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ON PECULIARITIES OF HYDROPOWER DEVELOPMENT IN THE WORLD AND IN UKRAINE

Abstract. *There have been presented results of a comparative analysis of features of hydropower development in the world and in Ukraine. The analysis was carried out on a basis of data concerning cost-efficient hydropower potential in different countries of the world, installed capacity of hydrogeneration facilities, generation of electricity by them, reservoirs surface area and hydrostatic pressure of hydropower plants (HPPs). As analogues of domestic HPPs for more detailed comparison some HPPs of France, Austria and Finland were considered. There were offered indicators that enable to estimate socio-economic attractiveness of HPPs and their impact on the environment. The results show a difference between the indicators of Ukrainian HPPs and foreign HPPs' ones, and this difference is not in favour of domestic objects.*
Keywords: *environmental impact, hydropower, cost-effective hydropower potential, comparative analysis.*

Introduction

According to the Program for the Development of Hydropower of Ukraine until 2026 approved by our Government in 2016 [1], it envisages to increase the share of hydrogeneration in the overall electricity balance of the country from the current 8–9% to 15% through the full use the cost-effective hydropower potential (CEHP) whose level of using in the country is estimated at 61–64% [2] that is lower than the level of most developed countries of the world (Table 1).

Table 1 – Countries with high level of using the CEHP (according to 2000 data) [2, 3]

Country	Total CEHP, 10^9 kWh	Power generation, 10^9 kWh	Level of using CEHP, %
Ukraine	**17,0–18,0**	**9,8**	**61,0–64,0**
Norway	179,6	116,3	64,8
Canada	536,0	350	65,3
Austria	53,7	37,5	69,8
Finland	19,7	14,6	74,0
Paraguay	68,0	51,3	75,4
Sweden	90,0	68,3	75,9
Mexico	32,2	24,6	76,4
USA	376,0	308,8	82,1
Spain	41,0	35,0	85,4
German	20,0	18,2	86,0
Japan	114,3	95,6	90,0
Italy	54,0	51,6	95,6
Switzerland	35,5	34,5	97,2
France	71,5	72,0	100,0

Among promising hydrogeneration objects, which are considered in the Government Program [1], there are allocated next ones. These are completion of construction the Dniester and the Tashlyk pumped-storage hydropower plants (PSHPP), the construction of the Kaniv PSHPP, the construction of the Kakhovka HPP-2 to expand the Kakhovka HPP on the Dnipro River, the construction of six new hydropower plants on the Dniester River (this is the so-called Upper Dnistrovskyi cascade of HPPs) as well as rehabilitation and construction of numerous small hydroelectric plants. Authors of the Program [1] count that its implementation will promote the sustainable socio-economic development and the enhancement of energy safety of our country, increasing the stability of the Integrated Power System of Ukraine, the overall improvement of the environment owing to reduction of greenhouse gas emissions through wider use of renewable energy sources, as well as the population flood protecting, etc. [1, 4–6].

However, the implementation of the plans [1] can be associated with significant risks [7, 8]. In many respects these plans contradict common world tendencies in limiting the new hydropower development, as result of increased attention to socio-environmental problems caused by hydropower in the past [9].

A general analysis of peculiarities of using the hydropower potential in the world and in Ukraine

The consequences accompanying construction and operation of hydropower plants have already been quite studied [10, 11] and there is no need to dwell on them in detail. Construction of dams and operation of HPPs, this activity affects the environment and the influence is often negative [9–11].

The first thing that should be mentioned in the context of expected results of the Program implementation [1] is that the aggregate CEHP of rivers of Ukraine (Table 1), in absolute terms, is one of the lowest in the world, compared with other countries, where it has been actively used.

Of course, gross metrics do not always adequately reflect the real value of the resource or effectiveness of its use. However, one of the lowest in the world is also the relation of the CEHP of Ukraine to the area of its territory (Table 2). This indicator is worse for Argentina, Mexico and Australia alone, where rivers within the majority of their land territory, as permanent watercourses, are absent at all.

This index may indicate that Ukraine has got quite limited hydrogeneration resources and that their usage due to the relatively low «density» can be associated with relatively greater negative environmental impacts. Similar conclusions can be valid even if the estimate of the CEHP of Ukraine that was used by domestic engineers while developing the Program [1] is fairly correct. But it is quite possible that if the more adequate estimation of the CEHP of Ukraine had been carried out in the past with paying more attention to heavy socio-economical and environmental losses caused by our HPPs’ construction and operation because of features of the country’s topography and relatively small gradients of the majority of domestic rivers the real estimate of the CEHP could have turned out worse [7–11]. Engineers and officials making decisions regarding hydropower development in our country should take into account various factors, not only economical ones, among them, for example, attractiveness of river valleys for urbanization, etc.

