# ESTIMATION OF WAVE POWER IN SHALLOW WATER USING DEEP WATER WIND AND WAVE STATISTICS

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## Abstract

The article addresses how the wave power in shallow water can be estimated based on available wind and wave statistics for a deep water ocean area. The average statistical properties of the wave power in shallow water expressed in terms of the mean value and the standard deviation are presented. Results are exemplified by using long-term wind and wave statistics from the same ocean area in the Northern North Sea. Overall, it appears that there is agreement between the results based on these inputs from wind and wave statistics. The presented analytical method should be useful for making preliminary estimates of the wave power potential in shallow water using either available deep water wind statistics or deep water wave statistics, which enhances the possibilities for assessing further the wave power potential in, for example, near-coastal zones.

**Keywords:** Wave power, shallow water, deep water wind statistics, deep water wave statistics, coastal zones.

# 1. Introduction

It is well recognized that ocean wave energy represents a promising alternative energy resource, but also that the engineering community has a challenge in making an optimum design of a wave power device to extract energy from waves. Generally, a device is frequency dependent, and the design will determine its natural frequency as well as the frequency range that might cause a significant response. Thus, the challenge in designing appropriate devices to convert energy from waves is twofold; it is required that the device can be controlled to give maximum power at low cost, and that the control system at the same time can protect it if exposed to extreme wave conditions. More details regarding such control issues are provided by e.g. Venugopal and Smith[1] and Valerio et al.[2]. Furthermore, Falnes[3] gave a comprehensive review of wave energy extraction.

Therefore, knowledge of the wave conditions is crucial for an optimum design of wave power devices. Sea states are characterized by the significant wave height $H_s$ and the mean zero-crossing wave period $T_z$ (or the spectral peak period $T_p$), and the individual random waves within a sea state are characterized by the wave height $H$ and the wave period $T$. Thus, the statistical properties of wave power for sea states and for individual waves are of interest; also jointly with the corresponding sea state wave parameters and the individual wave parameters. Wave power statistics for sea states based on wave statistics have been provided by e.g. Ertekin and Xu[4], Pontes[5], Beels et al.[6], Kerbiriou et al.[7] and Myrhaug et al.[8]. Previous works on wave power statistics for individual waves based on waves statistics are Smith et al.[9], Venugopal and Smith[1], Myrhaug et al.[10], and Leira and Myrhaug[11]. Izadparast and Niedzwechi[12] applied joint statistics of $H$ and $T$ and provided an example of how to evaluate the long-term potential of wave power. Both Sheng and Lewis[13] and Pastor and Liu[14] applied numerical validation methods to assess extraction of wave energy. One should notice that Ertekin and Xu[4] were the first to assess the wave power potential from observed wind statistics. Recently Myrhaug[15] demonstrated how the wave power for sea states can be assessed based on available wind statistics from a deep water location in the Northern North Sea.

The main purpose and the novelty of this article is to provide a simple analytical method which can be applied to make first assessments of the wave power potential for sea states in shallow water using either deep water wind statistics or deep water wave statistics, e.g. from global wind or wave statistics. Thus, the present aspects are new compared with the other papers referred to. Such a simple method should be useful to make first inexpensive wave power estimates before eventually using more work-intensive tools based on existing long-term wind or wave statistics from measurements or hindcast analysis, or by using wave simulation models.

The article contains an Introduction, followed by Section 2 giving the theoretical background and general formulation of the wave power in shallow water given in terms of the deep water sea state wave parameters $H_s$ and $T_z$ . Section 3 gives the results for a Pierson-Moskowitz deep water wave amplitude spectrum with the mean wind speed statistics from a deep water location in the Northern North Sea as input. Section 4 provides the results using a joint distribution of $H_s$ and spectral wave steepness from the same ocean area as the wind statistics. Section 5 gives examples of results, by first providing the validity of results for shallow water (Section 5.1), then presenting results based on wind and wave statistics (Section 5.2), and third by providing some comments (Section 5.3). Summary and conclusions are given in Section 6. Overall, the presented analytical method provides estimation of wave power in shallow water based on offshore wind or wave statistics, that can be linked to this energy resource. Thus, it is demonstrated how the present method can be applied to make preliminary assessments of the wave power potential in near-coastal zones.

