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Prospects for the Development of Energy in the World and Ukraine: A Novel View

Abstract The main priorities in the development of the energy industry both in Ukraine and in the world are considered. The analysis of the use of different energy sources in the world and in Ukraine, in particular gas, coal, nuclear energy, oil, and renewable energy sources, is carried out. The results of research by scientists in the energy industry, which are based in the Department of Physical and Technical Problems of Energy of the National Academy of Sciences of Ukraine, are presented. The main results are divided into four categories: electrical engineering, heat power engineering, cybersecurity and computer science, environmental safety. A special contribution to the creation of this book belongs to young scientists of the National Academy of Sciences of Ukraine.

Priority Areas of Energy Development

Energy is the basis for ensuring industrial production, the provision of services in the transport sector, the functioning of housing and communal services, the creation of favorable living conditions for the population, and energy is an industry, which largely determines the level of socio-economic development of the country. An important priority for the development of the energy sector in the long term should be the minimization of risks: economic, social, environmental, which should make the development of energy and the entire economy of any country sustainable.

Today's global energy market is hard to compare with the past, even within 5–10 years. The global striving for energy independence, environmental friendliness, global price fluctuations irrevocably change the usual relationship in the energy market. Renewable sources are no longer alternative. They are no longer the privilege of developed countries. Currently, many developing countries spend more on renewable energy sources than developed ones. A striking example in this matter is the experience of Ukraine in attracting foreign investment for the development of infrastructure for renewable energy sources.

Contents

Simulation of Efficiency Enhancement of Electric Power Generation by Wind Turbines in Wind Cadaster Various Zones

Volodymyr Podgurenko, Yulii Kutsan, Oleg Getmanets, and Volodymyr Terekhov

Abstract Based on the multi-year measurements of wind velocity and its distribution according to wind velocity levels at the Adzhigol pilot wind power station, the quantitative indicators of 43 wind turbines of megawatt-class by the world's major manufacturers were analyzed in various wind cadaster zones. The obtained parameters (energy production and operation time in various zones of wind cadaster) were taken as a basis for the developed mathematical models of optimal power generation by a wind turbine. A new mathematical model was pioneered for calculating a capacity factor with regard for the operation time period in the zone of strong winds and also a new model of multiple linear regression for defining the dependence of the operation duration in the zone of strong winds upon the hub height and rated wind speed of power characteristic of the wind turbine. The said models enable the calculation of annual production of electric power based only on the three passport parameters (rating, hub height and rated wind speed of the wind turbine) without reference to power curve and wind cadaster of expected construction site of the wind power station. Software-based methods of computer-assisted realization of these models are suggested in the article. An example is given regarding enhancement of operating efficiency for industrial wind power station owing to increase of operation time in the strong winds zone at the wind conditions of the Northern Black Sea region of Ukraine.

Keywords Wind turbine · Wind power station · Wind cadaster zones · Mathematical model · Efficiency

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1 Introduction

It is common knowledge that distribution of the wind velocity throughout the year adheres to the laws of probability. In such a case, wind velocity probability maximum distribution is, basically, asymmetrical towards low winds, and a mean wind velocity is always observed to its right [1] (Fig. 1).

From the entire wind cadaster it is possible to single out three typical zones [2, 3]: *A*—low winds, when a wind turbine (WT) cannot work at all ($V < V_{min}$), as a rule $V_{min} = 3$–4 m/s, which is below the starting one for the majority of WTs; *B*—medium winds ($V_{min} < V < V_{rate}$), usually 4–13 m/s, when WT operates not in a rated mode, at a reduced power; *C*—high winds ($V_{rate} < V < V_{max}$), usually 13–25 m/s, when WT operates in a rated mode, at full power. It is an obvious point that the best option, a so-called optimum, of utilizing the capacity will be in zone *C*, whereas a less effective variant will be in zone *B*. In numerous research papers by foreign authors dedicated to wind technologies, to the authors' knowledge, the matter relating to the WT operating efficiency in various zones has not yet been studied. Cavallo [4] alone implicitly points to the relationship between low values of capacity factor (CF) with short duration of operation in the zone of rated power (in our case, in zone *C*). Gipe [5] in his fundamental monograph "Wind energy comes of age" not only states that

