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by

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INTRODUCTION

This report was prepared under the ForskVE project WEPTOS#1 aiming at testing for the first time the wave energy device at sea. The results of this report are used to give an indication on the wave conditions at the selected location of testing and may also further be used for extrapolation of wave forces in extreme events.

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1. Objectives

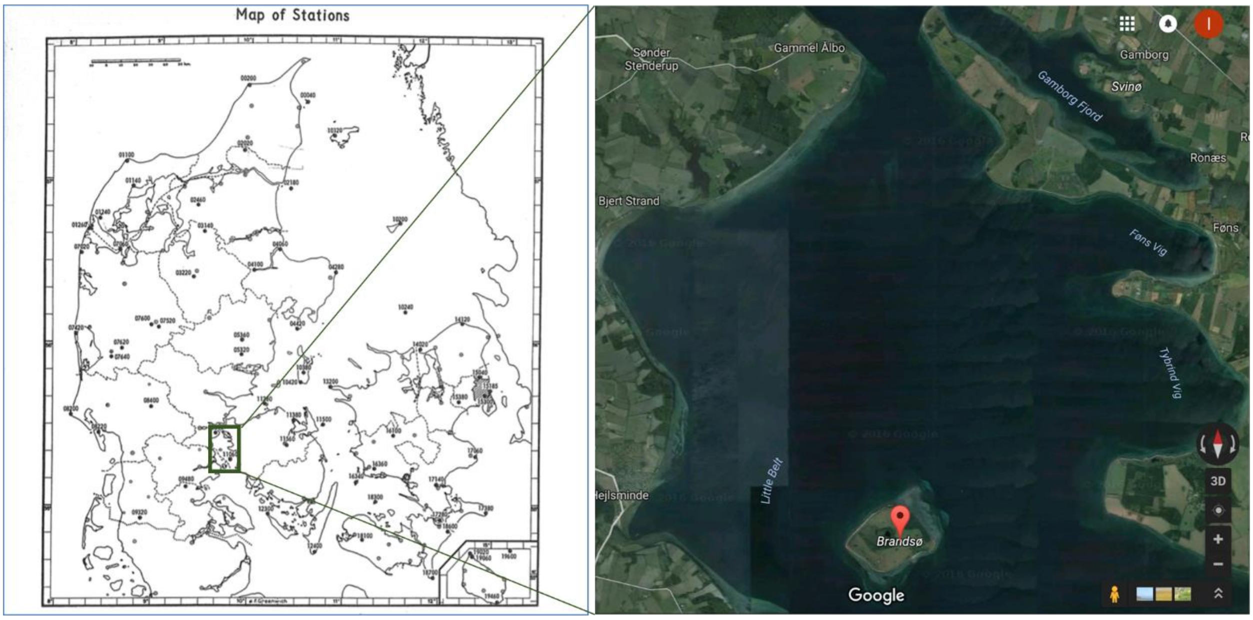
Brandsø in Denamrk is the selected location for the installation of WEPTOS prototype #1.

The objective of this report is to present the calculated wave highs at Brandsø form an analysis of wind data. The analysis of the wave conditions at location will give an indication on expected wave power. Additionally, consideration on extremes will also be presented.

Combining the wave climate with previous laboratory performance studies, it is then possible to estimate the expected performance for the WEPTOS in Brandsø.

2. Methodology

From the “Danmarks Klima I Vind” document, average wind speeds on the twelve-point Beaufort scale were found. The wind speeds were all measured from a height of 10m above the water for a ten-minute duration over a period of 30 years. Additionally, the probability of occurrence for each level on the twelve-point scale from every direction is provided in the report.
For the location of interest on the North North-West side of Brandsø (Fig. 1) the winds from South East, and South were discarded as the island is shadowing the waves generated by those winds. The only station used for the study is the location #6340 from the “Danmarks Klima I Vind” (Table 1). Previous analysis considering more than one location showed good accordance of results between stations (Report on Samsø wave climate).
The percentage of time with wind events with the possibility of producing waves in the location of interest on the North West side of Brandsø resulted to be 67.8%.



Figur 1. WEPTOS prototype location.