## 2. Background

The wave power is defined as the transport of wave energy per unit crest length of a progressive wave front given by the wave energy $E$ multiplied by the group velocity $c_g$, i.e. $J = Ec_g$ (Falnes[3]). For shallow water waves for a wave component with wave amplitude $a_n$ the wave energy is $E_n = \frac{1}{2}\rho g a_n^2$ , and the group velocity $c_{gn}$ equals the phase velocity $c_n = \sqrt{gh}$ . Thus, the wave power for this wave component is

$$\boldsymbol{J_n = \frac{1}{2}\rho g a_n^2 \sqrt{gh} \ \ (W/m)} \tag{1}$$

Here $\rho$ is the fluid density, $g$ is the acceleration of gravity, and $h$ is the water depth. The wave amplitude is obtained from the wave spectrum as $a_n^2 = 2S(\omega_n, h) \cdot \Delta\omega$ where $\Delta\omega$ is a constant separation between the wave frequencies $\omega_n$ , $S(\omega, h)$ is the wave spectrum for long-crested random waves in shallow water which can be expressed in terms of the deep water wave spectrum for long-crested random waves $S(\omega)$ as $S(\omega, h) = (h/2g)\omega^2 S(\omega)$ (Massel[16], Section 7.3). Implementation of this in Eq. (1) yields

$$\boldsymbol{J_n = \frac{1}{2}\rho h \sqrt{gh}\omega_n^2 S(\omega_n) \cdot \Delta\omega \ \ (W/m)} \tag{2}$$

The wave power in a sea state with shallow water random waves with an infinite number of wave components becomes

$$\boldsymbol{J = \frac{1}{2}\rho h \sqrt{gh} m_2 \ \ (W/m)} \tag{3}$$

where $m_2$ is the deep water second spectral moment. The deep water *nth* order spectral moments are defined as $\boldsymbol{m_n = \int_0^\infty \omega^n S(\omega) d\omega; n = 0, 1, 2, \ldots}$ . Now, the deep water zero-crossing wave period, $\boldsymbol{T_z = 2\pi\sqrt{m_0/m_2}}$ , and the deep water significant wave height, $\boldsymbol{H_s = 4\sqrt{m_0}}$ , can be combined to give

$$\boldsymbol{m_2 = \frac{\pi^2}{4}(\frac{H_s}{T_z})^2 \ \ (m^2/s^2)} \tag{4}$$

which substituted in Eq. (3) yields

$$\boldsymbol{J = \frac{\pi^2}{8}\rho h\sqrt{gh}(\frac{H_s}{T_z})^2 \ \ (W/m)} \tag{5}$$

As a result, the wave power $J$ in shallow water is obtained for known wave conditions in deep water, which either can be specified by a deep water wave amplitude spectrum or by the sea state wave parameters $H_s$ and $T_z$ in deep water. This will be discussed in the next sections; Section 3 applies the Pierson-Moskowitz (PM) deep water wave amplitude spectrum, while Section 4 uses the joint distribution of $H_s$ and the spectral wave steepness $s_m$ as input.

## 3. Application of a PM spectrum with mean wind speed statistics as input

The PM spectrum with the mean wind speed at the 10 m elevation above the sea surface, $U_{10}$, as the parameter is applied as the deep water wave amplitude spectrum. One should notice that the PM spectrum is valid for fully developed wind waves, but as a compromise between simplicity and accuracy it is adopted here to demonstrate how wind statistics can be used analytically. Some further comments are provided in Section 5.3. According to Tucker and Pitt[17] the PM spectrum is $S(\omega) = A\omega^{-5}\, exp(-B\omega^{-4})$ where the spectral moments for $n < 4$ are $m_n = 0.25AB^{n/4-1}\Gamma(1-n/4)$, $\Gamma$ is the gamma function, $A = \alpha g^2, \alpha = 0.0081$, $B = 1.25\omega_p^4$, $\omega_p = 2\pi/T_p$ is the spectral peak frequency corresponding to the spectral peak period $T_p$. Then it follows that $m_2 = 0.25\alpha g^2\sqrt{\pi}1.25^{-0.5}\omega_p^{-2}$ which combined with $T_p = 0.785U_{10}$ gives $m_2 = 0.00482U_{10}^2$ . Substitution of this in Eq. (3) yields

$$\boldsymbol{J = 0.00241\rho h\sqrt{gh}U_{10}^2 \ \ (W/m)} \tag{6}$$

Thus, $J$ in shallow water can be obtained from known mean wind speed statistics at a deep water site.