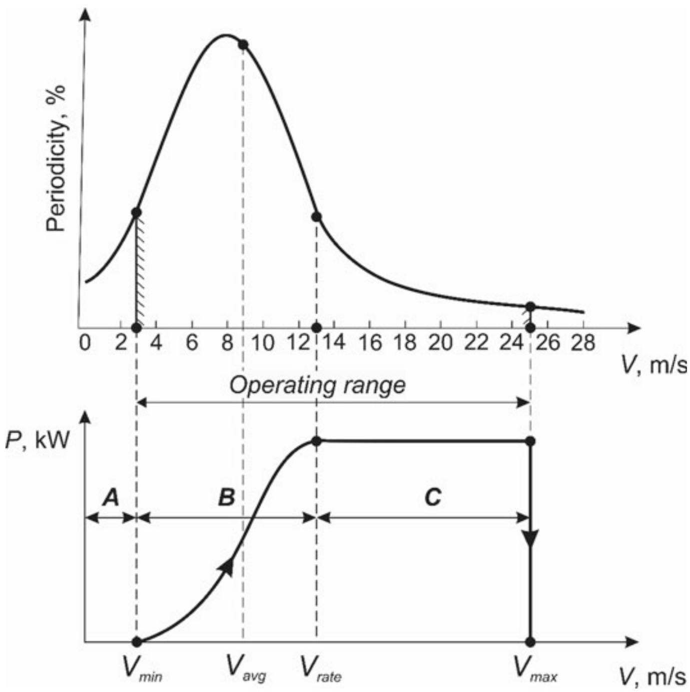

Fig. 1 Typical zones of wind cadaster

WTs, as compared to traditional electric power installations, rarely operate at rated power for a long time, but he also elucidates the point. The WT capacity in terms of generating capacity should be evaluated not by generator power, but by the size of rotor diameter. Evaluations of WT in kilowatts give but a rough idea of how much power can be generated, whereas the rotor diameter is a far surer indicator.

WT evaluations based on generator capacity were borrowed from the networking engineers who described them using the term well known to them: generator size. WT manufacturers persist in using a rated power for the purpose of identifying their products, though a rated power conveys little as to the quantity of power to be generated by WT. Regretfully, a rated power is on an upward trend all over the world. With this in mind, when choosing WT and the sites for wind power stations (WPS) construction, it is vitally important to assess the operation duration of a particular WT in zone *C* at a chosen site and, if required, to ensure the possibility of increasing the same.

2 Methods

The construction of industrial WPS in the Northern Black Sea region is being carried out on the adjacent to the Adzhigol pilot wind power station (AWPS) territories, for which the distribution according to velocity levels has been adequately researched [6, 7].

Figure 2 presents the distribution of wind velocities probability at wind vane height of 31.5 m based on the results of the wind velocity measurements at the AWPS site taken with the aid of the measuring complex NRG LOGGER Symphonie

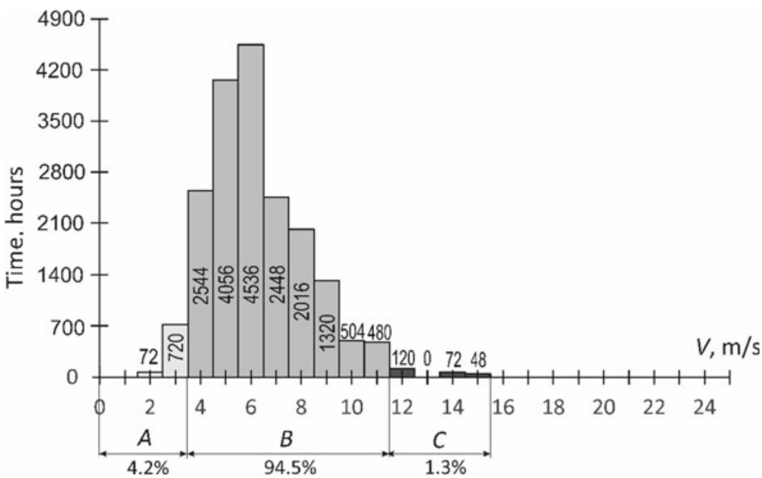

Fig. 2 Distribution of wind velocities probability at the wind vane height of 31.5 m

9200 (USA) for a period of 26 months (from May 1997 till March 1999 and from August till October 2003 [6]).

Figure 2 shows that WT (rated wind speed is 12 m/s) operates in a rated mode during only 1.3% of calendar time, i.e. there is available an unused reserve for enhancement of operating efficiency of WT (WPS) due to increase of operation time in zone *C*.

The paper [8] presents a detailed analysis of the WT parameters effect (generator rated power *P*, rotor diameter *D* and hub height *H*) upon annual energy production *Q* by means of simulated deployment of 43 WTs of megawatt class by major world manufacturers (Table 1) in the wind conditions of AWPS.

