WIND ENERGY POTENTIAL ASSESSMENT OF UKRAINE

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Key-words: enviroGRIDS, wind energy, theoretical wind power potential, technically achievable wind power potential, methodology, wind power potential of Ukraine.

The article presents a methodology for theoretical and technically achievable wind power potential assessment, developed in the framework of EnviroGRIDS Black Sea Catchment project. The methodology has considerable advantages: it contains a simple algorithm, minimum set of input data, at the same time it provides highly reliable results and allows adequately assess wind power potential of investigated area. Developed methodology was tested on wind power potential of Ukraine.

1. INTRODUCTION

The utilization of renewable energy in the Black Sea countries is increasing, driven by promotion measures adopted by the governments of these countries. The utilization of biomass, solar and hydro energies is growing. There are a lot of international projects in support of international research and innovation cooperation. One of such projects is EnviroGRIDS Black Sea Catchment project which is intended for information potentialities of modeling and forecasting the situations, concerned with climate change, and their impacts on Societal Benefit Areas.

The rise of Renewable Energy Sources (RES) development (particularly wind and solar energy) is becoming one of the major factors of sustainable development. It is caused by the fact, that energy is a basic sector of the economy. The strategic goal of the economic development of any country is to maximize the share of energy in its energy balance, produced by the country's own energy resources.

The energy resources of Ukraine consist of three main branches: nuclear power, thermal power and hydropower. All the above-mentioned areas of energy in industrialized countries are unpromising and environmentally unsafe. The intensive use of thermal power plants led to a number of environmental problems [1]. During the last decades, the issues related to the development of renewable energy in the world and in Ukraine are extremely relevant because of the scarcity and limitedness of energy resources and environmental deterioration.

Wind power is a very attractive field. Wind technologies have grown in scope, and in various places wind is becoming a feasible source of energy. This kind of natural resource is vulnerable to weather conditions, but in certain locations, mainly in coastal offshore areas and at high altitudes, there is a steady stream of wind.

Wind power is harnessed through the use of wind turbines, which are turned by the wind to produce electricity. Wind energy is reliable and efficient. Unlike other power plants, wind energy systems require minimal maintenance and have low operating expenses.

Ukraine currently uses only 0.2% of its wind capacity. At present the total installed capacity of the wind power plants in Ukraine amount to 146.515 MW. Most of the wind power plants have been constructed within the framework of the "State Complex Program for Construction of wind power plants in Ukraine".

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Most of currently known methodologies for wind power potential assessment are complicated by a large quantity of input data and labour-intensive calculations. In respect of the importance of this issue, the simplified methodology for wind power potential assessment has been developed in the framework of EnviroGRIDS project, which allows to adequately assess wind power potential of investigated area using a minimum set of data.

The corresponding information services for RES potential assessment of Black Sea Catchment area are scheduled; such services are oriented at wind and solar energy potential forecasting as easily accessible and non-polluting energy sources.

2. THEORETICAL WIND POWER POTENTIAL ASSESSMENT

Renewable energy potential assessment includes assessment and analysis of the theoretical and technical potential of renewable energy [2]. The theoretical potential represents all the natural resources of RES. The technical potential is that part of the theoretical potential of renewable resource whose energy use is limited by technical (technology) and non-technical terms (financial, legal and others).

It is exactly the technical potential of renewable energy that is the potential which is important and necessary for the selection of specific technology for renewable energy conversion.

For estimating the wind energy potential of Ukraine, the following statistic parameters were calculated:

2.1. Vertical wind speed gradient

The wind speed at the surface is zero due to the friction between the air and the surface of the ground. The wind speed increases with height most rapidly near the ground, increasing less rapidly greater the height. The vertical variation of the wind speed, the wind speed profile, can be expressed by different functions. One of the most common functions which have been developed to describe the change in the mean wind speed with the height is Power Exponent Function [2]:

$$V(z) = V_r \cdot \left(\frac{Z}{Z_r}\right)^{\beta}$$

where Z is the height above ground level (m); V_r is the wind speed (m/s) at the reference height Z_r above ground level (m); $V(z)$ is the wind speed (m/s) at height Z (m); β is an exponent which depends on the roughness of the terrain, can be calculated in approximation by using the formula:

$$\beta = \frac{1}{\ln \frac{Z}{Z_0}}$$

The parameter Z_0 for different types of terrain is shown in Table 1.