In order to demonstrate how wind speed statistics can be applied to assess the wave power in shallow water, the Johannessen et al.[18] cumulative distribution function (*cdf*) of $U_{10}$ is adopted. This *cdf* represents 1-hourly values of $U_{10}$ recorded during the period 1973 – 1999 at a deep water location in the Northern North Sea, and is given by the two-parameter Weibull model $P(U_{10}) = 1 - exp\left[-(U_{10}/\theta)^{\beta}\right]; U_{10} \geq 0$ with the Weibull parameters $\theta = 8.426m/s$ and $\beta = 1.708$.

The statistical quantities considered here are the expected value and the variance of $J$, which then requires the calculation of the expected value and the variance of $U_{10}^2$, i.e. $E[U_{10}^2]$ and $Var[U_{10}^2]$, respectively. For a Weibull-distributed variable (Bury[19])

$$\boldsymbol{E[U_{10}^n] = \theta^n \Gamma(1 + \frac{n}{\beta})} \tag{7}$$

$$\boldsymbol{\sigma^2[U_{10}^n] \equiv Var[U_{10}^n] = E\left[U_{10}^{2n}\right] - (E[U_{10}^n])^2} \tag{8}$$

In the present case this yields $E[U_{10}^2] = 77.0m^2/s^2$ and $\sigma[U_{10}^2] = 90.8m^2/s^2$, with the coefficient of variation $R = \sigma[U_{10}^2]/E[U_{10}^2] = 1.18$. Substitution of this in Eq. (6) yields

$$\boldsymbol{E[J] = 0.186\rho h\sqrt{gh}\ \ (W/m)} \tag{9}$$

Thus, the mean value (*m.v.*)$\pm 1$ standard deviation (*SD*) interval of the factor is 0 to 0.405.

Furthermore, $H_s = 0.0246U_{10}^2$ for a PM spectrum (Tucker and Pitt[17]), which gives $E[H_s] = 0.0246E[U_{10}^2] = 0.0246 \cdot 77.0m = 1.89m$.

## 4. Application of joint *pdf* of $H_s$ and $s_m$

As referred to in Section 2 the wave power in shallow water is also given in terms of the sea state parameters $H_s$ and $T_z$ in deep water. Thus, the statistical properties of the wave power can be derived from the joint statistics of $H_s$ and $T_z$ in deep water (see Eq. (5)) by following a procedure similar to that given in e.g. Myrhaug et al.[8]. However, here the alternative of using the joint probability density function (*pdf*) of $H_s$ and the spectral wave steepness $s_m$ provided by Myrhaug[20] is applied. The spectral deep water wave steepness is defined as $s_m = H_s/((g/2\pi)T_z^2)$. Thus, by defining $w = (H_s/T_z)^2$, $w$ can be expressed in terms of $s_m$ and $H_s$ as $w = (g/2\pi)H_s s_m$.

The joint *pdf* of $H_s$ and $w$ is obtained from the joint *pdf* of $H_s$ and $s_m$ given in Appendix 1 by following the same procedure as in Myrhaug[20], i.e. by a change of variables from $H_s, s_m$ to $H_s, w$, which yields

$$\boldsymbol{p(H_s, w) = p(w|H_s)p(H_s)} \tag{10}$$

where $p(H_s)$ is given in Eq. (28) (see Appendix 1). This change of variable from $s_m$ to $w$ only affects $p(s_m|H_s)$ since $s_m = (2\pi/g)H_s^{-1}w$. Then, by using the Jacobian $|ds_m/dw| = (2\pi/g)H_s^{-1}$, this yields the following conditional lognormal *pdf* of $w$ given $H_s$

$$\boldsymbol{p(w|H_s) = \frac{1}{\sqrt{2\pi}\sigma_w w} exp\left[-\frac{1}{2}\left(\frac{ln\, w - \mu_w}{\sigma_w}\right)^2\right]} \tag{11}$$

where $\mu_w$ and $\sigma_w^2$ are the mean value and the variance, respectively, of $ln\, w$, given by

$$\boldsymbol{\mu_w = \mu_{s_m} - ln\left(\frac{2\pi}{g} H_s^{-1}\right)} \tag{12}$$

$$\boldsymbol{\sigma_w^2 = \sigma_{s_m}^2} \tag{13}$$

where $\mu_{s_m}$ and $\sigma_{s_m}$ are given in Eqs. (30) and (31), respectively.

