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FEASIBILITY ANALYSIS OF CONSTRUCTION OF NEW HYDROPOWER PLANTS IN UKRAINE TAKING INTO ACCOUNT THE RISK OF UNUSED POSSIBILITIES

Abstract. *The article presents results of feasibility analysis of construction of new hydropower plants in Ukraine according to the Hydropower development program for the period till 2026, which was approved by our Government in 2016. In particular, there are analyzed perspective plans for building the Kakhovka hydropower plant #2 and six new hydropower plants on the river Dniester, as well as developing small hydropower in the country. The feasibility analysis is based on pairwise comparison of alternatives by the criterion of minimum aggregate risk taking into account the risk of unused opportunities. Components of aggregate risks of alternatives are estimated in dimensionless units for water-energy and operability characteristics and costs of commissioning of new hydro aggregates.*
Keywords: *aggregate risk; alternative; decision-making; feasibility analysis; hydropower; hydropower plants; optimization; pairwise comparison; renewable energy; risk of unused possibilities*

Introduction

In connection with the accelerated development of renewable energy in our country [1, 2], especially solar and wind [3-6], being observed in the last decade (Table 1), a number of difficult issues has appeared relating to sustainable and reliable functioning the national combined energy system (CES) in the conditions of a significant deficit of regulating capacities of large hydropower plants (HPPs) and pumped-storage hydropower plants (PSHPPs) [7-9].

Table 1 – Renewable energy in Ukraine (MW)[1] [3-6]

Renewable Energy	Years										
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019[3]
Wind[2]	84	87	151	194	334	426	426	438	465	533	706
Solar[2]	-	3	191	326	616	411	432	531	742	1388	2072
Household solar	-	-	-	-	-	0.1	2	17	51	157	157
Small hydropower	66	68	71	73	75	80	87	90	95	99	99
Biomass	-	-	-	6	17	35	35	39	39	52	52
Biogas	-	-	-	-	7	14	17	20	34	46	51
New	-	8	255	186	450	-83	33	136	291	849	862
Total	150	158	413	599	1049	966	999	1135	1426	2275	3137

[1] Without large hydropower generation
[2] Without power generation in the Autonomous Republic of Crimea and in the occupied territory of Donbas (in total, Russia has arrogated 633.7 MW of renewable energy of Ukraine)
[3] According to data for the first quarter of 2019

The role of manoeuvre power sources in the combined energy systems is best fulfilled by HPPs and PSHPPs. For example, starting hydropower units from a stopped position in a turbine mode with synchronization and a complete set of power is only 1-2 minutes; while at idling speed is 15-30 seconds. Changing the power of the hydro unit or its stop needs only a few seconds [9]. In conditions of significant unevenness of daily power load schedules in the combined energy systems, it is the HPPs and PSHPPs, which have the highest manoeuvrability and the largest regulatory range (Table 2), in general, can best provide a stable, efficient and reliable operation of the national energy system.

Table 2 – Comparative characteristics of manoeuvrable qualities of main types of power plants [9]

Types of power plants	Technical minimum load, % (the ratio of minimum permissible power to the installed power)	Regulation range, %	Time to set the full power, min	
			After stopping	From the “hot” state
Nuclear	85-90	10-15	390-660	60
Thermal (coal, fuel oil)	70-80	20-30	90-180	20-50
Gas turbines	0	100	15-30	0.5
Hydraulic	0	100	1-2	0.25-0.5
Pumped-storage	0	200	1-2	0.25-0.5

It is believed that for the stable and reliable operation of the CES of Ukraine, the share of manoeuvrable capacities in its overall electricity balance should be about 15-20% [7-9]. At present, the domestic hydropower is capable of reliably providing only about 8-9% of such regulating capacities. As a result, the main regulatory role in the CES of our country is mainly performed by thermal power plants (TPPs) [7]. However, utilization of capacities of the TPPs for adjusting load schedules is uncharacteristic, economically inexpedient and even dangerous for the specified type of power generation. The work of the TPP’s equipment with a change in load, frequent systematic shutdowns and start-ups of units, leads to decreasing in their efficiency, fuel overconsumption, accelerated aging of equipment, increasing probability of failures and cost price of electric power. In particular, it is associated with increasing environmental pollution.