For the above-mentioned set of WTs, the operation time in zone *C* was determined for further study of its influence on a full annual energy production *Q*.

For the above-mentioned set of WTs, the operation time in zone *C* was determined for further study of its influence on a full annual energy production *Q*.

Over the years of observation, a mean wind speed, by the results of the measurements taken by a representative meteorological station (MS), corrected to the measurements conditions at the AWPS site (the wind vane height of 31.5 m), amounted to 6.0 m/s [6, 7]. This wind speed was taken as a basic minimum value for calculations to be made by various methods, thus, in our opinion, providing most reliable prediction for a long period of WPS operation.

To evaluate the volume of electric power generation by various WTs, it is necessary to recalculate the wind speed levels with regard for the hub height of the WTs under examination instead of the wind vane location heights. For recalculation of wind velocities at various heights, the approximate power-law relation suggested by Hellman [9, 10] was applied:

$$\frac{V_{hub}}{V_{wane}} = \left(\frac{h_{hub}}{h_{wane}}\right)^m. \tag{1}$$

where: V_{wane}—wind speed at wind vane height = 31.5 m; V_{hub}—sought-for value of wind speed at hub height of the WT under investigation; *m*—wind shear exponent whose value is chosen depending upon the type of underlying surface at the WT site (a so-called vertical profile coefficient of wind velocity). According to special studies [6, 7], for the AWPS wind conditions, a mean value of $m = 0.227$.

Having adapted the formula (1) for the Eq. (2) below, it will be possible to determine the wind velocities on the rotor arrangement axes (speed at the hub heights) of the WTs under consideration in the AWPS conditions.

$$V_{hub} = V_{wane}\left(\frac{h_{hub}}{h_{wane}}\right)^m = V_{wane}\left(\frac{h_{hub}}{31.5}\right)^{0.227}. \tag{2}$$

Table 2 presents calculated quantitative data of WT operation from Table 1 in various zones of wind cadaster for typical wind conditions of AWPS.

It should be noted that the operation time in zone *C* for WT with $H > 100$ m is comparatively short and only comes to 17.2% of the calendar time (see Nos. 36

Table 1 Operation indices of WTs by some global major companies

No	Manufacturer, WT	P, MW	D, m	H, m	Q, MW·h	CF, %	V_{rate}, m/s
LEITWIND							
1	LTW70	1.7	70	65	4167	28.0	12
2	LTW77	1.5	77	65	4471	34.0	12
3	—‖—	1.5	77	80	4792	36.5	12
4	LTW80	1.5	80.3	60	4541	34.6	10.5
5	—‖—	1.5	80.3	80	5155	39.2	10.5
ENERCON							
6	E66/20.70	1.8	70	99	5295	33.6	12.5
7	E70–2.3	2.3	71	57	4564	22.7	14.5
8	—‖—	2.3	71	100	6221	30.9	14.5
9	—‖—	2.3	71	113	6491	32.2	14.5
10	E82–2.0	2.0	82	78	6284	35.9	12.4
11	E82–2.0	2.0	82	100	6899	39.4	12.4
12	—‖—	2.0	82	138	7819	44.5	12.4
MITSUBISHI							
13	MWT92–2.4	2.4	92	70	6746	32.1	12.5
VESTAS							
14	V80–2.0	2.0	80	78	5440	31.1	15
15	—‖—	2.0	80	80	5599	32.0	15
16	—‖—	2.0	80	100	6095	34.8	12
17	V90–1.8	1.8	90	80	6126	38.9	12
18	—‖—	1.8	90	95	6599	41.9	12
19	—‖—	1.8	90	105	6806	43.2	12
20	V90–2.0	2.0	90	95	6882	39.3	12
21	—‖—	2.0	90	105	7171	40.9	12
22	—‖—	2.0	90	125	7454	42.6	15
23	V90–3.0	3.0	90	80	7855	29.9	15

(continued)

Table 1 (continued)