Here results will be given in terms of $E[H_s], E[w|H_s]$ and the coefficient of variation $R = \sigma[w|H_s]/E[w|H_s]$ given by (Bury[19])

$$E[H_s] = \varepsilon_h + \zeta_h \Gamma(1 + \frac{1}{\theta_h}) \tag{14}$$

$$E[w|H_s] = exp(\mu_w + \frac{1}{2}\sigma_w^2) \tag{15}$$

$$R = (e^{\sigma_w^2} - 1)^{1/2} \tag{16}$$

Results are exemplified by using the wave data recorded during the period 1974-1986 representing wind sea, swell, and combined wind sea and swell from the deep water location at Utsira in the Northern North Sea as given in Appendix 1. Thus, these data represent the same ocean area and partly the same period as the wind speed statistics from Johannessen et al.[18]. First, substitution of the Weibull parameters in Eq. (32) in Eq. (14) yields $E[H_s] = 2.11m$, which compared with $E[H_s] = 1.89m$ based on the PM spectrum in Section 3, is about 10 percent larger. Second, by using this value of $H_s$ in Eqs. (30) and (31) together with the coefficients in Eqs. (33) and (34), substitution in Eqs. (12), (13), (15) and (16) yields, respectively,

$$\mu_w = -1.925\, m^2/s^2 \tag{17}$$

$$\sigma_w^2 = 0.0936\, m^4/s^4 \tag{18}$$

$$E[w|E[H_s] = 2.11m] = 0.153\, m^2/s^2 \tag{19}$$

$$R = 0.313 \tag{20}$$

Then, it follows from Eqs. (5) and (19) that

$$E[J|E[H_s] = 2.11m] = \frac{\pi^2}{8}\rho h\sqrt{gh}E[w|E[H_s] = 2.11m]$$

$$= 0.189\rho h\sqrt{gh}\ \ (W/m) \tag{21}$$

where the $m.v. \pm 1SD$ of the factor 0.189 is 0.130 to 0.248.

It appears that there is agreement between the results from the wind statistics (with $E[H_s] = 2.11m$ and Eq. (9)) and the wave statistics (with $E[H_s] = 1.89m$ and Eq (21)). This is elaborated further in Section 5.2. One should notice, however, that the coefficient of variation is smaller based on wave statistics ($R$ = 0.313) than that based on wind statistics ($R$ = 1.18), which is attributed to inherent features of the respective distribution.

# 5. Examples of results

Examples of estimating the wave power in shallow water based on the results in Sections 3 and 4 are provided in Section 5.2. Some additional comments on this method are provided in Section 5.3. However, first the validity of the results based on the shallow water approximation is discussed in Section 5.1.

## 5.1 Validity of results in shallow water

Hedges [21] provided the validity in terms of the wave steepness and the Ursell number. The upper limit of the wave steepness for linear regular waves in deep water is 0.04, and by adopting this upper limit to be valid for the spectral wave steepness $s_m$ defined in Section 4, it implies that

$$\boldsymbol{s_m = \frac{H_s}{\frac{g}{2\pi}T_z^2} \leq 0.04} \tag{22}$$

Next, the Ursell number $U_R = ka/(kh)^3 \leq 0.5$ for linear regular waves, where $k$ is the wave number, and $a$ is the wave amplitude. Further, for linear regular waves propagating over a gently sloping flat bottom towards a straight coastline at normal incidence, the wave amplitude in shallow water is derived assuming that the energy flux is constant, i.e. $a = a_\infty/(2kh)^{1/2}$