Table 2 – General characteristics of CEHPs and electricity generation by objects of hydrogeneration in different countries of the world depending on the area of land territory of the countries (according to 2000 data [2, 3])

Country	Total CEHP, 10^9 kWh	Power generation *E*, 10^9 kWh	Area of territory *S*, 10^3 km^2	CEHP / *S*, 10^6 kWh per km^2	*E* / *S*, 10^6 kWh per km^2
Egypt	50	11,5	1001,449	0,0499	0,0115
Nigeria	29,8	7	923,768	0,0323	0,0076
Russia	600	165,4	17075,4	0,0351	0,0097
Columbia	140	37	1141,748	0,1226	0,0324
Turkey	123	39,1	779,452	0,1578	0,0502
Mozambique	31,7	11,5	799,379	0,0397	0,0144
Brazil	763	282,6	8511,996	0,0896	0,0332
Argentina	80	32	2780,092	0,0288	0,0115
Serbia and Montenegro	27	12	88,375	0,3055	0,1358
Ecuador	15	7,2	272,045	0,0551	0,0265
Romania	30	16	238,391	0,1258	0,0671
Australia	30	17,5	7682,3	0,0039	0,0023
New Zealand	40	22,9	270,534	0,1479	0,0846
Venezuela	100	60,6	912,05	0,1096	0,0664
Ukraine	**17–18**	**9,8**	**603,7**	**0,0298**	**0,0162**
Norway	179,6	116,3	385,155	0,4663	0,3020
Canada	536	350	9976,14	0,0537	0,0351
Austria	53,7	37,5	83,858	0,6404	0,4472
Finland	19,7	14,6	338,145	0,0583	0,0432
Paraguay	68	51,3	406,752	0,1672	0,1261
Sweden	90	68,3	449,964	0,2000	0,1518
Mexico	32,2	24,6	1958,201	0,0164	0,0126
USA	376	308,8	9372,614	0,0401	0,0329
Spain	41	35	505,992	0,0810	0,0692
Germen	20	18,2	357,05	0,0560	0,0510
Japan	114,3	95,6	372,824	0,3066	0,2564
Italy	54	51,6	301,318	0,1792	0,1712
Switzerland	35,5	34,5	41,29	0,8598	0,8356
France	71,5	72	547,03	0,1307	0,1316

Results of efficiency evaluation of installed capacities of hydrogeneration in Ukraine and in other countries of the world for 2000 are also quite revealing (see Table 3 below). The indicators for Ukraine should be admitted as the worst ones among all the listed countries.

These results (Table 3) indicate not only a relatively low use efficiency of the installed capacity at domestic HPPs, which are already in operation. If the fact that the hydropower plants in Ukraine are mostly low-head ones and with large reservoirs is taken into account then the low values of these indicators can also attest to more negative environmental impacts that our HPPs bring about rivers and the environment compared with HPPs of other countries. For example, there such negative environmental effects should be mentioned as more prolonged artificial retention of rivers runoff in reservoirs resulting to less intense water exchange in rivers, as well as more sharp artificial fluctuations of water levels in the downstream of dams that differ from natural fluctuations of water levels in the rivers essentially and often dangerously.

Table 3 – Efficiency of using installed capacities of hydrogeneration in different countries of the world (according to 2000 data [2, 3])

Country	Power generation, 10^9 kWh	Installed capacity *N*, 10^6 kW	Time of use of *N*, hours per year	Use rate
USA	308,8	75,5	4090	0,47
Japan	95,6	27,2	3515	0,40
Ukraine	**9,8**	**4,73**	**2072**	**0,24**
France	71,5	25,2	2837	0,32
Mexico	24,6	10,5	2343	0,27
China	204	65	3138	0,36
India	80	24,5	3265	0,37
Russia	165,4	44	3759	0,43
Italy	51,6	15,3	3373	0,38
Spain	35	9,3	3763	0,43
Turkey	39,1	10,8	3620	0,41
Argentina	32	9,6	3333	0,38
Sweden	68,3	16,2	4216	0,48
Switzerland	34,5	13,2	2614	0,30
Canada	350	67	5224	0,60
Austria	37,5	13,57	2763	0,32
New Zealand	22,9	5,2	4404	0,50
Columbia	37	8,6	4302	0,49
Venezuela	60,6	13,2	4591	0,52
Brazil	282,6	58	4872	0,56
Norway	116,3	27,4	4245	0,48
Paraguay	51,3	8,1	6333	0,72

There is also a relatively low efficiency of using the installed capacity of small hydropower in Ukraine (see Table 4 for corresponding indicators). It is quite strange and unexplained thing because according to the national legislation owners of small hydropower plants (SHPPs) have opportunities to sell produced electricity at any time and in any quantity. It is also alarming for the similarity of these indicators concerning to SHPPs in various regions of the country.