Therefore, the decisions on further increase of hydro generating capacity in the country, laid out in the Hydropower development Program for the period till 2026 [7], at first glance, are quite rational. Ukraine requires additional high-manoeuvrability and regulatory electro generation capacities, including because of the development of renewable solar and wind energy, which is characterized by a high degree of dependence on climatic conditions and instability of electricity generation [1, 2, 7-9].

1. Some general remarks concerning current state of hydropower in Ukraine

The main functions of domestic hydropower are the regulation of frequency and load schedules in the CES and the formation of an emergency power reserve providing the technological energy safety of the country [8, 9].

Some quantitative characteristics of hydropower development in Ukraine from 2010 till 2018 are given in Table 3. During this period, in the country there have been commissioned three hydro aggregates on the Dniester PSHPP with total capacity of 972 MW in turbine mode (1263 MW in pumping mode) and 31 MW of small hydropower.

Table 3 – Hydropower in Ukraine (MW) (according to data from [3-6])

Power plants	Years								
	2010	2011	2012	2013	2014	2015	2016	2017	2018
Large hydropower	5400.2	5400.2	5400.2	5724.2	5724.2	6048.2	6048.2	6048.2	6048.2
Small hydropower	68	71	73	75	80	87	90	95	99
Total hydropower	5468.2	5471.2	5473.2	5799.2	5804.2	6135.2	6138.2	6143.2	6147.2
Share, %, of small hydro in total hydropower	1.24	1.30	1.33	1.29	1.38	1.42	1.47	1.55	1.61
Share, %, of hydropower in total renewable energy[1]	97.19	92.98	90.14	84.68	85.73	86.00	84.39	81.16	72.99
Share, %, of small hydro plants in renewable energy[2]	43.04	17.19	12.19	7.15	8.28	8.71	7.93	6.66	4.35

[1] With large hydropower
[2] Without large hydropower

In general, the share of hydropower in the overall balance of renewable energy in Ukraine from 2009 till the first quarter of 2019 decreased from 97.33% to 66.21%. Accordingly, in this period the potential for more efficient regulation of the load schedule in the CES of the country, by means of highly manoeuvrable hydropower facilities, has decreased too. It should also be mentioned that the small hydropower industry that has been developing in the country in recent years (Table 3) does not have sufficient regulatory capacity compared to large hydropower. Moreover, the work of small hydropower plants according to the "green tariff" in the CES of Ukraine, taking into account the climate, topography, and hydrological characteristics of domestic small rivers [10], can be considered more in the context of renewable energy that needs regulation. The only thing that can be calmed in this situation is that the share of small hydropower in the balance of hydropower facilities in the country is negligible. There is also a tendency for a significant reduction of the share of small hydropower in the structure of non-traditional renewable energy (see Table 3, without large hydropower). From 2009 till the first quarter of 2019 it has fallen from 44% to 3.16%. At present, the power of solar plants in households (see Table 1) in the country is already twice the installed capacity of small hydropower. Household solar, along with bioenergy (biomass and biogas), can be considered as a more acceptable "green" alternative to small hydropower, given that, in general, small hydropower in Ukraine can not be considered as environmentally friendly, including in comparison with the domestic large hydropower [10-12].

As for our large hydropower, one of its important features is a significant proportion of hydro-accumulation in installed capacity. In turbine mode, this share already makes up almost 25% (1508.5 MW). Taking into account the pumping storage mode (2016 MW), the overall regulation range in the CES thanks to the large hydropower currently reaches 8064.2 MW. Considering the world tendencies of hydropower development with gradual accent on hydro-accumulation, and limited reserves of hydropower potential of rivers in the country [13, 14], an increase in the share of hydro-accumulation can be considered as a positive aspect of the further development of hydropower in the country.