No	Manufacturer, WT	P, MW	D, m	H, m	Q, MW·h	CF, %	V_{rate}, m/s
24	—‖—	3.0	90	105	8497	32.3	13
25	V112–3.0	3.0	112	84	9895	37.7	13
26	—‖—	3.0	112	94	10,622	40.4	13
27	—‖—	3.0	112	119	11,269	42.9	12.5
FUHRLANDER							
28	FL2500–80	2.5	80	65	5707	26.0	14.5
29	—‖—	2.5	80	85	6114	27.9	14.5
30	FL2.5–90	2.5	90	85	7297	33.3	13
31	—‖—	2.5	90	100	7801	35.6	13
32	—‖—	2.5	90	117	8276	37.8	13
33	—‖—	2.5	90	141	8852	40.4	13
34	—‖—	2.5	90	160	9259	42.3	13
35	FL2.5–100	2.5	100	85	8533	39.0	11.5
36	—‖—	2.5	100	100	9049	41.3	11.5
37	—‖—	2.5	100	117	9573	43.7	11.5
38	—‖—	2.5	100	141	10,149	46.3	11.5
39	—‖—	2.5	100	160	10,548	48.2	11.5
40	WTU–3.2	3.2	120.6	90	11,665	41.6	13
41	—‖—	3.2	120.6	100	12,102	43.2	13
42	—‖—	3.2	120.6	120	12,759	45.5	13
43	—‖—	3.2	120.6	140	13,380	47.7	13

—‖— = the same

Table 2 Operation indices of WTs by some global major companies

WT No. as per Table 1	Zones						WT No. as per Table 1	Zones					
	A = 0	B	C	A = 0	B	C		A = 0	B	C	A = 0	B	C
	Energy production, MW h/% of total			Operation time, hours/% of annual				Energy production, MW h/% of total			Operation time, hours/% of annual		
1		**2710** 65	**1457** 35	**1463** 16.7	**6439** 73.5	**858** 9.8	23		**6253** 79.6	**1602** 20.4	**1463** 16.7	**6763** 77.2	**534** 6.1
2		**3197** 71.5	**1274** 22.5				24		**6895** 81.1	**1602** 18.8			
3		**3519** 73.4	**1274** 26.6				25		**6769** 68.4	**3126** 31.6	**1463** 16.7	**6255** 71.4	**1042** 11.9
4		**2982** 65.7	**1559** 34.3	**1463** 16.7	**6255** 71.4	**1042** 11.9	26		**6104** 57.5	**4518** 42.5	**1463** 16.7	**5791** 66.1	**1506** 17.2
5		**2896** 56.2	**2259** 43.8	**1463** 16.7	**5791** 66.1	**1506** 17.2	27		**6751** 59.9	**4518** 40.1			
6		**3706** 70	**1589** 30	**1463** 16.7	**6439** 73.5	**858** 9.8	28		**4372** 76.6	**1335** 23.4	**1463** 16.7	**6763** 77.2	**534** 6.1
7		**3674** 80.5	**890** 19.5	**1463** 16.7	**6910** 73.5	**38.7** 4.4	29		**4739** 78.2	**1335** 21.8			
8		**4988** 80.2	**1233** 11.8				30		**4698** 64.4	**2599** 35.6	**1463** 16.7	**6255** 71.4	**1042** 11.9
9		**4512** 69.5	**1979** 30.5	**1463** 16.7	**6439** 73.5	**858** 9.8	31		**5196** 66.6	**2605** 33.4			
10		**4148** 66	**2136** 34	**1463** 16.7	**6255** 71.4	**1042** 11.9	32		**5671** 68.5	**2605** 31.5			

(continued)

Table 2 (continued)

WT No. as per Table 1	Zones						WT No. as per Table 1	Zones					
	A = 0	B	C	A = 0	B	C		A = 0	B	C	A = 0	B	C
	Energy production, MW h/% of total			Operation time, hours/% of annual				Energy production, MW h/% of total			Operation time, hours/% of annual		
11		**4763** 69	**2136** 31	0	**7718** 88.1	**1042** 11.9	33		**6247** 70.6	**2605** 29.4			
12		**4732** 60.5	**3087** 39.5				34		**5494** 59.3	**3765** 40.7	**1463** 16.7	**5791** 66.1	**1506** 17.2
13		**4687** 69.5	**2059** 30.5	**2768** 31.6	**5134** 58.6	**858** 9.8	35		**5928** 69.5	**2605** 30.5	**1463** 16.7	**6255** 71.4	**1042** 11.9
14		**4373** 80.4	**1067** 19.6	**1463** 16.7	**6763** 77.2	**534** 6.1	36		**5285** 58.4	**3764** 41.6	**1463** 16.7	**5791** 66.1	**1506** 17.2
15		**4531** 80.9	**1068** 19.1				37		**5808** 60.7	**3765** 39.3			
16		**4383** 71.9	**1712** 28.1	**1463** 16.7	**6439** 73.5	**858** 9.8	38		**6384** 62.9	**3765** 37.1			
17		**4250** 69.4	**1876** 30.6	**1463** 16.7	**6255** 71.4	**1042** 11.9	39		**5644** 53.5	**4904** 46.5	**1463** 16.7	**5335** 60.9	**1962** 22.4
18		**3888** 58.9	**2711** 41.1	**1463** 16.7	**5791** 66.1	**1506** 17.2	40		**9957** 85.3	**1709** 14.7	**1463** 16.7	**6763** 77.2	**534** 6.1