It is well known that in order to the impact on the environment would be minimized SHPPs should operate using transit river runoff. So, the efficiency of using the installed capacity of SHPPs should be quite more than it is in our case.

Eventually, if the small intensity of using the installed capacity of large domestic hydroelectric plants is admitted justifying through their participation in the regulation of capacities within the Integrated Power System of the country, then in case of small hydropower plants this cannot be a sufficient argument owing to their small installed capacity and insufficient reliability.

A characteristic feature of domestic SHPPs is also one that they are mainly low head ones being located on plain rivers and have reservoirs. Therefore, the low efficiency of using the installed capacity at the SHPPs may indicate the similarity of their environmental impact to the impact of large hydropower plants.

Table 4 – Efficiency of using installed capacities
of small hydropower in Ukraine (according to [12])

Region	Installed capacity *N*, MW	Power generation *E*, 10^6 kWh	Time of use of *N*, hours per year	Use rate
Vinnytsia	22,45	59,6	2655	0,303
Zhytomyr	2,87	7,62	2655	0,303
Transcarpathian	7,98	21,2	2657	0,303
Ivano-Frankivsk	2,57	6,85	2665	0,304
Kirovograd	12,55	33,33	2656	0,303
Kyiv	1,84	4,9	2663	0,304
Lviv	0,45	1,2	2667	0,304
Poltava	1,66	4,4	2651	0,303
Rivne	1,16	3,08	2655	0,303
Sumy	1,13	3	2655	0,303
Ternopil	8,47	22,5	2656	0,303
Kharkiv	3,68	9,77	2655	0,303
Khmelnytsky	4,52	12	2655	0,303
Cherkasy	6,52	17,35	2661	0,304
Chernihiv	0,23	0,62	2696	0,308
Chernivtsi	1	2,66	2660	0,304

At first, the above-mentioned remarks may indicate an inappropriate level of substantiation of domestic SHPPs' projects. Secondly, although small hydropower can be considered relatively environmentally friendly one, total environmental losses trough a large number of SHPPs can exceed the loss trough one large HPP with the same installed capacity [9]. Eventually, a relative negative impact of a small hydropower plant on a small river may be not less, but possibly even greater one than the impact of a large hydropower plant on a large river [13].

In general, although indicators of using the installed capacity at domestic SHPPs exceed values of the corresponding indicators of hydro-energy objects in the country as a whole, they are, however, smaller than, for example, the indicators of HPPs in Austria and France.

A comparative analysis of some water-energy characteristics of large hydropower plants of Ukraine, France, Austria and Finland

Usually, in order to justify a feasibility of building new hydropower plants in Ukraine our engineers refer to the hydropower development experience in other countries. As a positive example the experience of France and Austria is often used. For comparison with the domestic experience the experience of Finland is interesting too. The CEHP of Finland is close to our one (Table 1, 2). Also Finnish hydropower plants are located on rivers with small fall of their streams.

At present, the largest share of electricity in France (up to 75%) is produced by nuclear power plants (this is the highest share in the world). The hydropower share in the overall energy balance is about 15%. At the same time, the level of using the CEHP in France reached 100%.

In Ukraine, nuclear power also has a significant share in the overall energy balance (up to 50% or more, depending on years) [5]. The purpose of the Program [1] approved by the Government in 2016 is to increase the share of hydropower in the electricity market in Ukraine from 5–8% today to 15–16% at the expense the full use the available CEHP.

At the same time, in Austria hydropower plays a leading role in electricity (up to 62% in the overall balance) (the level of using the CEHP in the country amounts to 70%). Thermal power complements the balance (with a share of 35% in the structure of electricity production) [5].

In Ukraine, thermal power plants also generate a significant share of electricity (up to 45%). This means a constant dependence on coal, gas, etc. There are significant problems with the environmental pollution too. Therefore, plans to make fuller using the CEHP, as stated in the Program [1], are, at first glance, quite appropriate.