2. Some general remarks concerning the Hydropower development program for the period till 2026

The Hydropower development program for the period till 2026 [7] was approved by our Government in 2016. This Program has envisaged achieving an ambitious goal, namely, increasing the share of hydrogeneration in the overall electricity balance of the country from the current 8-9% up to 15%.

Although the achievement of the hydropower share of 15% in the total balance of the CES due to the implementation of the Program [7] is quite questionable, in any case an increase in highly manoeuvrable regulatory capacity of hydropower in the national energy system will have a positive effect.

In particular, according to the Program, the following actions are foreseen to provide (See also Table 4):

– completion of construction the Dniester and the Tashlyk pumped-storage hydropower plants (PSHPP), the construction of the Kaniv PSHPP;

– the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades (in general, reconstruction of 76 hydro units is envisaged);

– construction of the Kakhovka HPP#2 to expand the Kakhovka HPP on the Dnipro River and the construction of six new hydropower plants on the Dniester River (the so-called Upper Dnistrovskyi cascade of HPPs);

– as well as rehabilitation and construction numerous small hydropower plants (with the participation of private investors and state support for their activities through the "green tariff").

Table 4 – The expected outcomes of the Program [7]

Power plants		Installed capacity N, MW	Power generation E, MW·h	Cost C, 10^9, hryvnias
Dniester PSHPP	the second stage	324 (421^I)	388.5 (515.5^II)	2.8
	the third stage	972 (1263^I)	1165.5 (1546.5^II)	8.4
Tashlyk PSHPP		604 (861^I)	582 (785^II)	14.9
Kaniv PSHPP		1000 (1120^I)	1017 (1153^II)	40.5^III
Reconstruction of existing HPPs		307	330	22.33
Kakhovka HPP#2		250	44	13.47^IV
Upper Dnistrovskyi cascade of HPPs		390	710	31.9^V
Small hydropower^VI		88	120	-
Total		3935 (3665^I)	4387 (4000^II)	134.3

^I Pumped-storage mode
^II Energy consumption in pumping mode
^III USD 1.5 billion at prices for January 1, 2013
^IV 0.42 billion Euros at prices for January 1, 2013
^V 1.1 billion Euros at prices for January 1, 2014
^VI Private investments

Provided the Program [7] is fully implemented, the installed hydrogeneration capacity in the national energy system will increase by 39%. The share of hydroaccumulation in the overall balance of hydrogeneration in the country will also increase and reach 43%. It can be concluded that the development of hydroaccumulation in the near future is a priority objective of the Program [7].

In particular, the Program [7] states that according to the National Renewable Energy Action Plan [1, 2], the total installed capacity of wind power plants and solar power stations, which are non-manoeuvrable power generating capacity, is expected to increase almost fivefold. It is also indicated that an increase in installed power of objects of power engineering using these renewable energy sources should be carried out within the limits that are technically feasible to ensure the reliability of the functioning of the CES of Ukraine. Finally, it is recognized that the use of pumped-storage hydropower plants is a universal mechanism for solving the problems that exist in the CES of Ukraine.

However, the Program also provides for the modernization and reconstruction of existing hydropower plants and the construction of new HPPs. At the same time, with the total capacity of additional hydrogeneration at large HPPs of about 947 MW, which is more than three times less than the expected new hydrogeneration capacity at the PSHPP (2900 MW), the total costs for commissioning of additional hydrogeneration at the HPPs will be even slightly higher than the costs concerning the PSHPPs. Small hydropower, which is financed by private investors, practically does not change this negative relation between hydrogeneration at the HPPs and the PSHPPs.

3. Topicality, general objective and particularities of the research

In practice, not only cost indicators and ratio of expected results determine feasibility of projects. Projects may be effective but not feasible. The effectiveness of any project can be stimulated by various kinds of preferences, for example, in the form of a "green tariff" for produced electricity, etc. However, a feasible project does not necessarily have to be absolutely effective too. For example, the Program's [7] project for the reconstruction of existing hydropower plants of the Dnipro and Dniester cascades may be considered quite feasible. Provided it is needed, various alternatives to its implementation may be analysed to find among them a more efficient (optimal, etc.) one.