(continued)

Table 2 (continued)

WT No. as per Table 1	Zones						WT No. as per Table 1	Zones					
	A = 0	B	C	A = 0	B	C		A = 0	B	C	A = 0	B	C
	Energy production, MW h/% of total			Operation time, hours/% of annual				Energy production, MW h/% of total			Operation time, hours/% of annual		
19		**4096** 60.2	**2710** 39.8				41		**8768** 72.4	**3334** 27.6	**1463** 16.7	**6255** 71.4	**1042** 11.9
20		**4798** 69.7	**2084** 30.3	**1463** 16.7	**6225** 71.4	**1042** 11.9	42		**7939** 62.2	**4819** 37.8	**1463** 16.7	**5791** 66.1	**1506** 17.2
21		**5087** 70.9	**2084** 29.1				43		**7102** 53.1	**6278** 46.9	**1463** 16.7	**5335** 60.9	**1962** 22.4
22		**4442** 59.6	**3012** 40.4	**1463** 16.7	**5791** 66.1	**1506** 17.2							

through 38 of Table 2). Against the other positions: 4.4% (No. 8), 6.1% (No. 24), 9.8% (Nos. 9, 16), 11.9% (Nos. 11, 21, 31) and so on.

The most important distinctive feature of the indices obtained was the use of actual multiple-year real measurements of wind velocities and distribution of their probabilities according to velocity levels at the AWPS site. That is what accounts for their main difference from those hypothetical values employed by many research fellows earlier. In view of the same, the present quantities data were taken as a basis for computer simulation.

3 Results and Discussion

3.1 Constructing the Model of Electric Power Generation with WT Operating in Various Zones of the Wind Cadaster

Let us study the effect of the operation duration in zone *C* of the wind cadaster upon WT annual energy production (AEP) with subsequent development of mathematical model (MM) for this dependence.

The aim of the model construction is to determine in the form of objective numerical indices the efficiency of operational modes of real WTs in each of the wind cadaster zones, thus facilitating the ascertainment of the essence of the current processes and effective utilization of capacities, and eventually—the optimization of operating parameters of industrial WPSs in specific wind conditions of Ukraine.

To identify the degree of correlational (statistical or stochastic) influence of all the parameters given in Tables 1 and 2 upon the operation time in zone *C* with further determination of their cross-impact [11, 12], draw up Table 3, leaving out manufacturers' names, but maintaining the line numbering of previous tables.

The following symbolic notations are used in Table 3: factors being explained: *Q* (MW·hour)—turbine AEP or *CF* (%); explanatory factors: *TC* (hour)—operating time in zone *C* of wind cadaster, *P* (MW)—turbine rated power, *H* (m)—hub height of WT, *D* (m)—rotor diameter, V_{rate} (m/s)—wind rated speed for the given WT.

To determine the degree of statistical correlation between all the factors of Table 3 with the aid of "Correlation" tool from the "Data Analysis" pack of MS Excel [13, 14] program we shall compute the correlation matrix (Table 4).

The correlation matrix is an evidence of a strong correlation between *TC* and *CF* (0.836) and also of a moderate correlation [15] between *TC* and *Q* (0.536). A sufficiently close correlation between *CF* and *TC* shows that *TC* can be used as an integral index of WT operational efficiency, similar to *CF*. The *TC* criterion integrity proves its dependence both upon *WT* technical characteristics in the form of parameter V_{rate} (−0.631—moderate negative correlation), and upon wind load at the hub height *H* (0.620—moderate correlation).

