MW)
Use of fuel resources	R	329280.0 t.c.f.	–
Production of electricity	A_r	–	–
	W_r	3000.0 thousand m^3	20468.0 thousand m^3
	Z_r	–	–
Direct effects on environmental components:	A_{de}	190900.0 T	–
	W_{de}	2100.0 thousand m^3	–
	Z_{de}	1409.74 ha	21558860.0 Ar-equiv.
Indirect effects on the environment:	A_{ie}	72574.3 T	–
	W_{ie}	3000.0 thousand m^3	–
	Z_{ie}	20.0 ha	20438.0 Ar-equiv.
The total violated number of natural components:	A_{gen}	142198.9 T- equiv.	–
	W_{gen}	51.1 thousand m^3-equiv.	–
	Z_{gen}	143624.0 Ar-equiv.	21579298.0 Ar-equiv.
Coefficients of integral reducing	K^A	17.3	17.3
	K^W	2.1	2.1
	K^L	1.0	1.0
Reduced indicators of ecological impact	$K^A \cdot A$	2460041.0	–
	$K^W \cdot W$	107.31	–
	$K^L \cdot Z$	143624.0	21579298.0
Integral indicator of ecological impact	I_{IEI}	448.91 Ar-equiv./ million kW·h	14492.4 Ar-equiv./ million kW·h

The indicator of the environmental impact of the Kakhovka HPP with taking into account their direct and indirect values in I_{IEI} units, will be:

$$I_{IEI} = 121558860\ \text{Ar - equiv.} + 20438\text{Ar - equiv.} = 21579298\text{Ar - equiv.}$$

A specific indicator of environmental impact during the production of one million kW·h of electricity from the Kakhovka HPP will be:

$$I_{IEI} = \frac{21579298\text{Ar - equiv.}}{1489\ \text{million kW} \cdot \text{h}} = 14492.4\text{Ar - equiv./ million kW} \cdot \text{h}.$$

The indicator of the environmental impact of the Kakhovka HPP (I_{IEI} – 14492.4 Ar-equiv./million kW·h) exceeds the indicator of the environmental impact of the Burshtyn TPP (I_{IEI} – 448.93 Ar-equiv./ million kW·h) by 32.3 times.

The proposed methodology for assessing nature management technologies was tested at two technologically different energy-generating enterprises, which refer to the main ecologically costly spheres of business. A comparative assessment was made based on the indicator of the integral environmental impact of energy-generating enterprises – the Kakhovka hydroelectric power plant and the Burshtyn thermal power plant. The results showed that the thermal power plant is technologically 32.3 times better than the hydroelectric power plant in terms of integrated environmental impact I_{IEI}.

4. Conclusions

The developed methodology for assessing nature management technologies is based on the application of the first proposed integrated indicator of environmental impact, the determination of which occurs in two stages: by reducing the quality indicators of environmental components according to the degree of their damage to normative ones and integrating them to a single indicator with taking into account the costs of a possible full restoration of natural components.

The developed methodology allows to objectively compare any technologies providing an effective solution to the problems of managing natural and man-made systems at the regional level in the process of their transition to sustainable functioning.

REFERENCES

1. Shapar, A.G., Polishuk, S.Z. and Antonov, V.V. (1996), *Metodicheskie podhody k vyboru strategii ustoychivogo razvitiya territory: v 2 tomah* [Methodological approaches to the choice of a strategy for sustainable development of the territory: in 2 volumes], Institute for Nature Management Problems and Ecology of NAS of Ukraine, Dnipro, Ukraine.

2. Shapar, A.G., Emets, M.A. and Kopach, P.I. (2004), *Strateriya I taktyka stalogo rozvytku* [Strategy and tactics of steel development], Monolit, Dnipropetrovsk, Ukraine.

3. Shapar, A.G., Emets, M.A. and Kopach, P.I. (2003), *Metodychni vkazivky z rozrobky regionalnyh strategiy stalogo rozvytku* [Guidelines for the development of regional sustainable development strategies], Monolit, Dnipropetrovsk, Ukraine.

4. Shapar, A.G., Scripnyk, O.O. and Kopach, P.S. (2007), *Naukovo-metodychni rekomendacii schodo polipshennya ecologichnogo stanu zemel, porushenyh girnychymy robotamy (stvorennya tehnogennyh landshaftnyh zakaznykiv, ecologichnyh korydoriv, vidnovlennya ecosystem)* [Scientific and methodological recommendations for improving the ecological condition of lands disturbed

by mining operations (creation of man-made landscape reserves, ecological corridors, restoration of ecosystems)], Monolit, Dnipropetrovsk, Ukraine.

