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Comparison of cost indicators of Ukrainian wind farms with cost indicators of wind energy global producers

V Podhurenko¹, Yu Kutsan² and V Terekhov²

¹ Admiral Makarov National University of Shipbuilding, 9 Prospect of Heroes of Ukraine, Nikolayev, Ukraine, 54025.

² G.E. Pukhov Institute of Problems Modeling in Energetics NAS of Ukraine, 15 General Naumov Street, Kyiv, Ukraine, 02000

E-mail: vl.terekhov86@gmail.com

Abstract. Efficiency improvement in wind conversion field is the most critical scientific-and-technical problem, which is chiefly settled by increasing the power of wind turbines. A new technique was pioneered for determining the efficiency of wind turbines operation in the wind conditions of the Northern Black Sea region of Ukraine. It is found out that the main parameters that have an impact on the cost of electricity are as follows: the cost of a wind turbine itself and annual electric energy production. The cost indicators of wind turbines of the Ukrainian wind farms were defined in the wind conditions of the Northern Black Sea region in 2018, according to which it was ascertained that the cost of electric energy generated in Ukraine was by 17 % cheaper as compared to the world cost value. In illustration of application of the first ever developed technique, we have made the assessment of effective operation of the Ukrainian wind farms in the years of 2019 – 2020. The results obtained bear compelling evidence as to the correlations between the cost of produced electric energy and the size of wind turbines. In view of the above, application of wind turbines of super-large sizes in the conditions of the Northern Black Sea area of Ukraine (as well as in other regions of the world) is hardly expedient due to increase in the cost of electric power generated by them.

1. Introduction

Ukraine possesses extensive resources of wind energy and owing to its individual natural and climatic characteristics it can take the lead in the world in wind energy utilization [1]. It is possible to attain the declared results only by choosing a wind turbine (WT) with optimal quality-price ratio, which generates least-cost electric power.

The first-ever developed mathematical models [2] allow to estimate the cost indicators of Ukrainian wind farms.

2. Assessment of efficiency of Ukrainian wind farms operation in 2018

In our further assessment we will be orienting towards the following data:

1) In the year of 2018, the cost of electric energy (COE) for land WT with parameters $P = 2.4$ MW, $D = 115.6$ m, $H = 88.1$ m and with annual electricity production $AEP = 8755$ MW·h amounted to \$42/MW·h [3].



2) Global COE generated by land-based wind power stations (WPS) amounted in 2018 to \$56/MW·h and in 2019 – to \$53/MW·h, with expected decrease in 2020–2021 to \$45 – 43 per MW·h, respectively [4,5].

Let us determine and compare with the above information the energy cost values for the most in-demand Ukrainian WTs in 2018. An example of calculation of COE for Fuhrlander FL 2.5 – 100 wind turbine. By using the first-ever developed mathematical models obtained in [2], we can calculate the initial data:

$P_{18} = 2.55$ MW; $D_{18} = 104$ m; $H_{18} = 104$ m; $FCR_{18} = 0.075$; $AC_{18} = \$0.9568$ mln/MW; $k_{18} = 0.936$; $c_{18} = \$0.895$ mln/MW; $C_{18} = \$2.238$ mln; $CapEx_{18} = \$2.984$ mln and from [6, 7] $AEP = 8879$ MW·h; capacity factor $CF = 40.5\%$.

$$COE = (0.075 \cdot 2.984 \cdot 10^6 + 44 \cdot 2.5 \cdot 10^3) / 8879 = \$37.6/\text{MW}.$$

Calculations of COE for other WTs were determined in a similar way (Table 1).

Under the conditions of information deficit, when the values of annual operating expenses OpEx and of fixed charge rates FCR are taken as equal for all sizes of the WTs under consideration, and initial capital expenses CapEx are determined only in accordance with WT cost C , the main parameters influencing the energy cost COE come out to be the WT cost C and AEP. When choosing WT, in order to avoid the necessity of additional calculations and of required data search, it is possible to use indicator C/AEP , which characterizes the value of COE that ensures covering of expenses for purchasing WT in a single year.

Table 1. WT indicators of Ukrainian wind farms in 2018.