The revealed correlations allow suggesting linear regression model of the type:

Table 3 Source table

No	Q	CF	TC	P	H	D	V_{rate}	No	Q	CF	TC	P	H	D	V_{rate}
1	4167	28.0	858	1.7	65	70	12	23	7855	29.9	534	3.0	80	80	15
2	4471	34.0	858	1.5	65	77	12	24	8497	32.3	534	3.0	105	105	15
3	4792	36.5	858	1.5	80	77	12	25	9895	37.7	1042	3.0	84	84	13
4	4541	34.6	1042	1.5	60	80.3	10.5	26	10,622	40.4	1506	3.0	94	94	13
5	5155	39.2	1506	1.5	80	80.3	10.5	27	11,269	42.9	1506	3.0	119	119	13
6	5295	33.6	858	1.8	99	70	12.5	28	5707	26.0	534	2.5	65	80	14.5
7	4564	22.7	387	2.3	57	71	14.5	29	6114	27.9	534	2.5	85	80	14.5
8	6221	30.9	387	2.3	100	71	14.5	30	7297	33.3	1042	2.5	85	90	13
9	6491	32.2	858	2.3	113	71	14.5	31	7801	35.6	1042	2.5	100	90	13
10	6284	35.9	1042	2.0	78	82	12.4	32	8276	37.8	1042	2.5	117	90	13
11	6899	39.4	1042	2.0	100	82	12.4	33	8852	40.4	1042	2.5	141	90	13
12	7819	44.5	1042	2.0	138	82	12.4	34	9259	42.3	1506	2.5	160	90	13
13	6746	32.1	858	2.4	70	92	12.5	35	8533	39.0	1042	2.5	85	100	11.5
14	5440	31.1	534	2.0	78	80	15	36	9049	41.3	1506	2.5	100	100	11.5
15	5599	32.0	534	2.0	80	80	15	37	9573	43.7	1506	2.5	117	100	11.5
16	6095	34.8	858	2.0	100	80	15	38	10,149	46.3	1506	2.5	141	100	11.5
17	6126	38.9	1042	1.8	80	90	12	39	10,548	48.2	1962	2.5	160	100	11.5
18	6599	41.9	1506	1.8	95	90	12	40	11,665	41.6	534	3.2	90	120.6	13
19	6806	43.2	1506	1.8	105	90	12	41	12,102	43.2	1042	3.2	100	120.6	13
20	6882	39.3	1042	2.0	95	90	12	42	12,759	45.5	1506	3.2	120	120.6	13
21	7171	40.9	1042	2.0	105	90	12	43	13,380	47.7	1962	3.2	140	120.6	13
22	7454	42.6	1506	2.0	125	90	12								

Table 4 Correlation matrix

	Q	CF	TC	P	H	D	V_{rate}
Q	1						
CF	0.706	1					
TC	0.536	0.836	1				
P	0.845	0.229	0.106	1			
H	0.629	0.732	0.620	0.337	1		
D	0.928	0.676	0.517	0.765	0.373	1	
V_{rate}	−0.050	−0.563	−0.631	0.363	−0.115	−0.171	1

$$CF = a_o + a_1 TC. \tag{3}$$

After using the "Regression" tool from the "Data Analysis" pack of MS Excel [14] program, we shall obtain the summary Table 5.

Table 5 Summary table of regression analysis

Regression statistics						
Multiple R		0.836				
R square		0.699				
Adjusted R square		0.692				
Standard error		3.363				
Observations		43				
ANOVA (Analysis of variance)						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1078.508	1078.508	95.378	2.925E−12	
Residual	41	463.619	11.308			
Total	42	1542.127				
Coefficients		*Standard error*	*t-stat*	*P-value*	*Lower 95%*	*Upper 95%*
a_0	24.261	1.447	16.770	5.828E−20	21.339	27.183
a_1	0.0124	0.001	9.766	2.925E−12	0.010	0.015

And MM of equation:

$$CF = 24.261 + 0.0124 \cdot TC. \tag{4}$$

A very-low value of R^2 [16] is indicative of the fact that the present model describes only around 69% of observations data, which is its disadvantage. A low value of determination coefficient R^2 is largely due to a poor accuracy of determination of annual energy production *Q*, and respectively, *CF* value, as well as of operation time in typical zones of wind cadaster.

The analysis of Table 2 indicates the presence of only six values of operational time in zone *C*. Let us form WT into groups with regard for time *TC*, with simultaneous averaging of their parameters *CF*, *H* and V_{rate} (Table 6).

Let us again use the "Correlation" tool from the "Data Analysis" pack of MS Excel program.

It is evident from Table 7 that grouping and averaging have essentially improved the correlation relationship indices between the factors under investigation.