(Dean and Dalrymple[22]), where $a_\infty = H_\infty/2$ is the wave amplitude and $H_\infty$ is the wave height in deep water. Then, combined with this and using the dispersion relationship in shallow water, $k = 2\pi/(T\sqrt{gh})$ where $T$ is the wave period, and replacing $H_\infty$ and $T$ with $H_s$ and $T_z$, respectively, the Ursell number criterion in shallow water becomes

$$\boldsymbol{U_R = 0.062 \frac{H_s T_z^{5/2}}{h^{9/4}} \leq 0.5} \tag{23}$$

Eq. (22) implies that $T_z \geq 4H_s^{1/2}$, and by substituting the lower value $T_z = 4H_s^{1/2}$ in Eq. (23), the results in shallow water is valid for

$$\boldsymbol{h \geq 1.85H_s} \tag{24}$$

However, one should notice that the results will be valid for larger water depths if $T_z > 4H_s^{1/2}$.

## 5.2 Examples based on wind and wave statistics

For wind statistics from Section 3, $E[H_s] = 1.89m$, which substituted in Eq. (24) yields $h \geq 3.5m$. Substitution of $h = 3.5m$ in Eq. (9) by taking $\rho = 1025\text{kg/m}^3$ gives

$$\boldsymbol{E[J] = 3.91}\ \text{kW/m} \tag{25}$$

Now, since the $m.v. \pm 1SD$ interval of the factor 0.186 in Eq. (9) is 0 to 0.405, this yields the interval 0 to 8.52 kW/m for $E[J]$ (these results are summarized in Table 1).

For wave statistics from Section 4, $E[J|E[H_s] = 2.11m]$, which substituted in Eq. (24) yields $h \geq 3.9m$. Substitution of $h = 3.9m$ (and $\rho = 1025\text{kg/m}^3$) in Eq. (21) gives

$$\boldsymbol{E[J|E[H_s] = 2.11m] = 4.67}\ \text{kW/m} \tag{26}$$

Similarly, the $m.v.\pm\ 1SD$ interval of the factor 0.189 in Eq. (21) is 0.130 to 0.248, which for Eq. (26) yields the interval 3.21 kW/m to 6.13 kW/m (as summarized in Table 1).

The estimate obtained from wind statistics using this water depth, i.e. substitution of $h = 3.9m$ instead of $h = 3.5m$ in Eq. (9) is also summarized in Table 1, showing that the result is changed to $E[J] = 4.60\text{kW/m}$ from $E[J] = 3.91\text{kW/m}$ for $h = 3.5m$ , i.e. corresponding to an increase of 18 percent. If the standard deviations are taken into account, the range of values associated with $J$ based on wave statistics, i.e. 3.21 kW/m to 6.13 kW/m, are within the range of values based on wind statistics for $h = 3.9$ m , i.e. 0 to 10.03 kW/m (see Table 1). Thus, as discussed in Section 4, this demonstrates that there is agreement between the results based on wind statistics and wave statistics from the same deep water ocean area and partly the same period. One should notice that the presented results for the wave power in shallow water are valid for this ocean area. It should also be emphasized that that this agreement is not enough to show the ability of the present method; a conclusion regarding that can only be made by validating the method by comparing it with observed wave data and/or numerical wave models.

## 5.3 Comments

Although the results presented in Sections 3, 4 and 5.2 are based on a specific wave amplitude spectrum, wind speed distribution and joint *pdf* of $H_s$ and $s_m$ , the method can also be applied for other wave amplitude spectra, wind speed statistics and joint distributions of sea state wave parameters, or for a given deep water wave amplitude spectrum including directional spreading effects. However, in such cases numerical calculations are most probably required. Many studies would also use appropriate physics-based numerical wave model tools (e.g. SWAN, Holthuijsen[23]) to obtain the wave power at the shallow water site. Here an alternative is presented providing a simple analytical method which can be applied to make first-order estimates of wave power in shallow water based on given values of $H_s$ and $T_z$ in deep water from observed wind or wave statistics; here exemplified by using wind and wave statistics representing in-situ data obtained from the same ocean area and partly the same period. Comparisons with observed data and/or numerical wave models are required to validate the method, but is beyond the scope of this note.