Finland, like Ukraine and Austria, also depends on the import of energy carriers (oil, gas, coal, nuclear fuel). Finland imported up to 10% of electricity too [5]. At the same time, according to data about the consumption level of per capita electricity, Finland is among the top five countries in Western Europe, and although in the 50–70s of the last century the main share of electricity in the country was produced by HPPs, now, in Finland, where there are still reserves of the CEHP (up to 25%, see Table 1) the authorities are cautious about the construction of new hydropower plants.

Thus, the comparative analysis of water-power characteristics of large hydropower plants of Ukraine, Finland, France and Austria can be interesting, informative and indicative.

Objects selected for comparison, input data and results of the analysis are given in the tables 5–8. Hydropower plants with large reservoirs and corresponding heads (up to 40 m) to provide maximum analogy with domestic HPPs were considered. Characteristics of installed capacities and annual power generation depending on reservoirs surface areas and HPPs' heads were compared.

Table 5 – The water-energy characteristics of large HPPs in Ukraine

Hydropower plant	Reservoir area *F*, km^2	Installed capacity *N*, MW	*F* / *N*, km^2 per MW	Power generation *E*, 10^6 kWh	*F* / *E*, km^2 per 10^6 kWh	Head *H*, m
Kakhovska	2155	351	6,140	1489	1,447	13,8
Kremenchug	2250	632,9	3,555	1506	1,494	14,2
Kyivska	922	408,5	2,257	683	1,350	12,0
Kanivska	675	444	1,520	972	0,694	11,0
Middle Dniprovska	567	352	1,611	1328	0,427	10,5
Dniprovska	410	1569	0,261	4008	0,102	34,3
Dnistrovska	142	702	0,202	865	0,164	40,0
Dniester HPP-2	6,1	40,8	0,150	105	0,058	11,4

The choice of reservoir areas (km^2) for determining the offered water-energy characteristics is explained by the fact that reservoirs are one of the main attributes of most domestic HPPs and the majority of negative impacts of the HPPs on the environment are associated with exploitation of their reservoirs [10, 11].

Table 6 – The water-energy characteristics of the selected HPPs of Austria

Hydropower plant	Reservoir area *F*, km^2	Installed capacity *N*, MW	*F* / *N*, km^2 per MW	Power generation *E*, 10^6 kWh	*F* / *E*, km^2 per 10^6 kWh	Head *H*, m
Annabruecke	3,5	90	0,039	390	0,009	24,3
Greifenstein	10	293	0,034	1752	0,006	12,6
Edling	10,5	87	0,121	407	0,026	21,5
Ybbs-Persenbeug	10	236,5	0,042	1370	0,007	10,9
Feistritz-Ludmannsdorf	3,3	88	0,038	351	0,009	27,0
Ferlach-Maria Rain	2,8	75	0,037	316	0,009	21,4

Table 7 – The water-energy characteristics of the selected HPPs of France

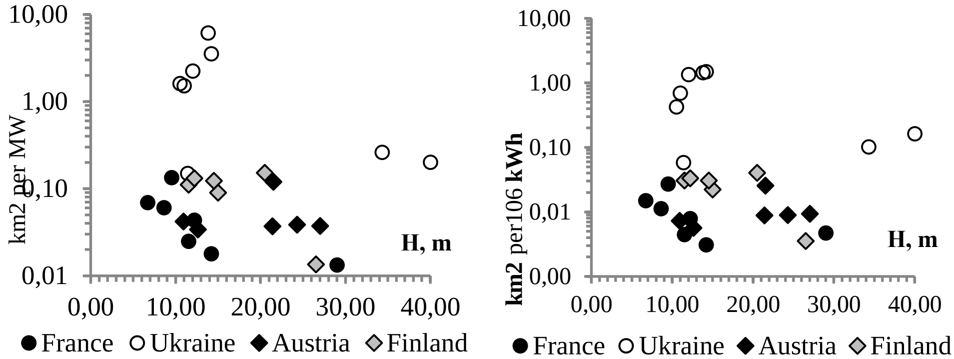
Hydropower plant	Reservoir area *F*, km^2	Installed capacity *N*, MW	*F* / *N*, km^2 per MW	Power generation *E*, 10^6 kWh	*F* / *E*, km^2 per 10^6 kWh	Head *H*, m
Vaugris	5	72	0,069	335	0,015	6,7
Gervans	3	120	0,025	668	0,004	11,5
Caderousse	9,5	156	0,061	843	0,011	8,6
Kembs	2,8	156	0,018	900	0,003	14,2
Sablons	7	160	0,044	885	0,008	12,2
Salignac	1,18	88	0,013	250	0,005	29
Sauveterre	7	52	0,135	257	0,027	9,5