Table 1

Roughness lengths and roughness classes for various surface characteristics [2]

Z_0 (m)	Types of terrain surfaces	Roughness class
1.00	City	III
0.80	Forest	
0.50	Suburbs	
0.30	Built-up terrain	

Table 1 (continued)

0.20	Many trees and/or bushes	II
0.10	Agricultural terrain with a closed appearance	
0.05	Agricultural terrain with an open appearance	
0.03	Agricultural terrain with very few buildings, trees, etc.	I
0.02	Airports with buildings and trees	
0.01	Airports, runway	
0.005	Meadow	
$5 \cdot 10^{-3}$	Bare earth (smooth)	0
10^{-3}	Snow surfaces (smooth growth)	
$3 \cdot 10^{-4}$	Sand surfaces	
10^{-4}	Water surfaces (lakes, seas, etc.)	

2.2. Average wind speed

Wind speed is the most important constituent for assessing the wind energy potential of investigated area. The wind speed measurement period must be long enough to cover all meteorological conditions in that region with a sufficient amount of data. In order to obtain the stable value of mean wind speed, the observation period should cover no less than 10 years [3]. For obtaining wind frequency data, the observation period has to be longer (about 25 years).

In order to assess the wind potential of Ukraine, the USRIEP team has obtained an averaged climatic data from the State Hydrometeorological Service of Ukraine, the measured at 187 meteorological stations of Ukraine. Meteorological stations are uniformly distributed all over Ukraine and the distance between them does not exceed 50–100 km (Fig. 1). The observation period covers 30 years.

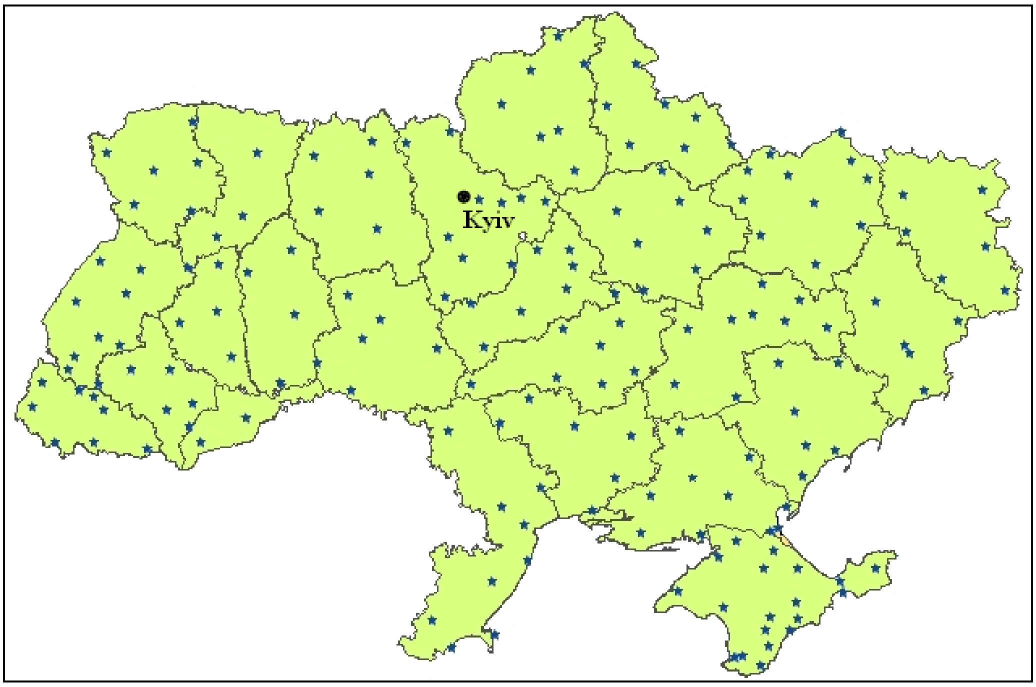

Fig. 1 – Location of hydrometeorological stations.