WT	AEP (MW·h)	CF (%)	k_{18} (r.u.)*	c_{18} (\$ mln/ MW·h)	C_{18} (\$ mln)	$CapEx_{18}$ (\$ mln)	COE (\$/ MW·h)	$C_{18} \cdot 10^6 /$ AEP (\$/MW·h)
FL 2500 – 100 $P = 2.5$; $D = 100$; $H = 100$	8 879	40.5	0.936	0.895	2.238	2.984	37.59	252.0
WTU 3.0 $P = 3.0$; $D = 120$; $H = 100$	11 504	43.8	1.106	1.059	3.176	4.234	39.08	276.1
WTU 3.2 $P = 3.2$; $D = 120$; $H = 100$	11 774	42.0	1.051	1.006	3.219	4.292	39.30	273.4
V 112 $P = 3.075$; $D = 112$; $H = 94$	10 652	39.5	0.938	0.897	2.758	3.678	38.60	259.0
V 112 $P = 3.3$; $D = 112$; $H = 94$	10 955	37.9	0.876	0.838	2.765	3.687	38.49	252.4
V 126 $P = 3.45$; $D = 126$; $H = 117$	13 186	43.6	1.146	1.096	3.781	5.042	40.19	286.8
V 126 $P = 3.65$; $D = 126$; $H = 117$	13 455	42.1	1.091	1.043	3.808	5.078	40.24	283.0
GE 3.6 $P = 3.6$; $D = 137$; $H = 131$	14 864	47.1	1.332	1.274	4.587	6.117	41.52	308.6
$P_{18} = 2.55$ MW; $D_{18} = 104$ m; $H_{18} = 104$ m; $AC_{18} = 0.9568$ \$ mln/MW								

Note: * r.u. – relative unit.

The analysis of COE of Ukrainian multimegawatt WTs speaks volumes about increase in value with the growth of WT sizes. Its range of variation in 2018 amounted from \$37.6/MW·h to \$41.5/MW·h (more than 9%), yet the range of C/AEP variation is twice as large (18.3 %), which is indicative of crucial importance of WT choice for WPS particular construction site.

Let us, for the sake of discussion, place the reference WT [3] ($P = 2.4$ MW; $D = 115.6$ m, $H = 88.1$ m) in the wind conditions of the Northern Black Sea region, the said WT characterizing average parameters of the US wind farms being commissioned in 2018 with the following indices: $AEP = 9368$ MW·h; $CF = 47.2\%$ [6, 7]; $AC_{18} = 0.9568$; $k = 1.153$; $C = 1.103$; $CapEx = 1.471$; $COE = 37.3$ [2].

COE of US reference WT has almost coincided with the COE of the smallest WT FL 2500–100 installed in Ukraine. It is evidently for this reason that the USA, as opposed to Ukraine, were in no haste in 2018 to install more powerful WTs because of increase in the cost of generated power.

Back to initial data [3]. For US reference WT the following is indicated: energy production the same cost value amounted to \$42.3/MW·h (the values have basically coincided), which fact proves the accuracy of the method. In 2018 the actual COE on a global level amounted to \$56/MW·h [4]. In accordance with [8], generally recognized losses in energy production are estimated at 15%. The calculation shows that losses lead to increase of COE by a factor of 1.176, i.e. world theoretical value C_T without losses is equal to \$47.6/MW·h. Comparison of this value with the data given in Table 1 (the next-to-last column) demonstrates significant reduction in value of the electric energy produced in Ukraine, on average by more than 17% of global value (minimum – by 13%, maximum – by 21%).

3. Assessment of wind farms operating efficiency in Ukraine in 2019

Table 2 contains cost indicators of Ukrainian wind farms operation in 2019 making use of the values of FCR (fixed charge rate) and OpEx (operational expenses) from [9]. The tendency of increase in electrical power theoretical cost C_T and actual cost C_{Act} and their range of variation have practically increased by 14% (from \$37.4/MW·h to \$42.6/MW·h for C_{Act}).

Table 2. WT indicators of Ukrainian wind farms in 2019.

