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# ON THE UTILIZATION OF THE WIND WAVES ENERGY ALONG THE BULGARIAN BLACK SEA COAST

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**Abstract:** This paper investigates the possibilities for utilisation of the wind waves energy in the exclusive economic zone of Bulgaria in Black sea by water turbines with oscilating blades. Information about the wave climate in this zone is obtained by analysis of the published results about offshore wave energy based on long-term hindcast and studies on wave exposure of Bulgarian Black Sea coast.

Keywords: Water turbine with oscilating blades, Wave energy, Energy conversion.

#### **INTRODUCTION**

There are two groups of energy inputs to the geobioshpere: external (renewable) and internal (non-renewable). The main external inputs to the geobiosphere, as they existed before the development of civilization (Odum 2000) include: the solar energy with a total amount of  $3.93 \times 10^{24}$  J/year (in terms of power - 124619.482 TW), the heat energy from the deep earth -  $6.72 \times 10^{20}$  J/year (21.309 TW), and the tidal energy -  $0.52 \times 10^{20}$  J/year (1.649 TW). There are some other external energy inputs to the geobioshere from the space such as the high energy radiation of solar flares, cosmic rays, meteorites and stellar dust that vary with oscillations and pulses but their contribution to the global energy budget may be neglected (Odum 2000). Through various processes in the atmosphere and in the ocean these three main external energy inputs generate secondary renewable energy sources (atmospheric processes – *winds*, ocean processes – ocean circulation, jet currents) and tertiary one (ocean processes – *wind waves*) (Odum 2000).

The wind wave energy resource can be defined in different ways (Mørk 2010): *the theoretical resource* is the actual hydrodynamic power contained in the waves; *the technical resource* is the power that can be produced by WECs (Wave Energy Converters); *the accessible resource* is the power that can be produced in an area/region by a WEC.

When calculating the emergy of the products of the global energy system Odum (2000) uses the figure  $E_w=3.4 \times 10^{20}$  J/year for the global energy potential of wind waves reaching the shore based on an estimation done in 1965. According to it the theoretical global (gross) wave power resource is 9.79 TW. It is greater than the world total primary energy supply (TPES) for 1973 of 6101 Mtoe (IEA 2017), which in terms of yearly averaged power supply is equal to 8.1 TW.

Mørk et al (2010) provides a new estimation of 3.702 TW for the theoretical global wave power resorce, which is limited to deep water off the coastlines bounding each ocean basin but including the coastlines of Baltic Sea and Mediterranian Sea. The coastlines of the internal seas were *a priori* excluded from this estimation due to the very low level of wave power ( $\leq$  5 kW/m of the wave front) making it practically unusable. Furthermore, when zones along which the wave power level is below 5 kW/m are subtracted from the length of the coastlines on which the above mentioned estimation is based the theoretical wave power resource decreases to 3.475 TW. If in addition from the above estimation are excluded all locations, which at certain times of the year may experience ice coverage, then the theoretical wave power resource decreases to 2.985 TW (Mørk et al, 2010).

According to (IEA, 2017) world electricity generation for 2015, was 24255 TWh that corresponds to yearly averaged power of 2.769 TW. This means that the theoretical global wave power resource slightly exceeds the world consumption of electricity for 2015. However, the accessible wave power resource, i.e. the electricity that could be generated by a WEC (Wave Energy Converter) machine in a certain area, which is characterized by the wave-to-wire (overall) efficiency, is far below the theoretical wave power resource. Usually the overall efficiency of a WEC is lower than 60%. WEC overall efficiency depends on many technical specifications of hydrodynamic and power takeoff subsystems as well as on the wave climate that exibits significant short term, monthly, seasonal, and interannual variation.

The principal goal of this paper is to evaluate accessible wave power resource in the EEZ of Bulgarian part of the Black Sea by WECs using water turbine with osscilating blades (WTOB) as a power takeoff (PTO) subsystem.

## **EXPOSITION**

#### Water turbine with oscillating blades (WTOB)

The WTOB has been recently invented at the Department of Hydroaerodyamics and hydraulic machines in the Technical University of Sofia (Agontsev 2017) and is still under investigation and improvement (Velichkova 2017). The construction of the runner blades, which can oscillate around its horizontal axis, allows converting the relative to the turbine runner vertical reciprocating motion of sea water into unidirectional rotary motion of the vertical turbine shaft (Agontsev et al, 2017). Expected mechanical efficiency of WTOB was estimated to 35 % (Velichkova, 2017). Although WTOB is intended to work primarily with a vertical shaft, it may work properly with inclined and even with a horizontal shaft. It may be used as PTO subsystem of several WEC machines.