Obtained data includes:

– Averaged wind speed values for 30 years (m/s), measured at 10 meters above ground level;

– Wind speed frequency (%) for the following wind speed ranges:

  – 0–1 m/s;
  – 2 5 m/s;
  – 6–9 m/s;
  – 10–15 m/s;
  – 16–20 m/s;
  – 21–24 m/s;
  – 25–28 m/s;

– Annual calm period (%).

All the above-mentioned meteorological parameters are included in the standard list of measurements for each Ukrainian meteostation.

Mean wind speed (V_c), as the most commonly used indicator of wind production potential, is defined as [4]:

$$V_c = \frac{\sum_{i=1}^{n} \Delta V_i \cdot P_i}{\sum_{i=1}^{n} P_i}$$

where ΔV_i is a middle of i^{th} wind speed range; P_i is the wind speed frequency of i^{th} wind speed range; n is a number of wind speed ranges.

The averaged values of wind speed measured at 10 m above ground level were analyzed and mapped in GIS environment (Fig. 2).

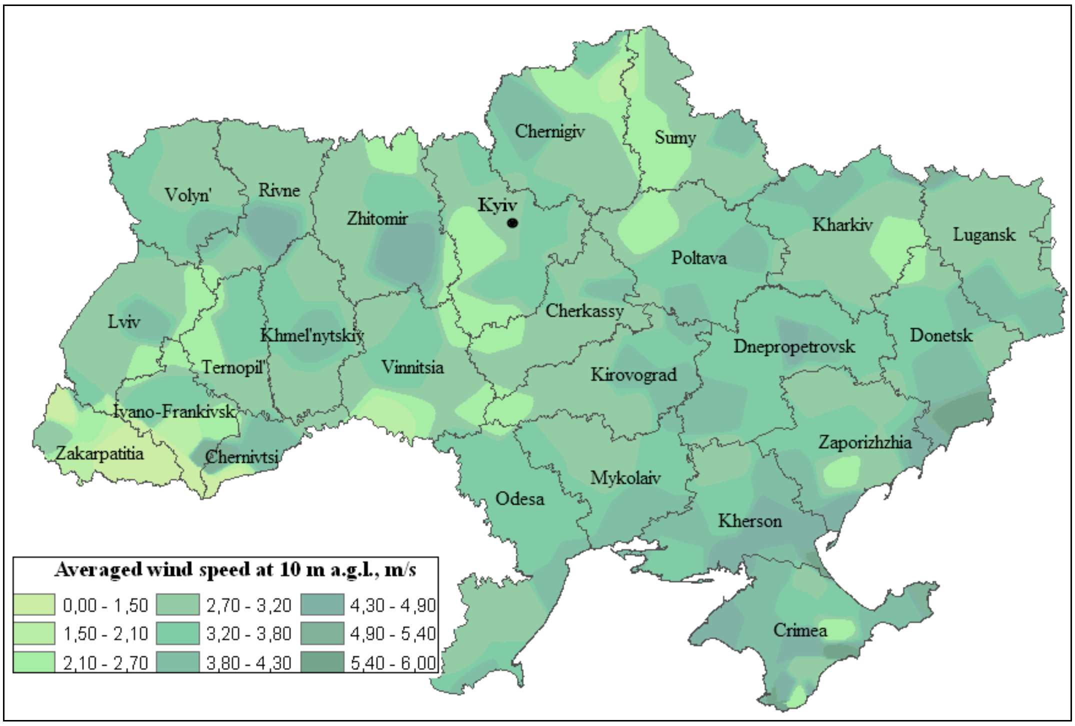

Fig. 2 – Averaged wind speed at 10 m a.g.l.