WT	AEP		c_{19} (\$ mln/MW)	C_{19} , (\$ mln)	CapEx ₁₉ (\$ mln)	COE (\$/MW·h)	
	(MW·h)	k_{19} (r.u.)				C_T	C_{Act}
FL 2500 – 100 $P = 2.5; D = 100; H = 100$	8 879	0.899	0.808	2.020	2.693	31.83	37.43
WTU 3.0 $P = 3.0; D = 120; H = 100$	11 504	1.070	0.961	2.884	3.845	32.95	38.75
V 112 $P = 3.075; D = 112; H = 94$	10 652	0.901	0.810	2.490	3.320	32.68	38.43
WTU 3.2 $P = 3.2; D = 120; H = 100$	11 774	1.015	0.912	2.919	3.892	33.18	39.02
V 112 $P = 3.3; D = 112; H = 94$	10 955	0.839	0.754	2.488	3.317	32.65	38.40
WTU 3.3 $P = 3.3; D = 120; H = 100$	11 908	0.987	0.887	2.928	3.904	33.24	39.09
V 126 $P = 3.45; D = 126; H = 117$	13 186	1.109	0.997	3.439	4.585	33.86	39.82
WTU 3.5 $P = 3.5; D = 138; H = 100$	13 934	1.223	1.100	3.794	5.059	34.48	40.55
GE 3.6 $P = 3.6; D = 137; H = 131$	14 864	1.295	1.164	4.191	5.588	34.86	41.00
V 126 $P = 3.65; D = 126; H = 117$	13 455	1.054	0.947	3.457	4.609	33.94	39.91
V 126 $P = 3.8; D = 126; H = 112$	13 514	0.992	0.892	3.388	4.517	33.83	39.78
GE 3.8 $P = 3.8; D = 137; H = 110$	14 529	1.153	1.037	3.939	5.252	34.75	40.87
WTU 4.5 $P = 4.5; D = 151; H = 120$	17 126	1.218	1.095	4.926	6.568	36.24	42.62
WTU 4.8 $P = 4.8; D = 151; H = 120$	17 531	1.135	1.021	4.899	6.532	36.00	42.34
$P_{19} = 2.6 \text{ MW}; D_{19} = 106.8 \text{ m}; H_{19} = 105.8 \text{ m}; AC_{19} = 0.899 \text{ \$ mln/MW}$							

We can also observe from Table 2 that actual value of COE for all WTs of Ukrainian wind farms has risen beyond \$ 37 mln/MW of the average size WT, operated in the USA in 2019, minimum by 1.2 % (FL 2500 – 100), maximum by 15.2 % (WTU 4.5). Practically, the COE of the smallest WT FL 2500 – 100 installed in Ukraine have coincided with it. Isn't it for that reason that the USA, as distinct from Ukraine, were in no haste in 2019 to install more powerful WTs in order not to raise the cost of the electricity produced? So, for instance, average generating capacity of WT in the USA in 2019 amounted to 2.5 MW, in China – to 2.4 MW [10], whereas in India the average installed rated power even decreased from 1.93 to 1.89 MW in 2018 [11].

4. Assessment of wind farms operating efficiency in Ukraine in 2020

We will place, for the purposes of discussion, the WTs operating as a part of various wind farms of Ukraine in the wind conditions of the Northern Black Sea region and, as an example of practical application of the first-ever developed technique, we will estimate their operating efficiency in 2020.

With the aid of the first-ever proposed mathematical model [6, 7] there were determined the theoretical values of AEP and capacity factors CF for WTs, which were used as basic integral globally recognized criterion for placing them in the rating list (Table 3).

Table 3. WT indicators of Ukrainian wind farms in 2020.