It is known that hydropower projects, like any other projects, may be burdened with various risks, including the risks of unused (lost, etc.) possibilities (or opportunities, etc.). The latter risks should also be taken into account when comparing alternatives and making decisions. It is also known that traditional hydropower can have a significant impact on the environment [15, 16]. Besides of the expected positive effects, unexpected negative socio-environmental and economic effects may occur, affecting other perspective fields of human activity, limiting possibilities for other natural resources users. Taking into account even the most significant socio-ecological and socio-economic effects is a complicated task of analyzing and comparing alternatives. It is quite difficult to get rid of the influence of various subjective conclusions while solving similar tasks. However, the task could be simplified if, at the final stage of decision-making, the best alternatives are compared in their spheres, fields, etc. These chosen alternatives may be considered more feasible than others.

In the research, a method of decision-making was used on the basis of a pairwise comparison of alternatives taking into account the risk of unused possibilities (opportunities). The fundamentals of the method are given in [17]. The method has already been used to solve several tasks related to development of the national hydropower. The first task concerned selecting the optimal variant for the development of the Dnipro HPPs cascade taking into account the risk. The task had been considered in 2010 [18] before approving the Program [7]. There had been established the feasibility of construction of the Kaniv PSP in comparison with the construction of the Kakhovka HPP#2. As the next feasible option of the cascade development it was determined the construction of the Kakhovka HPP#2 with three or four additional units and total installed capacity of 168-224 MW. The second task concerned grounding of an optimal scenario for setting of new hydrogeneration capacities at PSHPPs in Ukraine in accordance with the Program [7]. In particular, it was concluded the feasibility of the commissioning at first of the fourth aggregate of the Dniester PSHPP with the subsequent construction of the Kaniv PSHPP in comparison with other possible alternatives [19].

The purpose of this article is to ground the feasibility of building new hydropower plants in Ukraine in accordance with the Program [7] taking into account the risk of unused possibilities. Among the possible options is the construction of the Kakhovka HPP#2, the Upperdnistrovsky cascade of the HPPs and the further development of small hydropower (See Table 4). The problem is solved on the basis of a pairwise comparison of alternatives according to the method [17]. The peculiarity of the solution of the problem is that the project of the second stage of the reconstruction of existing hydroelectric plants of the Dnipro and Dniester cascades in the Program [7] is accepted as a "zero" alternative.

4. Formalization of the research: Risks of alternatives and decision making

According to the method presented in [17], the aggregate (or total) risk of each of alternatives is determined in the form of a linear combination of possible costs or other negative effects and results l associated with the corresponding decision, and the expected positive effects or results (benefits, gains, achievements, advantages) g that can be obtained in the case of an alternative solution.

The task of multicriteria optimization on a countable set of admissible alternatives $\mathbf{A}=\{a_i\}$, $i=\overline{1,n}$, while their pairwise comparison, is reduced to the next optimization problem:

$$d_{opt}=\{a_{i,opt}\,|\,a_{i,opt}\in\mathbf{A}\wedge r_{i,opt}=\min(r_{i,j},r_{j,i})\ \forall(a_i,a_j)\}\,,i,j=\overline{0,n}\,,i\neq j\,, \quad (1)$$

where $r_{i,j}$, $r_{j,i}$ are aggregate risks, respectively, for an alternative a_i when comparing it with a_j, and a_j comparing with a_i: $r_{i,j}=l_i+g_j$, $r_{j,i}=l_j+g_i$, where l_i, l_j and g_i, g_j are the values of the correspondingly normalized convolutions of criteria, which are subject to minimization or maximization, of the alternatives a_i and a_j presented as own (or systemic) risks and risks of unused possibilities of the alternatives a_i, a_j.