2.3. Standard deviation

Standard deviation is a widely used statistic measurement of variability or diversity. The standard deviation of wind speed is an indicator of the turbulence level and atmospheric stability.

$$\sigma = \sqrt{\sum_{i=1}^{n} (\Delta V_i - V_c)^2 \cdot P_i / \sum_{i=1}^{n} P_i}$$

2.4. Coefficient of variation

The coefficient of variation (C_v) is a normalized measure of dispersion of a probability distribution. The coefficient of variation is defined as the ratio of the standard deviation to the mean wind speed:

$$C_v = \sigma / V_c$$

2.5. Full medium cube of a wind speed

To achieve lasting results, such parameter as medium cube of a wind speed, required for wind-power density assessment, should include statistic parameters as well:

$$\overline{V_c^3} = (V_c)^3 \cdot (1 + 3 \cdot C_v^2 - 0{,}9 \cdot C_v^3 + 2{,}9 \cdot C_v^4)$$

where $\overline{V_c^3}$ is a medium cube of a wind speed (m^3/s^3).

The value of the full medium cube of a wind speed should be calculated for each meteostation at the reference height. Usually, wind speed measures at 10 m height above ground level and average height of a wind turbine is about 70–80 meters. Therefore, in this article, the cube of wind speed is calculated for 75 m above ground level. The distribution of the wind speed at 75 m a.g.l. across the territory of Ukraine is shown in Fig. 3.

2.6. Wind power density

Wind power density is generally considered as a better indicator of the wind resource than wind speed, so, it is the amount of wind power available per unit of area perpendicular to the wind flow. Wind power density (WPD) should be calculated at the height of expected wind turbine (here it is assumed that the height is 75 m a.g.l.). WPD (W/m^2) can be calculated using the following equation:

$$WPD = \frac{1}{2} \rho \cdot \overline{V_c^3}$$

where ρ is an air density (kg/m^3); $\overline{V_c^3}$ is the full medium cube of a wind speed (m^3/s^3) at the height 75 meters.

2.7. Annual specific wind power density:

Annual specific wind power density WPD_{annual} is calculated by the following formula:

$$WPD_{annual} = WPD \cdot 24 \cdot 365 \cdot (1 - F/100)$$

where WPD_{annual} is an annual specific wind power density (Wh/m^2); F is an annual wind calm period, %.

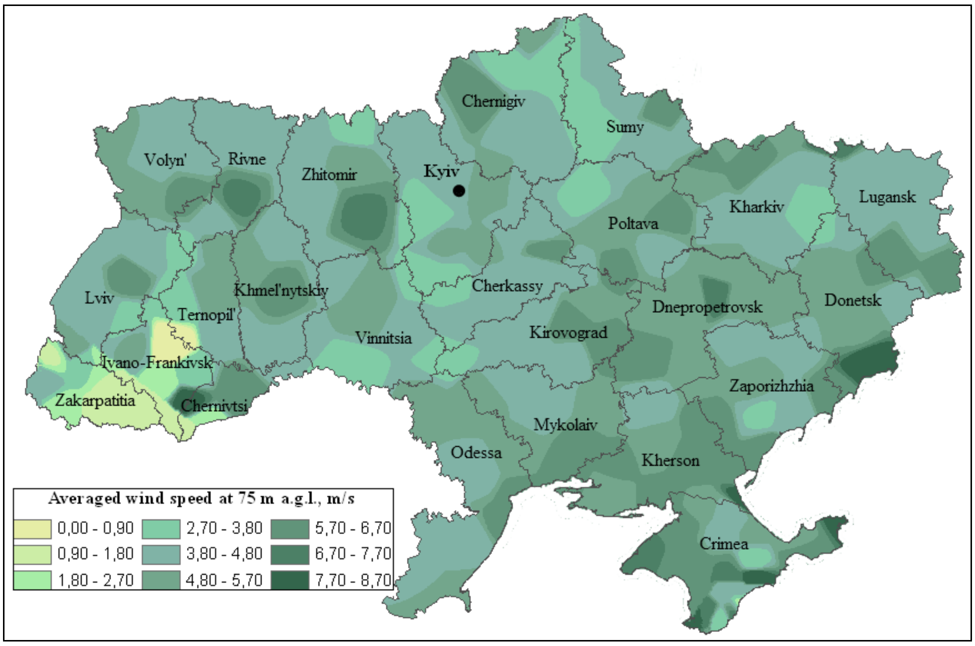

Fig. 3 – Averaged wind speed at 75 m a.g.l.