WTOB can be used for construction of WECs based on the Osscilating water column (OWC) concept. In this case WTOB can be used either separately or in combination with an air turbine (unidirectional or Wells). The hydrodynamic subsystem of the WEC can be part of engineering sturctures that protect the coastline from erosion located both onshore (sea walls, groynes) and nearshore (e.g. organized in floating farms). Additionally, WTOBs can be part of a power supply system located on offshore platforms. Expected capture width ratio ( $\eta_1$ ) of a WEC machine based on the OWC application of a WTOB is estimated to be 85%. In this case the expected wave-to-wire WEC efficiency would be around 29%.

Moreover, WTOB can be part of WECs applying the Point absorber (PA) concept. In this case the WEC must be located in deep water, i.e in areas where the wavelength ( $\lambda$ ) is significantly smaller than the water depth (d)  $\lambda$ <<d. Expected capture width ratio ( $\eta_1$ ) of a WEC machine based on the PA application of a WTOB is estimated to be 70%, so the wave-to-wire WEC efficiency would be around 24%.

#### Wind wave properties

Wind waves are generted on the free surface of every water body under the action of wind blowing over that surface. Once generated, even if there is no wind energy input, the wind waves may travel for very large distances, with virtually no loss of energy, until they reach the shore. Wind waves carry energy, which if not dicipated/attenuated or utilized can causes beach or cliff erosion and even washing out of unprotected shoreline. Hence, besides production of electricity, there is another benefit from the utilization of the wind wave energy – protection of the shoreline from erosion. Since shore protection is of high priority, it is possible coastal protection structures, such as seawalls or groynes to be combined with onshore WECs even when wind wave power resource is small (lower than 5 kW/m). Shore protection can be achieved by locating WECs in the nearshore areas as well. In this case WECs should be orginesed in farms in such way that the degree of achieved wave attenuation is acceptable..

The waves propagating in a certain water area at a given moment of time (sea state) can be generated by the action of wind blowing over that area at the same time point or, as in the case of swell, they may be generated elsewhere some time ago. Hence, the sea state properties have a random nature. The waves in a sea state may differ in shape, height, frequency, and direction of propagation. Wind waves can be described as a stochastic process, in combination with the physics governing their generation, growth, propagation and decay. For description of the wave climate in a certain area, temporal, directional and spectral characteristics are used, which are preconditioned by the wave spectrum of the individual sea states.

The theoretical power resource of the wind waves in deep water location may be calculated by the expression, (Akpinar at el. 2017):

$$P = \rho g \int_{0}^{2\pi} \int_{\omega_{min}}^{\omega_{max}} S_{(\omega,\theta)} C_{g(\omega,d)} d\omega d\theta, \frac{kW}{m}$$
(1)

where  $\rho$  is sea water density; g – acceleration of gravity;  $S_{(\omega,\theta)}$  – directional wave variance density spectrum;  $C_{g(\omega,d)}$  – wave group velocity;  $\omega$  – wave frequency;  $\theta$  – direction of propagation of a spectral component; d – water depth.

For the locations where water depth is greater than the half of wavelength ( $\lambda_x$ ), i.e.  $d \ge 0.5\lambda_x$ , from expression (1) one may obtain

$$P = \frac{\rho g^2}{64\pi} H_{m,0}^2 T_g , \frac{kW}{m}$$
(2)

with  $H_{m,0} = 4\sqrt{m_0}$  - significant wave height and  $T_e = m_{-1}/m_0$  -wave energy period.