In general, various positive and negative effects or results may have different units of measurement. Therefore, the quantitative assessment of the relevant components of aggregate risk is carried out in dimensionless units (scores) based on a universal log scale (see also [17-19]). Then, the score of some value y_k of the corresponding characteristic will be like that:

$$r(y_k)=\mu_k\cdot\lg y_k+y_{k,0}, \quad (2)$$

where μ_k is module, $y_{k,0}$ is zero point on the integral log scale length L (let L be equal to 10) for characteristic y_k:

$$\mu_k=\frac{L}{\lg y_{k,\max}-\lg y_{k,\min}}\,,\ y_{k,0}=-\mu_k\lg y_{k,\min}\,, \quad (3)$$

where $y_{k,\max}$, $y_{k,\min}$ are maximum and minimum values of y_k.

If $y_{k,\min}=0$ it will be counted that $y_{k,0}=0$, $\mu_k=\dfrac{L}{\lg y_{k,\max}}$, $r(0)=0$.

Further, the components of aggregate risks (systemic risks l and risks of unused possibilities g) of each alternative a_i in comparison with a_j are represented by the sums of scores of the corresponding characteristics, namely:

$$l_i=\sum_{k=1} l_{k,i}\,,\ g_j=\sum_{k=1} g_{k,j}\,. \quad (4)$$

After the formation of the assessments of risk (4), the aggregate risks of alternatives are determined in the form of linear combinations $r_{i,j}=l_i+g_j$, $r_{j,i}=l_j+g_i$. Pairwise comparisons of alternatives with choosing better one among them are carried out according to the rule (1).

5. Solving the problem and results obtained

While researching there were considered and pairwise compared eight alternatives. They were ordered and numbered according to increasing installed capacity. These are alternatives $a_0 \div a_7$ (See their characteristics in Table 5):

– a_0 is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades (the “zero” alternative);

– a_1 is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades, and also the further development of small hydropower;

– a_2 is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades, and also the construction of the Kakhovka HPP#2;

– a_3 is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades, the construction of the Kakhovka HPP#2 and the further development of small hydropower;

– a_4 is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades and the building of the Upper Dnistrovskyi cascade of HPPs;

– a_5 is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades, the construction of the Upper Dnistrovskyi cascade of HPPs and the further development of small hydropower;

– a_6 is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades, the construction of the Kakhovka HPP#2 and the construction of the Upper Dnistrovskyi cascade of HPPs;

– a_7 is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades, the construction of the Kakhovka HPP#2 and the Upper Dnistrovskyi cascade of HPPs and the development of small hydropower.

Table 5 – The characteristics of alternatives $a_0 \div a_7$

Alternatives	Characteristics				
	N, MW	E, MW·h	C, 10^9, hrs	C_E	N_{reg}, MW
a_0	307	330	22.33	330	276.3
a_1	395	450	22.33	930	293.9
a_2	557	374	35.8	374	513.8
a_3	645	494	35.8	974	531.4
a_4	697	1040	54.23	1040	529.8
a_5	785	1160	54.23	1640	547.4
a_6	947	1084	67.7	1084	767.3
a_7	1035	1204	67.7	1684	784.9

As characteristics, from which the components of the risk l were formed, costs of construction (or reconstruction) C of HPPs and averaged (weighted) expected costs of power buying C_E depending on alternatives $a_0 \div a_7$ were considered. Costs C_E were determined according to formula:

$$C_E = \sum_{k=1} E_k \cdot v_k \;, \tag{5}$$

where E_k is the total quantity and v_k is score value of tariff of the unit of electricity produced by the source of hydrogeneration with the index k .

For our research, if electricity is produced at large HPPs score value of tariff v_k is equal 1. If electricity is produced at small HPPs, let v_k will be 5.

As characteristics, from which the components of the risk of unused possibilities g were formed, the power capacities N_{reg} , which can be used in adjusting the load schedule in the CES of the country, and power generation E depending on alternatives $a_0 \div a_7$ were considered. The corresponding power capacities N_{reg} were determined according to the formula:

$$N_{reg} = \sum_{k=1} N_k \cdot c_k \,, \tag{6}$$

where N_k is the installed capacity and c_k is the reliability coefficient concerning regulation possibilities in the framework of the CES depending on the source of hydrogeneration with the index k , respectively.