3. TECHNICALLY ACHIEVABLE WIND POWER POTENTIAL OF UKRAINE

Wind farms require large sites, potential wind farm sites are preferably open areas of flat land or on top of hilly areas. Obviously, the sites should be known to be windy, with high and recurrent wind resources. A considerable percent of the Ukrainian area is unsuitable for wind turbine placing. For technically achievable wind power potential assessment the following areas, unsuitable for wind turbine placing, were chosen and excluded from the calculations:

– urbanized areas;
– roads, highways and railways; and 300 m of buffer zone around each side of the road;
– forests;
– water body surfaces;
– cultivated areas.

The total area unsuitable for wind turbine placement was calculated using GIS software, the results are shown in Table 2.

Wind turbines operate over a limited range of wind speeds. If the wind is too slow, they would not be able to turn, and if it is too fast, they shut down to avoid being damaged. To make wind farms profitable enough, annual average wind speed should not be under 6 m/s, otherwise wind farm placing at low wind speed sites is not reasonable.

The mutual distance between the wind turbines has to meet the requirements of the manufacturers. If the wind turbines are too close together output may be reduced. Another, more serious, consequence may be damage to primary structural parts caused by the wake of wind turbines sited upwind. The minimum distance depends on the placing with regard to the prevailing wind direction. For turbines sited perpendicular to the prevailing wind direction, the mutual separation distance has to be at least four, and preferably, five times the rotor diameter. In this report, the methodology for wind power potential assessment takes as its foundation the Technical report on Europe's onshore and offshore wind energy potential [5], so technically achievable wind energy potential is calculated assuming the use of 2 MW wind turbines onshore with a view to prospects for 2030. Regarding average wind energy production potential per square kilometer, it is considered that five 2 MW wind turbines can be sited per square kilometer onshore within the area suitable for wind turbine placing [6], and for the average turbine of 2 MW, the related rotor diameter would be 80 m.

Table 2

Areas excluded from calculations, suitable area for the wind turbines placing

Region name	**Total area of the region, km^2**	**Urbanized area, km^2**	**Forest-lands, km^2**	**Roads, railways + buffer zone, km^2**	**Water bodies surface, km^2**	**Cultivated area, km^2**	**Total area suitable for the placing of wind turbines, km^2**
Kherson	28,500	230.9	1324	3022	1096.7	11341	11,485.43
Crimea	27,000	225.8	3087	4032,4	8.6	6819	12,827.3
Donetsk	26,500	1,097.4	1855	4915,7	203.9	11944	6,483.99
Zhytomyr	29,900	367.9	9890	5197,2	111.8	4549	9,784,18
Chernihiv	31,900	324.1	6566	4688,6	251.9	7571	12,498.4
Luhansk	26,700	746.3	2829	3547	64.7	8513	11,000.07
Odesa	33,300	305	1953	5025,6	1311.2	16388	8,317.15
Rivne	20,100	98.1	7317	3086,7	88.5	3236	6,273.74
Dnipropetrovsk	31,900	777.2	1528	5605,6	1038.6	16884	6,066.59
Mykolaiv	24,600	262.3	949	2949,3	354	13720	6,365.38
Kharkiv	31,400	578.9	3727	5830,9	371.6	13838	7,053.56
Volyn	20,200	118	6324	3784,5	180.1	2972	6,821.34
Sumy	23,800	330.6	4038	4445,1	88.7	7820	7,077.61
Poltava	28,800	248.7	2362	5394,4	880.8	14502	5,412.18
Ivano-Frankivsk	13,900	163.8	5767	2539,7	121.1	1465	3,843.39
Zaporizhzhia	27,200	336.1	1054	4257,6	2386	14759	4,407.24
Kyiv	28,900	394.9	6322	5183,1	2005.7	8496	6,498.27
Lviv	21,800	396.2	6264	5087,9	68.3	3158	6,825.57
Khmelnytskyi	20,600	215.7	2627	4356,5	210.5	7552	5,638.33
Kirovohrad	24,600	243.2	1588	3995,7	388.9	14585	3,799.21
Chernivtsi	8,100	92.4	2378	1751,5	151	1658	2,069.11
Vinnytsia	26,500	213.6	3514	5811,3	234.8	12024	4,702.2
Zakarpattia	12,800	68.6	6529	2033	68.2	891	3,210.18
Cherkasy	20,900	281.4	3193	3735	544	9772	3,374.6
Ternopil	13,800	125.4	1924	3091	59.9	6178	2,421.7
TOTAL	**603,700**	**8242.3**	**94,909**	**103,367.4**	**12,289.6**	**220,635**	**164,256.72**