Table 8 – The water-energy characteristics of the selected HPPs of Finland

Hydropower plant	Reservoir area *F*, km^2	Installed capacity *N*, MW	*F* / *N*, km^2 per MW	Power generation *E*, 10^6 kWh	*F* / *E*, km^2 per 10^6 kWh	Head *H*, m
Valajaskosken	11,3	101	0,112	365	0,031	11,5
Harjavalta	1,49	110	0,014	420	0,004	26,5
Isohaaran	15	113	0,133	450	0,033	12,2
Ossauskosken	11,2	124	0,090	501	0,022	15
Petäjäskosken	27,9	182	0,153	687	0,041	20,5
Taivalkosken	16,5	133	0,124	536	0,031	14,5

Graphically, the results of assessing the ratio of reservoirs surface areas to installed capacities (km^2 per MW) (a) and to generation of electricity (km^2 per 10^6 kWh) (b) at HPPs depending on the HPPs' heads are illustrated on Fig. 1. The obtained results may indicate a significant difference between the water-energy characteristics of most large hydropower plants in Ukraine compared to the corresponding characteristics of HPPs in Finland, France and Austria; this difference is not in favour of our facilities.

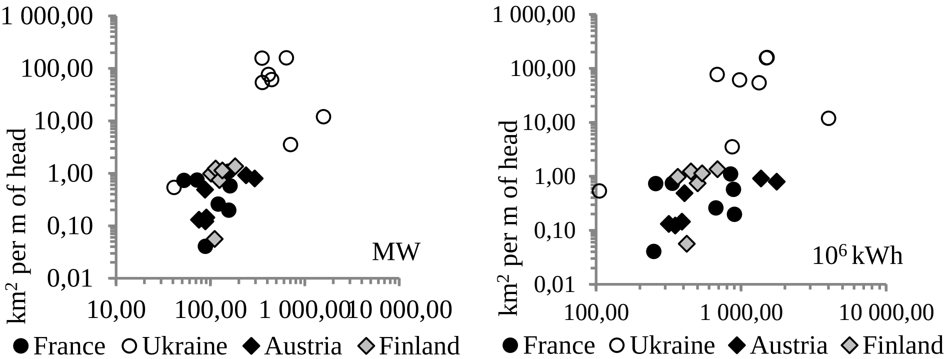
The Dniester HPP-2 is the only domestic HPP, which, according to the offered water-energy indicators, is a rather similar one to corresponding hydropower plants of Finland, Austria and France. At the same time, along with a significant variability of estimates of the indicators for our HPPs an essential similarity of these indicators for French, Austrian and Finnish objects has been received.



a) b)

Fig. 1 – Comparison the water-energy characteristics of hydropower plants of Ukraine, Finland, Austria and France

Similar conclusions (see Fig. 2) can be formulated on the results of comparing the ratio of reservoirs surface areas to HPPs' heads (km^2 per m of head) depending on installed capacity (a) and electricity generation (b).



a) b)

Fig. 2 – Comparison the ratio of reservoirs surface areas to HPPs' heads (km^2 per m) depending on installed capacity (a) and electricity generation (b) for HPPs of Ukraine, Finland, Austria and France

It is seen that established water-energy characteristics of the large Ukraine's HPPs are rather worse in comparison with corresponding characteristics of the similar French, Austrian and Finnish HPPs.

In particular, average estimates of these indicators are as follows:

– specific surface areas of reservoirs of the large hydropower plants of Ukraine of Dnipro and Dnistrovsky cascades: 1,962 km^2 per MW of installed capacity; 0,717 km^2 per 10^6 kWh of produced electricity; 65,36 km^2 per m of head;

– specific surface areas of reservoirs of the similar hydropower plants in Austria: 0,052 km^2 per MW of installed capacity; 0,011 km^2 per 10^6 kWh of produced electricity; 0,433 km^2 per m of head; the indicators are less than the corresponding indicators of the Ukrainian hydropower plants essentially; in 37 times, 65 and 151 times, respectively;

– specific surface areas of reservoirs of the similar hydropower plants in France: 0,052 km^2 per MW of installed capacity; 0,010 km^2 per 10^6 kWh of produced electricity; 0,523 km^2 per m of head; the indicators are less than the corresponding indicators of the Ukrainian hydropower plants essentially; in 37 times, 68 and 124 times, respectively;

– specific surface areas of reservoirs of the similar hydropower plants in Finland: 0,122 km^2 per MW of installed capacity; 0,031 km^2 per 10^6 kWh of produced electricity; 1,054 km^2 per m of head; and again, the indicators are less than the corresponding indicators of the Ukrainian hydropower plants essentially; in 16 times, 23 and 62 times, respectively.