For our research the following values c_k are taken: the HPPs of the Dniprovsky and Dnistrovsky cascades, the reliability coefficient c_k = 0.9; the Kakhovka HPP#2, c_k = 0.95; the Upper Dnistrovskyi cascade of HPPs, c_k = 0.65; in the case of small hydropower, c_k = 0.2.

The results of numerical assessment of risk components of the considered alternatives $a_0 \div a_7$ are given in Table 6. The results of their pairwise comparison in accordance with the rule (1) are given in Table 7.

Table 6 – Results of numerical assessment of risk components of the alternatives $a_0 \div a_7$

Alternatives	Systemic risk			Risk of unused possibilities		
	C	C_E	l	N_{reg}	E	g
a_0	0.00	0.00	0.00	0.00	0.00	0.00
a_1	0.00	6.36	6.36	0.59	2.40	2.99
a_2	4.26	0.77	5.02	5.94	0.97	6.91
a_3	4.26	6.64	10.90	6.26	3.12	9.38
a_4	8.00	7.04	15.04	6.24	8.87	15.10
a_5	8.00	9.84	17.84	6.55	9.71	16.26
a_6	10.00	7.30	17.30	9.78	9.19	18.97
a_7	10.00	10.00	20.00	10.00	10.00	20.00

Table 7 – Decision table for pairwise comparison of the considered alternatives

a_i / a_j	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
a_0	-	**2.99**	**6.91**	9.38	15.10	16.26	18.97	20.00
a_1	**6.36**	-	**13.27**	9.97	21.46	22.62	25.33	26.36
a_2	**5.02**	**8.01**	-	**14.40**	**20.13**	**21.28**	**24.00**	**25.02**
a_3	10.90	13.88	**17.80**	-	26.00	27.16	29.87	30.90
a_4	15.04	18.03	**21.95**	24.42	-	31.30	34.01	35.04
a_5	17.84	20.83	**24.75**	27.22	32.94	-	36.81	37.84
a_6	17.30	20.28	**24.21**	26.68	32.40	33.56	-	37.30
a_7	20.00	22.99	**26.91**	29.38	35.10	36.26	38.97	-

So, the best alternative is a_2. This alternative is burdened with the lowest risk when pairwise comparison with any other alternative among the considered alternatives a_i, $i = \overline{0,7}$.

Conclusions

The results of our research show that the best alternative to build new hydropower plants in the country among the considered alternatives the alternative a_2 is. This is the second stage of reconstruction of the HPPs of the Dniprovsky and Dnistrovsky cascades and also the construction of the Kakhovka HPP#2. This alternative should be considered the most feasible to improve situation in the domestic hydropower without significant risks.

As well as, it should be noted that alternatives, which provide for the further development of small hydropower in the country, are worse than alternatives which neglect its development. It may indicate that decision to develop small hydropower in the country under the current conditions and thanks to the “green tariff” is questionable and ungrounded.

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АНАЛІЗ ДОЦІЛЬНОСТІ БУДІВНИЦТВА НОВИХ ГЕС В УКРАЇНІ З УРАХУВАННЯМ РИЗИКУ НЕВИКОРИСТАНИХ МОЖЛИВОСТЕЙ

Анотація. У статті представлено результати аналізу доцільності будівництва нових гідроелектростанцій в Україні відповідно до Програми розвитку гідроенергетики України до 2026 року, затвердженої Урядом у 2016 році. Зокрема, аналізуються перспективні плани щодо розширення Каховської ГЕС з побудовою Каховської ГЕС-2, будівництва каскаду з шести нових гідроелектростанцій на річці Дністер та розвиток малої гідроенергетики в країні. Аналіз базується на попарному порівнянні альтернатив за критерієм мінімального сумарного ризику з урахуванням ризику невикористаних можливостей. Складові сумарних ризиків альтернатив оцінюються в безрозмірних одиницях, якими описуються водноенергетичні і експлуатаційні характеристики та затрати на введення нових гідроагрегатів.

Ключові слова: сукупний ризик; альтернатива; аналіз доцільності; прийняття рішень; гідроенергетика; гідроелектростанції; оптимізація; попарне порівняння; відновлювана енергетика; ризик невикористаних можливостей

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