It was mentioned above that areas with an annual average wind speed lower than 6 m/s are unsuitable for wind farm placing, so, such areas should be excluded from the calculations. An annual average wind speed of the main part of Ukraine is 6.3–6.8 m/s; but wind speed in some regions is exceeding the range of 7–8 m/s. Obviously, such territories are more attractive for the building of wind farms. Also, it can be expected that at such windy sites the number of wind turbines per square kilometer might be somewhat more than five on average (for example seven). Generalizing the developed concept, the territories of Ukraine, suitable for wind farms placing, with an average wind speed of 3 different ranges (<6 m/s; 6-7 m/s; >7m/s) were calculated and presented in Table 3.

The wind power capacity of each region of Ukraine $W_{capacity}$ was calculated using the following equation:

$$W_{capacity} = \sum_{i=1}^{n} S_i \cdot N_{i\,turb} \cdot P_{turb}$$

where S_i – area with respective wind speed range, km^2; $N_{i\,turb}$ is a number of wind turbines per square kilometer corresponding to wind speed range; P_{turb} is the power of wind turbine (2 MW); n is the number of ranges (note that one of the ranges has been excluded, so, calculations perform only for two left ranges). The results of calculations are shown in Table 3.

Table 3

Results of wind power potential assessment of Ukraine

Region name	Annual averaged specific wind power density, kWh/m^2	Total area suitable for the placing of wind turbines, km^2	The area of average wind speed			Wind power capacity for the areas of the following wind speed ranges, GW		Total technically achievable wind power capacity, GW
			<6 m/s	6-7 m/s	>7m/s	6-7 m/s	>7m/s	
Kherson	3236.77	11485.43	8843.78	2297.09	344.56	22.97	4.82	27.79
Crimea	1420.52	12827.30	4489.56	6413.65	1924.10	64.14	26.94	91.07
Donetsk	1308.42	6483.99	4992.67	518.72	972.60	5.19	13.62	18.80
Zhytomyr	711.07	9784.18	7533.82	782.73	1467.63	7.83	20.55	28.37
Chernihiv	524.68	12498.40	9998.72	624.92	1874.76	6.25	26.25	32.50
Luhansk	549.73	11000.07	8800.06	2200.01	0.00	22.00	0.00	22.00
Odesa	687.39	8317.15	7069.58	1247.57	0.00	12.48	0.00	12.48
Rivne	840.24	6273.74	5018.99	501.90	752.85	5.02	10.54	15.56
Dnipropetrovsk	848.87	6066.59	4489.28	1213.32	364.00	12.13	5.10	17.23
Mykolaiv	745.16	6365.38	5410.57	954.81	0.00	9.55	0.00	9.55
Kharkiv	618.71	7053.56	5995.53	1058.03	0.00	10.58	0.00	10.58
Volyn	560.80	6821.34	6139.21	682.13	0.00	6.82	0.00	6.82
Sumy	523.39	7077.61	5662.09	1415.52	0.00	14.16	0.00	14.16
Poltava	626.33	5412.18	4329.74	1082.44	0.00	10.82	0.00	10.82
Ivano-Frankivsk	826.83	3843.39	3420.62	115.30	307.47	1.15	4.30	5.46
Zaporizhzhia	706.73	4407.24	3658.01	749.23	0.00	7.49	0.00	7.49
Kyiv	463.16	6498.27	5523.53	974.74	0.00	9.75	0.00	9.75
Lviv	427.94	6825.57	5801.73	1023.84	0.00	10.24	0.00	10.24
Khmelnytskyi	507.75	5638.33	4510.66	1127.67	0.00	11.28	0.00	11.28
Kirovohrad	739.27	3799.21	3039.37	759.84	0.00	7.60	0.00	7.60
Chernivtsi	1044.61	2069.11	993.17	931.10	144.84	9.31	2.03	11.34
Vinnytsia	438.04	4702.20	4231.98	470.22	0.00	4.70	0.00	4.70
Zakarpattia	583.25	3210.18	3049.67	160.51	0.00	1.61	0.00	1.61
Cherkasy	448.25	3374.60	3138.38	236.22	0.00	2.36	0.00	2.36
Ternopil	504.57	2421.70	2058.45	363.26	0.00	3.63	0.00	3.63
TOTAL		**164,256.72**	**128,199.16**	**27,904,77**	**8,152.80**	**279.05**	**114.14**	**393.19**