No.	WT	AEP (MW·h)	CF	
			(%)	rating
1	FL 2500 – 100 $P = 2.5; D = 100; H = 100$	8 879	40.5	14
2	WTU 3.0 $P = 3.0; D = 120; H = 100$	11 504	43.8	4
3	V 112 $P = 3.075; D = 112; H = 94$	10 652	39.5	15
4	V 112 $P = 3.075; D = 112; H = 119$	11 372	42.2	8
5	WTU 3.2 $P = 3.2; D = 120; H = 100$	11 774	42.0	10
6	V 112 $P = 3.3; D = 112; H = 94$	10 955	37.9	16
7	WTU 3.3 $P = 3.3; D = 120; H = 100$	11 908	41.2	12
8	V 126 $P = 3.45; D = 126; H = 117$	13 186	43.6	5
9	WTU 3.5 $P = 3.5; D = 138; H = 100$	13 934	45.4	2
10	GE 3.6 $P = 3.6; D = 137; H = 131$	14 864	47.1	1
11	V 126 $P = 3.65; D = 126; H = 117$	13 455	42.1	9
12	V 136 $P = 3.65; D = 136; H = 120$	14 517	45.4	3
13	V 126 $P = 3.8; D = 126; H = 112$	13 514	40.6	13
14	GE 3.8 $P = 3.8; D = 137; H = 110$	14 529	43.6	6
15	WTU 4.5 $P = 4.5; D = 151; H = 120$	17 126	43.4	7
16	WTU 4.8 $P = 4.8; D = 151; H = 120$	17 531	41.7	11

The places occupied in the rating list, on the whole, prove dependence of AEP on the value of rated power P , whose increase leads to increase in energy production. However, the rating based on CF criterion obviously demonstrates that high figures of electricity production can be attained by means of qualitative choice of parameters irrespective of the rated power value as it appears, for instance, from rating correlation of line 10 with line 13 (nearly 14% difference), with line 16 (11.5% difference) and with other lines (12, 14 and 15). The first place in the rating list was taken by WT GE 3.6 (line 10). Common sense seems to tell us that of the sixteen WT sizes we would obtain the most effective result if wind farms are equipped with that particular WT. And such argument would correspond to the existing global trend and practice. Yet the present-day industrial WPS's belong, first and foremost, to the category of business ventures. Hence, they should be estimated from the standpoint of economic expediency and investment attractiveness according to the first-ever offered calculation algorithm [2].

First, it is necessary to determine numerical average values of the parameters of the WT considered as a reference one in 2020:

$$P_{20} = 2.7 \text{ MW}; D_{20} = 109 \text{ m}; H_{20} = 108 \text{ m};$$

$$k_{20} = 1 - 0.27505 (P - P_{20}) + 0.01542 (D - D_{20}) + 0.00414 (H - H_{20})$$

cost values C_{20} of each of the 16 WTs, and on their basis to calculate the cost values of produced energy C_T and C_{Act} , C/AEP values, cost of 1 kW of WT installed capacity C_{kW} and, for example, payback time L in years.

The results of these researches are shown in Table 4 wherein WT serial numbers correspond to the serial numbers in Table 3. Comparison of the places, occupied in the rating list, as illustrated in Tables 3 and 4, obviously demonstrates the inverse relationship in terms of cost indices.

Which of the WTs is the most effective for the wind conditions of the Northern Black Sea region? The answer will be obtained by comparing cost indices and places occupied in the rating list.

Let's consider, for the purposes of discussion, one of the most powerful WT – GE 3.6 (line 10) and compare with the indices of WT with lesser power. The comparison shows that the cost of GE 3.6 is higher by a factor of 1.4 – 1.7 than the cost of other WTs (lines 2 – 6) and almost by a factor of 2.1 more expensive than WT FL 2500 – 100 (line 1). Also, the actual cost of the electric energy generated by it is higher too, and the energy cost generated by WT WTU 4.5 (line 16) is still higher.