Table 6 Averaged parameters in terms of operation time in zone *C*

TC	$\overline{CF}$	$\overline{H}$	$\overline{V}_{rate}$
387	26.8	78.5	14.5
534	31.5	83.3	14.6
858	33.0	84.6	12.9
1042	38.6	97.7	12.4
1506	42.7	114.2	12.1
1962	48.0	150.0	12.2

Table 7 Correlation matrix

	TC	$\overline{CF}$	$\overline{H}$	$\overline{V}_{rate}$
TC	1			
$\bar{CF}$	0.706	1		
$\bar{H}$	0.536	0.836	1	
$\bar{V}_{rate}$	0.845	0.229	0.106	1

Using the data given in Table 6, we shall conduct the regression analysis (Table 8). As the result, we obtain high-quality [17, 18] MM of regression:

$$CF = 23.2504 + 0.0129 \cdot TC. \quad (5)$$

And now let's construct the model of multiple linear regression to determine the dependence of operation time in zone C (TC) on the V_{rate} and H parameters.

Let us again employ (use) the " Regression" tool from the "Data Analysis" pack of MS Excel program (Table 9).

As the result, we obtain MM of regression:

$$TC = 1892.234 + 15.669 \cdot H - 185.459 \cdot V_{rate}. \quad (6)$$

From MM (6) it follows that increase in the hub height by 1 m causes the increase in the operation time in zone C, basically by 16 h, whereas decrease in rated speed V_{rate} by 1 m/s increases the time TC by 185 h.

With the aid of a widely known [19] relationship

Table 8 Summary table of regression analysis

Regression statistics						
Multiple R		0.984				
R Square		0.969				
Adjusted R square		0.961				
Standard error		1.551				
Observations		6				
ANOVA (Analysis of variance)						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	296.387	296.387	123.158	0.000375	
Residual	4	9.626	2.407			
Total	5	306.013				
Coefficients		*Standard error*	*t-stat*	*P-value*	*Lower 95%*	*Upper 95%*
a_0	23.2504	1.3728	16.9370	0.0001	19.4390	27.062
a_1	0.0129	0.0012	11.0977	0.0004	0.0097	0.0161

Table 9 Summary table of regression analysis

Regression statistics						
Multiple R		0.995				
R Square		0.991				
Adjusted R square		0.984				
Standard error		74.847				
Observations		6				
ANOVA (Analysis of variance)						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	2	1,765,607	882803.3	157.5858	0.0009156	
Residual	3	16,806	5602.048			
Total	5	1,782,413				
Coefficients		*Standard error*	*t-stat*	*P-value*	*Lower 95%*	*Upper 95%*
a_0	1892.234	680.776	2.780	0.069	−274.298	4058.76
a_H	15.669	1.748	8.965	0.003	10.107	21.232
a_V	−185.459	41.403	−4.479	0.021	−317.221	−53.697

$$Q = CF \cdot P \cdot T, \tag{7}$$

where: T—annual operation time of WT, it is possible with the aid of MM (5) and (6) to quickly determine the annual energy production Q at the Northern Black Sea region conditions on the basis of three passport parameters (P, V_{rate}, H) alone, without reference to WT power curve and to the wind cadaster at the area of expected construction of WPS.

Let's determine common relative errors of MM (5) and (6) through an example of annual energy production Q predictions (Table 10):

Maximum relative error of predictions of MM (5) and (6) reaches 16%, yet, on average, deviations amount to about 7%, which is considered to be a quite acceptable result.

3.2 Comparison of MM Predictions with Actual Results of Operation

Validity and admissibility of assumed idealizations in developing any dynamic model of real system can be checked and evaluated only by comparison of theoretical research results with empirical data. Commercial operation of the first WPSs in the wind conditions of Ukraine provided a rich actual material. We shall use the results of their operation in the comparative study with the purpose of increasing the extent of conclusive force and validity of inferences.