In accordance with the obtained results, the technically achievable wind power capacity has been assessed and mapped (Fig. 5).

The actual power will be somewhat less than the calculated one, because available power cannot be totally extracted by any wind machine. The maximum extractable power from any wind machine is limited by the famous Betz relation which assigns a power co-efficient Cp=16/27 for the maximum performance of a wind machine [1]:

$$WP(Max.ExtractablePower) = \frac{1}{2} \cdot \rho \cdot C_p \cdot A \cdot \overline{V_i^3}$$

where WP is maximum extractable power (W); A is the rotor swept area, (m^2); $\overline{V_c^3}$ is the cube of the wind speed at the reference height, expressed as m^3/sec^3.

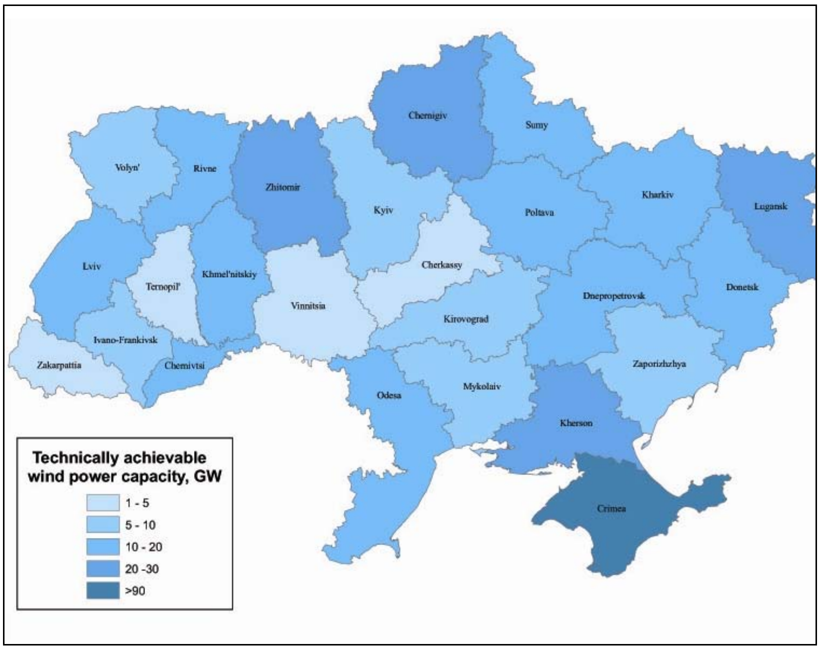

Fig. 5 – Technically achievable wind power potential.

According to the obtained results, the southern and eastern parts of Ukraine have outstanding wind potential, particularly the Autonomous Republic of Crimea, Kherson, Donetsk and Lugansk regions.

As for annual specific values of wind power potential, the existing data indicate a promising wind potential around the Autonomous Republic of Crimea, Kherson, Donetsk, Chernigiv, and Zhitomyr regions. For these areas the average annual wind speed varies between 5 to 8 m/sec at 75m a.g.l.

Ukraine is one of the more promising wind markets of the world. The Law on "green" tariff adopted in 2009 and other similar incentives aimed at promoting and stimulating renewable energy development in the country have begun to bear fruit in the commissioning of new wind and solar power plants with advanced international technology and equipment.

In accordance with key principles of the EU green paper, the long-term renewable energy development in Ukraine should be based on the economic competition with other energy sources, with the state providing support to renewable energy sources advanced technologies which reflect public interest as regards enhancing the energy security level, environmental cleanness and combating global climate change.

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