5. Kopach, P.I., Emets, M.A. and Kozlova, L.M. (2000), "Assessment of the level of perfection of technological systems in the context of regional nature management", *Ecologiya i pryrodokorystuvannya*, no.2, pp. 153–160.

6. Ministry of Health Protection of Ukraine (2020), *Stattya 608, kod akta 98079/2020: Hihiyenichni rehlamenty. Hranychno dopustymi kontsentratsiyi khimichnykh i biolohichnykh rechovyn v atmosfernomu povitri* [*Article 608, act code 98079/2020:* Hygienic regulations, Maximum permissible concentrations of chemicals and biological substances in the air], *Official Gazette of Ukraine*, no.15, pp. 20, Kyiv, Ukraine.

About authors

Kopach Pavlo Ivanovych, Candidate of Technical Sciences (Ph.D.), Senior Researcher, Senior Researcher in Department of Ecology of mastering Natural Resources, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, kopach.pavlo@gmail.com

Yakubenko Leonid Viktorovych, Candidate of Technical Sciences (Ph.D.), Senior Researcher, Senior Researcher in Department of Ecology of mastering Natural Resources, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, lalex-pod@i.ua

Mormul Taras Mykolaiovych, Candidate of Technical Sciences (Ph.D.), Senior Researcher, Senior Researcher in Department of Ecology of mastering Natural Resources, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, mormult33@gmail.com

Danko Tamara Timofiivna, Senior Engineer in Department of Ecology of mastering Natural Resources, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, lalex-pod@i.ua

Gorobets Natalia Vasyliivna, Senior Engineer in Department of Ecology of mastering Natural Resources, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, natgor490@gmail.com

Halchenko Zariana Serhiivna, Senior Engineer in Department of Ecology of mastering Natural Resources, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, zorichka85@gmail.com

ПОРІВНЯЛЬНА ОЦІНКА ЕНЕРГОГЕНЕРУЮЧИХ ТЕХНОЛОГІЙ ЗА ПРИНЦИПОМ ЕКОЛОГІЧНОЇ РЕСУРСОЄМНОСТІ

Копач П.І., Якубенко Л.В., Мормуль Т.М., Данько Т.Т., Горобець Н.В., Гальченко З.С.

Анотація. Запропонована порівняльна оцінка енергогенеруючих технологій виконана за методологією оцінки технологій природокористування повної екологічної ресурсоємності. Методологія базується на застосуванні вперше розробленого інтегрального показника екологічного впливу. Доведено, що приведення до цього показника усіх показників якості компонентів довкілля за ступенем їхнього пошкодження та зведення їх з урахуванням вартісних витрат забезпечує майже повне відновлення природних компонентів. Проведено оцінку технологій природокористування, яка основана на застосуванні методології повної екологічної ресурсоємності. Запропонована методологія дає можливість відслідковувати зміни у споживанні, пошкодженні та вилученні природних ресурсів. Розглянуті проблема оцінки технологій та шляхи її вирішення. Розроблена схема розрахунку інтегрального показника екологічного впливу. Визначені показники впливу по компонентам довкілля. Виведені коефіцієнти приведення до критичного показника за ступенем пошкодження природного компоненту (земля, вода, атмосферне повітря). Виведені формули приведення до критичних показників для компонентів довкілля. Визначено системоутворюючу компоненту природно-техногенної системи. Зроблено розрахунок коефіцієнтів приведення показників стану компонентів довкілля до єдиного інтегрального значення. Доведено, що інтегральний показник екологічного впливу є характеризуючим показником, який у зведеному до одного числа вигляді відтворює техногенні впливи на усі природні компоненти, що дозволяє досягти суттєвої ефективності у прийнятті оптимальних управлінських рішень. Методологію оцінки технологій природокористування апробовано на основних енергогенеруючих підприємствах, які належать до основних екологічно витратних сфер господарювання. Виконано порівняльну оцінку енергогенеруючих технологій на прикладі гідроелектростанції і теплової електростанції (на основі показників Бурштинської теплової електростанції та Каховської гідроелектростанції). Доведено розрахунком, що показник інтегрального екологічного впливу теплоелектростанції технологічно в 32,3 рази кращий за показник інтегрального екологічного впливу гідроелектростанції.

Ключові слова: інтегральна екологічна ресурсоємність, енергогенеруючі технології, екологічно витратні технології природокористування.