The  $m_n$  moment of  $S_{(\omega,\theta)}$  is calculated by

$$m_n = \int_0^{2\pi} \int_{\omega_{min}}^{\omega_{max}} \omega^n S_{(\omega,\theta)} d\omega d\theta \tag{3}$$

When the zero-crossing period  $T_z$  ( $T_z \cong T_{0,2} = \sqrt{m_0/m_2}$ ) and the root mean squared wave height  $H_{rms}$  are used relation (2) takes the form

$$P = \frac{\rho g^2}{32\pi} H_{rms}^2 T_z \,, \frac{kW}{m} \tag{4}$$

Annual energy production (AEP) by a WEC in kWh can be roughly estimated by the relation

$$AEP_{WEC} = 8760 x A x P_{year} x W_{abs} x \eta_{w2w}$$
<sup>(5)</sup>

where A is WEC annual availability (-);  $P_{y \in ar}$  – mean wave power (kW/m);  $W_{abs}$  – width of WEC absorber (m);  $\eta_{w2w}$  – wave-to-wire (overall) WEC efficiency (-).

#### Wind wave characteristics in Bulgarian Black Sea exclusive economic zone (EEZ)

Many scientists from all countries surrounding Black Sea have performed numerical studies of the wave climate, including storm events. Among all those studies, those published by Akpinar et al. (2017), Rusu et al. (2017) and Valchev et al. (2012, 2013, and 2014) meet the most the needs of the present research. The results reported in these studies are obtained by hincasting, i.e numerical wave modeling forced with historical data of atmospheric fields – wind, atmospheric pressure and temperature. Wave simulations are done for different periods within a domain covering the entire Black Sea, including Azov Sea. The above mentioned studies provide data for both spatial analysis of wave climate in Black Sea (contour plots of the investigated properties over the entire computational domain) and point analysis (detailed data for selected locations). In Valchev et al. (2012 and 2013) wave results are reported in terms of H<sub>rms</sub> and T<sub>z</sub>, while Akpinar et al. (2017) and Rusu et al. (2017) provide data about H<sub>m,0</sub> and T<sub>e</sub>.

Data for point analysis of wave climate in Bulgarian EEZ of Black Sea extracted from the above mentioned studies are presented in Fig. 1 and in Table 1. In



Fig. 1. Wave climate at selected shore units on Bulgarian Black Sea coastline and at selected points in Bulgarian EEZ of Black Sea

Fig. 1 represens a map of Bulgarian Black Sea litoral with part of Bulgarian EEZ in Black Sea, prepared in Google Earth, on which are shown the points (BG01-BG08) for wich there are detailed data about the wave climate found in the sources referred to in Table 1. In Fig. 1 with color lines are marked, after (Valchev et al. 2014), the shore units from Bulgarian Black Sea coast which are extremely exposed (EE) and very exposed (VE) to the action of strong winds and large waves. Predominant wind directions for the marked shore units are denoted with white arrows. Based on the wind data for the period [2000-2012] at the marked shore units in the northen part of Bulgarian coast Valchev et al (2014) reports maximum wind velocity in the interval [19, 20] m/s and maximum significant wave height in the interval [9, 10] m. At the marked shore units in the middle part of Bulgaria these figures are [19, 20] m/s and [8, 9] m, respectively. At the marked shore units in the south part of Bulgaria these figures are [20, 22] m/s and [9, 11] m, respectively.

Contour plots of theoretical wave power resource distribution in the Bulgarian EEZ of Black Sea are presented in Fig. 2. Using eq. (5) it is estimated that AEP, of a WEC (based on the OWC concept) equipped with a 1m diameter runner WTOB and constructed onshore in the northen part of Bulgarian coastline with availability of 93.2 % would be 4023 kWh electricity per year. Under the same conditions in case it is constructed in the middle part of Bulgarian coastline the AEP would be 3550 kWh, while in the south part of Bulgaria it would be 4260 kWh.

Point analysis				Coordinates		d	Sds	Period		$P_{year}$	COV	SV	MV	AEP	
ID	Source P		Point	Longitude	Latitude	m	km			years	kW/m	-	-	-	kWh
BG-01	Valchev	2012	А	N 43.167°	E 28.300°	35	23.79	1948	2006	59	1.150	NE	NE	NE	4351.97
BG-02	Valchev	2012	В	N 42.500°	E 27.800°	35	11.75	1948	2006	59	1.120	NE	NE	NE	4238.44
BG-03	Valchev	2013	2	N 43.000°	E 28.500°	91	47.63	1948	2006	59	1.796	NE	NE	NE	6796.64
BG-03	Akpinar	2017	DCS	N 43.000°	E 28.500°	91	47.63	1979	2009	31	4.300	2.50	1.5	1.8	16272.58
BG-04	Akpinar	2017	BR	N 42.000°	E 28.500°	91	38.60	1979	2009	31	5.000	2.60	1.5	1.8	18921.60
BG-05	Rusu	2017	P4	N 43.190°	E 28.350°	50	21.59	1997	2016	20	2.480	2.67	1.3	1.5	9385.11
BG-06	Rusu	2017	P5	N 42.430°	E 27.960°	50	19.42	1997	2016	20	2.680	3.14	1.2	1.5	10141.98
BG-07	Rusu	2017	P13	N 43.300°	E 28.830°	100	27.64	1997	2016	20	3.530	2.74	1.5	1.5	13358.65
BG-08	Rusu	2017	P14	N 42.850°	E 28.380°	100	39.02	1997	2016	20	3.310	2.93	1.5	1.5	12526.10