## 6. Summary and conclusions

The paper provides a simple analytical method which can be used to make preliminary assessments of the wave power potential for sea states in shallow water using deep water wind and wave statistics. The results are valid for long-crested random waves which are transformed from deep water to shallow water and the deep water wave conditions are given in terms of the sea state wave parameters significant wave height and mean zero-crossing wave period. Thus, the wave power in shallow water is expressed in terms of these deep water sea state wave parameters. The average statistical features of the wave power expressed in terms of the mean value and the standard deviation are provided. First, results are given by applying a Pierson-Moskowitz model wave amplitude spectrum for deep water wind waves with the mean wind speed at the $10 \text{ m}$ elevation above the sea surface as the parameter, and using long-term mean wind speed statistics from a deep water location in the Northern North Sea as input. Second, results are given for sea states described by a joint distribution of significant wave height and spectral wave steepness representing swell, wind waves, and combined swell and wind waves from the same ocean area as the wind statistics. Examples of results typical for field conditions using inputs from the wind and wave statistics are provided.

The main conclusions are:

First, overall it appears that the present assessment of wave power in shallow water based on long-term wind statistics from a deep water location in the Northern North Sea agrees with that using long-term wave statistics from the same deep water ocean area and partly the same period.

Second, the novelty of this study is that it demonstrates how the provided simple analytical method can be applied to make quick and preliminary estimates of the wave power potential in shallow water within sea states using either available deep water wind statistics or deep water wave statistics. However, comparisons with data and/or numerical wave models are required in order to make a firm validation of the method. Meanwhile this approach should enhance the possibilities of assessing further the wave power potential in e.g. near-coastal zones.

## Appendix 1. Joint *pdf* $H_s$ and $s_m$ from Myrhaug[20]

The joint *pdf* of $H_s$ and $s_m$ provided by Myrhaug[20] is given as

$$p(H_s, s_m) = p(s_m|H_s)p(H_s) \tag{27}$$

where $p(H_s)$ is the marginal *pdf* of $H_s$ given by the following three-parameter Weibull *pdf*

$$p(H_s) = \frac{\theta_h}{\zeta_h}\left(\frac{H_s-\varepsilon_h}{\zeta_h}\right)^{\theta_h-1} exp\left[-\left(\frac{H_s-\varepsilon_h}{\zeta_h}\right)^{\theta_h}\right]; H_s \geq \varepsilon_h \tag{28}$$

where $\theta_h, \zeta_h, \varepsilon_h$ are the Weibull parameters. Furthermore, $p(s_m|H_s)$ is the conditional *pdf* of $s_m$ given $H_s$, given by the following lognormal *pdf*

$$p(s_m|H_s) = \frac{1}{\sqrt{2\pi}\sigma_{s_m} s_m} exp\left[-\frac{1}{2}\left(\frac{lns_m-\mu_{s_m}}{\sigma_{s_m}}\right)^2\right] \tag{29}$$

where $\mu_{s_m}$ and $\sigma_{s_m}^2$ are the mean value and the variance, respectively, of $lns_m$, given as

$$\mu_{s_m} = ln\left(\frac{H_s}{g/2\pi}\right) - 2(a_1 + a_2 H_s^{a_3}) \tag{30}$$

$$\sigma_{s_m}^2 = 4(b_1 + b_2 e^{b_3 H_s})^2 \tag{31}$$

where $a_1, a_2, a_3, b_1, b_2$ and $b_3$ are coefficients. In this study the joint *pdf* of $H_s$ and $s_m$ representing deep water swell, wind waves, and combined swell and wind waves conditions recorded during the period 1974-1986 at the Utsira location (in the Northern North Sea) on the Norwegian continental shelf is chosen to exemplify the results. For these data the Weibull parameters in Eq. (27) and the coefficients in Eqs. (30) and (31) are given as (see Myrhaug[20] for more details)