Table 4. Cost indices of WTs in Ukrainian wind farms in 2020

No.	k	C_{20}		C_T	C_{Act}	C / AEP			C_{kW}		L	
	(r.u.)	(\$ mln)	rating	(\$/MW·h)	rating	(\$/MW·h)	rating	(\$)	rating	(years)	rating	
1	0.883	1.859	1	30.25	35.57	1	209.4	2	743.6	2	7.8	2
2	1.054	2.661	5	31.27	36.77	5	231.4	8	887.5	9	8.4	9
3	0.885	2.292	3	31.06	36.53	3	215.2	3	745.3	3	7.9	3
4	0.989	2.560	4	31.14	36.62	4	225.1	4	832.4	6	8.2	5
5	0.999	2.692	6	31.50	37.04	6	228.6	6	841.1	7	8.2	6
6	0.823	2.288	2	31.05	36.51	2	208.8	1	693.2	1	7.6	1
7	0.971	2.699	7	31.56	37.11	7	226.7	5	818.0	4	8.1	4
8	1.093	3.175	9	32.12	37.77	8	240.8	10	920.4	10	8.5	10
9	1.194	3.519	11	32.69	38.44	11	252.5	12	1005.5	14	8.8	13
10	1.279	3.878	14	33.03	38.84	14	260.9	15	1077.3	15	9.0	16
11	1.038	3.190	10	32.21	37.88	10	237.1	9	874.1	8	8.3	8
12	1.192	3.664	13	32.88	38.67	12	253.9	13	1003.9	13	8.8	14
13	0.976	3.123	8	32.12	37.77	9	231.1	7	821.9	5	8.2	7
14	1.137	3.639	12	32.96	38.76	13	250.5	11	957.8	12	8.6	11
15	1.202	4.555	16	34.35	40.40	16	266.0	16	1012.3	16	8.8	15
16	1.120	4.525	15	34.15	40.16	15	258.1	14	942.8	11	8.6	12

$$P_{20} = 2.7 \text{ MW}; D_{20} = 109 \text{ m}; H_{20} = 108 \text{ m}; AC_{20} = 0.842 \text{ \$ mln/MW}.$$

$$FCR = 0.065; OpEx = 43.0 \text{ \$/kW in 2019 [8]}$$

In terms of cost values per 1 kW power, C/AEP values and payback time L , WT GE 3.6 occupies the last places in the rating list, whereas WTs FL 2500–100 and V112 come out on top with far lesser indices of cost and power production (Table 3).

Whilst in 2018, maximum rated power of WT in Ukraine did not exceed 3.6 MW, yet following the global trend, in 2020 there appeared WTs with power up to 4.8 MW, which fact has materially worsened the cost statistics.

Comparative analysis of the results of Table 4 and of global average cost indices of 2020 [12] demonstrates the behavior pattern of reducing the difference between the global average cost of produced energy and that of Ukrainian wind farms from 17% in 2018 to 3% in 2020. As regards the cost of 1 kW of installed capacity for WTs of Ukrainian wind farms, there has been observed exceedance of global average indices of \$ 700 – 910 for 7 WTs of 16 WTs.

But then again, the stand of the USA, China and India on the matter of equipping their wind farms with wind turbines of relatively low rated power proves the validity and importance of the set of studies conducted by the authors.

It is necessary to place the emphasis on difference of the tasks for various countries in the world that are involved in development of wind power industry.

The countries with good wind power potential, but with limited possibilities in terms of selecting appropriate sites for WPS construction (chiefly, European countries) follow the course of steady growth of WT indices, such as, for example, GE 3.6 in Table 3. Maximum average installed rated power, for instance, is observed in Finland – 4.2 MW, in Norway – 3.8 MW [10]. What counts most for them is more “green” electricity at any price. The countries that are practically not limited in respect of site selection (USA, China, India, Ukraine and others) are faced with quite a different task – attaining electric power at minimum cost. Solution of the task is of great current interest and importance, for Ukraine in particular. Hence, apparent practical value and good perspectives of the presented research.

The results of the rating convincingly demonstrate that WTs of large sizes remain still too expensive, therefore their use in the wind conditions of the Northern Black Sea region of Ukraine is of doubtful value.

5. Conclusions

With the help of the developed models, it turned out to be possible to calculate the cost of electric power generated by the Ukrainian wind farms, which fact allowed to analyze for the first time ever the economic efficiency of their operation. The relationship was defined between the electric power cost and WT sizes, and also the fact of insufficient profitability was found out regarding the employing of WTs of super-large sizes in the wind conditions of the Northern Black Sea area of Ukraine (as well as in other regions of the world).

The wind power potential of the Northern Black Sea area with regard for cost indices allows producing electric power at much cheaper cost as compared to the global electric power cost.

A set of conducted studies recommends the owners of Ukrainian industrial wind farms to follow not only the global tendencies but also to be necessarily guided by specialists’ recommendations in the choice of WTs for WPS particular construction site.

The set of undertaken scientific investigations ensures the construction of WPSs with optimal cost indices-based choice, which fact allows to propel Ukraine into the world leaders in the field of wind conversion.

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