Table 1 Wave climate and AEP at selected points in Bulgarian EEZ of Black Sea



Fig. 2. Theoretical wave power resource (in kW/m) in Bulgarian EEZ of Black Sea for the period 2000 – 2012 (after Valchev et al. 2014)

Let us estimate the maximum effect of the utilisation of the wave energy resource at the Bulgarian Black Sea coast on the electricity market. For this purpose it is constructed the following hypothetical situation. Firstly, let us assume that the theoretical wave power resource on the entire Black Sea coast of Bulgaria, with a total length of 378 km, is the same as at the one marked for the south part of the coast (Fig. 1). Secondly, let us assume that the entire Black Sea coastline of Bulgaria is protected by a sea wall on which 378000 WECs are incorporated. Each WEC is based on the OWC concept and is equipped with 1 m diameter runner WTOB with and the availability of each WEC is 93.2 %. The maximum possible annual electricity that could be generated under this

hypothetical situation is 1610.1 GWh. This figure is equal to 4.75 % of the net electricity consumption in Bulgaria for 2016. Obviously, the power that can be extracted from the wind waves at Bulgarian Black Sea coast would be much lower and energy production is not feasible.

In Table 1  $S_{ds}$  is the shortest length between the point of interest and Bulgarian Black Sea coastline,  $P_{year}$  is yearly averaged wave power resource for the entire period. For better understanding of temporal variability of wind climate at each point in Table 1 is presented information about the Coefficienct of Variation (COV), Seasonal Variability (SV) and Monthly variability of wave power resource there, calculated for the entire period covered by the study. The lower are the values of these temporal variability indece characteristics the more appropriate is a site for location of a WEC. COV is defined as follows, (Rusu et al. 2017):

$$COV = \frac{Standard \ Deviation \ of \ P_{year}}{Mean \ of \ P_{vear}} \tag{6}$$

Monthly Variability (MV) and Seasonal Variability (SV) of wave power resorce at the point of interest for the entire period are defined as follows, (Rusu et al. 2017):

$$MV = \frac{P_{max,M} - P_{min,M}}{P_{vear}}, \frac{kW}{m}$$
(7)

$$SV = \frac{P_{max,S} - P_{min,S}}{P_{vear}}, \frac{kW}{m}$$
(8)

 $P_{max,M}/P_{max,S}$  and  $P_{min,M}/P_{min,S}$  are the most energetic month/season and the less energetic month/season during the entire period covered by the study. The winter season includes December of the previous year and January and February of the current year. Spring months are March, April and May, summer months are June, July and August, and autumn months are September, October and November.

AEP values presented in Table 1 are calculated for a WEC based on PA concept realized by WTOB with 2m diameter of the runner and availability of 90%.

## CONCLUSION

The accessible wave power resource at 8 points in Bulgarian EEZ of Black Sea was evaluated based on the application of a WEC realising/using PA concept with a WTOB with 2 m diameter of the runner used as PTO subsystem. Accessibale wave power resource at the extrimely and very exposed parts of the Bulgarian Black Sea coast was evaluated based on the application of a WEC realising/using OWC concept with a WTOB with 1 m diameter of the runner used as PTO subsystem. It is concluded that construction of WECs on Bulgarian Black Sea coastline with the purpose to cover electricity demand is not feasible. However, it is feasible to incorporate WECs in the existing and planned for construction sea walls and groynes used for shore protection from wave action, since in the case of WTOB as a PTO subsystem the reaction subsystem, which is more than half of the investment, will be available.

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