$$\zeta_h = 1.50\text{m}, \theta_h = 1.15, \varepsilon_h = 0.679m \tag{32}$$

$$a_1 = 0.933, a_2 = 0.578, a_3 = 0.395 \tag{33}$$

$$b_1 = 0.0550, b_2 = 0.336, b_3 = -0.585 \tag{34}$$

## References


1. Venugopal V and Smith GH. The effect of wave period filtering on wave power extraction and device tuning. *Ocean Eng* 2007; 34(8-9):1120-1137.
2. Valerio D, Beirao P and Sa da Costa J. Optimization of wave energy extraction with the Archimedes wave swing. *Ocean Eng* 2007; 34(17-18): 2330-2340.
3. Falnes J. A review of wave-energy extraction. *Mar Struct* 2007; 20(4): 185-201.
4. Ertekin RC and Xu Y. Preliminary assessment of the wave-energy resource using observed wave and wind data. *Energy* 1994; 19(7): 729-738.
5. Pontes MT. Assessing the European wave energy resource. *ASME J Offshore Mech Arct Eng* 1998; 120(4): 226-231.
6. Beels C, Henriques JCC, De Rouck J, et al. Wave energy resource in the North Sea. In: *Proc. of the 7th European Wave and Tidal Energy Conference.* Portugal CD-Rom, Porto, 2007.
7. Kerbiriou M-A, Prevosto M, Maisondien C, et al. Influence of sea-states description on wave energy production assessment. In: *Proc. of the 7th European Wave and Tidal Energy Conference.* Portugal CD-Rom, Porto, 2007.
8. Myrhaug D, Leira BJ and Holm H. Wave power statistics for sea states. *ASME J Offshore Mech Arct Eng* 2011; 133(4): 044501-044501-5.
9. Smith GH, Venugopal V and Wolfram J. Wave period group statistics for real sea waves and wave energy extraction. *Proc IMechE M J Eng Marit Environ* 2006; 220(3): 99-115.
10. Myrhaug D, Leira BJ and Holm H. Wave power statistics for individual waves. *Appl Ocean Res* 2009; 31(4): 246-250.
11. Leira BJ and Myrhaug D. Long-term wave-power statistics for individual waves. *ASME J Energy Resour Technol* 2015; 137(4): 041202-041202-7.

12. Izadparast AH and Niedzwecki JM. Estimating the potential of ocean wave power resources. *Ocean Eng* 2011; 38(1): 177-185.

13. Sheng E and Lewis A. Assessment of wave energy extraction from seas: numerical validation. *ASME J Energy Resour Technol* 2012; 134(4): 041701-041701-8.

14. Pastor J and Liu Y. Power absorption modeling and optimization of point absorbing wave energy converter using numerical method. *ASME J Energy Resour Technol* 2014; 136(2): 021207-021207-8.

15. Myrhaug D. Wave power statistics for sea states based on wind statistics. *J Ocean Eng and Marine Energy* 2018; 4: 89-92.

16. Massel SR. *Hydrodynamics of coastal zones.* Amsterdam: Elsevier, 1989.

17. Tucker MJ and Pitt EG. *Waves in ocean engineering*. Amsterdam: Elsevier, 2001.

18. Johannessen K, Meling TS and Haver S. Joint distribution for wind and waves in the Northern North Sea. In: *Proc. of the 11th offshore and polar engineering conference,* Vol. III. Stavanger 2001; pp. 19-28.

19. Bury KV. *Statistical models in applied science.* New York: Wiley, 1975.

20. Myrhaug D. Some probabilistic properties of deep water wave steepness. *Oceanologia* 2018; 60(2):187-192.

21. Hedges TS. Regions of validity of analytical wave theories. *Proc Inst Civ Eng Water Marit Energ J* 1995; 112: 111-114.

22. Dean RG and Dalrymple RA. *Water wave mechanics for engineers and scientists.* Upper Saddle River, NJ: Prentice Hall, 1984.

23. Holthuijsen LH. *Waves in oceanic and coastal waters.* Cambridge, UK: Cambridge University Press, 2007.

Table 1. Example of estimates obtained from deep water wind statistics versus those obtained from deep water wave statistics. The results for waves are given for the shallow water depth $h$ = 3.9 m, while the results for wind are given for $h =$ 3.5 m$/h = 3.9m$; *SD* = standard deviation.

| Wind | | Waves | |
|---|---|---|---|
| $E[H_s](m)$ | 1.89 | $E[H_s](m)$ | 2.11 |
| $E[J](kW/m)$ | 0, 3.91/4.60 | $E[J\|E[H_s] = 2.11m](kW/m)$ | 4.67 |
| $E[J] \pm 1SD(kW/m)$ | 0, 8.52/10.03 | $E[J\|E[H_s] = 2.11m] \pm 1SD(kW/m)$ | 3.21,6.13 |