Table 10 Relative errors of models (5) and (6) predictions

No. WT	Measured Q	Predicted Q	Residuals	Relative error, |%|	No. WT	Measured Q	Predicted Q	Residuals	Relative error, |%|
1	4167	4778	−611	15	23	7855	7343	512	7
2	4471	4216	255	6	24	8497	8671	−174	2
3	4792	4615	177	4	25	9895	8813	1082	11
4	4541	4555	−14	0	26	10,622	9344	1278	12
5	5155	5086	69	1	27	11,269	10,672	597	5
6	5295	5954	−659	12	28	5707	5717	−10	0
7	4564	4934	−370	8	29	6114	6602	−488	8
8	6221	6685	−464	7	30	7297	7388	−91	1
9	6491	7214	−723	11	31	7801	8052	−251	3
10	6284	5914	370	6	32	8276	8805	−529	6
11	6899	6693	206	3	33	8852	9867	−1015	11
12	7819	8039	−220	3	34	9259	10,708	−1449	16
13	6746	6707	39	1	35	8533	8174	359	4
14	5440	4824	616	11	36	9049	8838	211	2
15	5599	4895	704	13	37	9573	9591	−18	0
16	6095	5604	491	8	38	10,149	10,653	−504	5
17	6126	5537	589	10	39	10,548	11,494	−946	9
18	6599	6016	583	9	40	11,665	9740	1925	16
19	6806	6334	472	7	41	12,102	10,307	1795	15
20	6882	6684	198	3	42	12,759	11,440	1319	10
21	7171	7038	133	2	43	13,380	12,573	807	6
22	7454	7746	−292	4					

The analysis of the source Table 2 shows that of the annual theoretical time resource (8760 h), the share of the wind annual available resource, at which the wind turbines operate, is $T_{op} = 7297$ wind hours (83%). This is the situation for 40 WTs out of the 43 WTs being under examination. Two turbines No. 11 and No. 12 have $T_{op} = 100\%$, whereas No. 13 has $T_{op} = 68\%$. Of the total time resource, the share of zone *A* is 1463 h (16.7%), the vast majority of hours is in zone *B*, wherein WTs run not in a rated mode, but in a partial one, producing essentially smaller volume of traded electrical power than they could produce.

MM (5) indicates the feasibility of enhancing the WT production efficiency due to increase of the operating hours in zone *C*, whereas MM (6) indicates the ways of increasing the operating hours not only by increasing the height H, but also by decreasing rated velocity V_{rate}. This can be done by enlarging the rotor diameter without changing rated power *P*.

Let's evaluate the energy production of WT FL $2.5 - 100$ (No. 36) at the present time of operation in zone *C*:

$TC = 1892.234 + 15.669 \cdot 100 - 185.459 \cdot 11.5 = 1326$ h; [by (5)]
$CF = 23.250 + 0.0129 \cdot TC = 40.36\%$; [by (6)]
$Q = 0.4036 \cdot 2.5 \cdot 8760 = 8838$ MW hour, [by (7)]

i.e. relative error in calculation is 2%.

In the Northern Black Sea region conditions, it is quite realistic to increase the time *TC*, for instance, by enlarging the rotor diameter of WT FL 2500-100 or by replacing the same with WT Gamesa G126 of similar power (2.5 MW) and hub height of 102 m, but with rotor diameter $D = 126$ m and rated speed $V_{rate} = 10.0$ m/s.

Now we shall determine its energy production:

$TC = 1892.234 + 15.669 \cdot 102 - 185.459 \cdot 10.0 = 1636$ h (by 23% more than that of FL $2.5 - 100$);
$CF = 23.50 + 0.0129 \cdot 1636 = 44.35\%$ (by 10% more than that of FL $2.5 - 100$);
$Q = 0.4435 \cdot 2.5 \cdot 8760 = 9713$ MW hour (by 10% more than that of FL $2.5 - 100$).

Thus, the increase of operation time in zone *C* is an essential reserve for enhancing the operational efficiency of commercial WPS.

The traditional practice in WPS construction does not consider such reserve. Neglect of the importance of the wind cadaster various zones in WT energy production is encountered in the wind power generation literature. Notably, the fact is disregarded that the operation time in zone *C*, as well as *CF*, is an integral index of WT operational efficiency in specific wind conditions.

An invaluable and major feature of practical importance of the developed models consists in absence, when using the models, of any additional direct measurements of various parameters, in particular the models do not require the processing of meteorological data for representative MS (meteorological stations), which contributes to considerable reduction of errors. And it is owing to the fact that the development is based on actual many-year measurement, performed with the help of Logger computer-aided system, of wind velocities at the pilot AWPS; apart from that, use is made of actual exponent of wind velocity change versus height, which fact has essentially improved the validity of calculations.

4 Conclusions

The mathematical models of WT operation in the wind cadaster various zones, first developed by using the computer-based simulation methods allow to promptly and truly determine its optimal parameters depending upon the wind load of the area where the construction of a commercial WPS is expected.

The suggested mathematical models make possible to design and manufacture the required wind turbine in case of unavailability of the WTs with necessary design parameters in the world market. Such approach determines a practical value of the present paper, as at the stage of engineering design it helps to make a choice of a WT with optimal technical-and-economic features.

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