Conclusions

A comparative analysis of peculiarities of using the cost-effective hydropower potential in Ukraine and in the world was conducted. The analysis was as formalized as possible. Key circumstances of construction and operation of HPPs in different countries, including subjective ones, were not taken into account. In particular, it was not taken into account what particular areas were flooded by reservoirs, whether the elimination of settlements was conducted and how exploitation of reservoirs influenced the hydrology of the rivers, the environment, etc. It was assumed that all these circumstances for HPPs that were built in Ukraine and in other countries were similar.

According to results of the comparative analysis, significant differences in approaches to hydropower development in Ukraine and in the world, in particular in European countries such as France, Austria and Finland were revealed. These differences can be related not only to different topographical and other natural conditions of countries, but also to different approaches of taking into account socio-environmental factors in decision-making concerning hydropower and assessing negative consequences this activity for the environment.

In general, the analysis showed that natural and geographical conditions of Ukraine are not favorable for hydropower development in the context of sustainable development of territories and rational nature resources use, minimization of socio-environmental risks. Therefore, schemes and decisions regarding to assessing and using the available hydropower potential in Ukraine cannot be simple, standard, aimed only at solving current problems.

Prospects for hydropower development in Ukraine should be sought in deep modernization and reconstruction of existing HPPs. For example, the modernization of hydropower equipment on existing hydropower plants and the construction of the Kakhovka HPP-2 within the existing Kakhovka HPP can be considered as the best solution among possible options [1]. It is also necessary to review the operation modes of existing hydropower plants, especially our large Dnipro and Dnister HPPs, in order to increase efficiency of using their installed capacity. This approach will help to resolve some of the rather complicated environmental problems created by construction and exploitation of these HPPs.

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Стефанишин Д.В.
ПРО ОСОБЛИВОСТІ РОЗВИТКУ ГІДРОЕНЕРГЕТИКИ В СВІТІ І В УКРАЇНІ

Анотація. Наведено результати порівняльного аналізу особливостей використання доступного гідроенергетичного потенціалу в світі та в Україні. Аналіз здійснювався на основі наявних даних щодо економічно ефективного гідроенергетичного потенціалу в різних країнах світу, встановленої потужності об'єктів гідрогенерації і виробітку електроенергії на них, даних щодо площ водосховищ та напорів на гідроелектростанціях (ГЕС). В якості аналогів вітчизняних ГЕС при порівнянні розглядалися ГЕС Франції, Австрії та Фінляндії. Запропоновано показники, за якими можна оцінювати соціально-економічну привабливість ГЕС та їх вплив на довкілля. Отримані результати вказують на відмінність між встановленими показниками ГЕС України та зарубіжними ГЕС, не на користь вітчизняних об'єктів.

Ключові слова: вплив на довкілля, гідроенергетика, економічно ефективний гідроенергетичний потенціал, порівняльний аналіз.

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Стефанишин Д.В. **Про особливості розвитку гідроенергетики в світі і в Україні** // Екологічна безпека та природокористування. – 2018. – Вип. 1 (25). – С. 12–23.
Наведено результати порівняльного аналізу особливостей використання доступного гідроенергетичного потенціалу в світі та в Україні. Запропоновано показники, за якими можна оцінювати соціально-економічну привабливість ГЕС та їх вплив на довкілля. Отримані результати вказують на відмінність між встановленими показниками ГЕС України та зарубіжними ГЕС (Франції, Австрії та Фінляндії), не на користь вітчизняних об'єктів.

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Stefanyshyn D. **On peculiarities of hydropower development in the world and in Ukraine** // Environmental safety and natural resources. – 2018. – Issue 1 (25). – P. 12–23.
There have been presented results of a comparative analysis of features of hydropower development in the world and in Ukraine. There were offered indicators that enable to estimate socio-economic attractiveness of HPPs and their impact on the environment. The results show a difference between the indicators of Ukrainian HPPs and foreign HPPs' ones of France, Austria and Finland, and this difference is not in favour of domestic objects.

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