Tabel 1. Probabilities for given wind speed and direction at station #6340

Beaufort Scale	1	2	3	4	5	6	7	8	TOT on direction
N	1,6	1,2	1,3	0,9	0,2	0,1	0	0	5,3
NE	2,8	1,9	2	1,1	0,4	0,1	0	0	8,3
E	1,8	1,9	2,3	1,5	0,8	0,2	0,1	0	8,6
SW	3,7	3,7	4,3	3,1	1,5	0,6	0,2	0	17,1
NW	3,9	2,8	2,7	1,7	0,7	0,3	0	0	12,1
W	3,4	3,2	3,9	3,3	1,7	0,6	0,2	0,1	16,4
								TOT	**67,8**

The SPM-method was then applied. An estimation of fetch was measured using Google Earth where the longest fetch within twelve degrees of each direction was taken. This was done to project the largest possible waves that could make it to our point of interest (Table 2). The water depth used in the calculations is 10 m. This is a conservative choice as especially on the North and North West directions the water depth encounters shallower spots.

Tabel 2. Fetches for selected wind directions

	F[m]
N	11100
NE	9100
E	8800
SW	4600
NW	8700
W	4700

The necessary correction factors were included before obtaining the wind stress factor for each level of the Beaufort scale.
For the air-sea temperature difference, an R of 1.1 was assumed due to the absence of temperature information. The station #6340 is on the coast so no multiplication factor was taken for the land to sea correction.
Once the wind stress factor was accurately computed, the value could be used to find the wave heights and periods. This calculation required the following equations, which include the correction made in the "Revision of SPM 1984 Wave Hindcast Model to Avoid Inconsistencies in Engineering Applications".

The transformation of the wind speeds into the corresponding wave height and periods allowed us to group the results into various classes (Table 3, 4). After careful consideration, both of these variables were broken up into nine classes in order to organize the calculated wave and periods into sea states.

$$(1) \quad U_A = 0.71\, U_{10}^{1.23}$$

$$(2) \quad H_{m0} = 0.25 \tanh\left(0.6\left(\frac{dg}{{U_A}^2}\right)^{0.75}\right) tanh^{0.5}\left[\frac{4.3\times 10^{-5}\frac{Fg}{{U_A}^2}}{tanh^2\left(0.6\left(\frac{dg}{{U_A}^2}\right)^{0.75}\right)}\right]\frac{{U_A}^2}{g}$$

$$(3) \quad T_p = 8.3 \tanh\left(0.76\left(\frac{dg}{{U_A}^2}\right)^{0.375}\right) tanh^{1/3}\left[\frac{4.1\times 10^{-5}\frac{Fg}{{U_A}^2}}{tanh^3\left(0.76\left(\frac{dg}{{U_A}^2}\right)^{0.375}\right)}\right]\frac{U_A}{g}$$

Tabel 3. Wave height [m] for chosen fetch and selected direction for given Beaufort Number.

Beaufort Scale	1	2	3	4	5	6	7	8
N	0,013	0,120	0,270	0,455	0,684	0,961		
NE	0,013	0,112	0,245	0,412	0,621	0,873		
E	0,013	0,111	0,241	0,406	0,611	0,858	1,129	
SW	0,013	0,084	0,175	0,294	0,443	0,623	0,823	
NW	0,013	0,110	0,240	0,403	0,607	0,854		
W	0,013	0,085	0,177	0,297	0,447	0,630	0,832	1,063

Tabel 4. Calculated Periods [s], for chosen fetch and selected direction for given Beaufort Number.

Beaufort Scale	1	2	3	4	5	6	7	8
N	0,59	1,75	2,35	2,81	3,22	3,61		
NE	0,59	1,67	2,21	2,63	3,02	3,39		
E	0,59	1,65	2,18	2,60	2,99	3,35	3,67	
SW	0,59	1,37	1,77	2,10	2,41	2,70	2,96	
NW	0,59	1,65	2,17	2,59	2,97	3,34		
W	0,59	1,38	1,78	2,12	2,43	2,72	2,98	3,24

3. Data Analysis

In order to consider the wave conditions that are relevant for power production and in general the operation of the WEPTOS, wave heights below 0.125 m and periods below 1.75 s are neglected, resulting in 37.2% cumulative probability of occurrence for wave conditions of interest (Table 5). The wave heights were grouped into five classes with a step of 0.25 m and the period into four classes with a step of 0.5 s. The representative value for each class is the middle value of the range. The probability of occurrence of a specific combination of wave/period class was then approximated to be the sum of the original probabilities related to the winds that have been calculated to generate the specific wave heights in the class considered.

Tabel 5. Calculated probability of occurrence for the combination of wave heights and periods.

PROBABILITIES	period range	1.75<=x<2.25	2.25<=x<2.75	2.75<=x<3.25	3.25<=x<3.75	
	Tp [s]	2	2,5	3	3,5	
wave height range	Hm0 [m]					
0.125<=x<0.375	0,25	21,6	1,3			
0.375<=x<0.625	0,50		9,4	2,8		
0.625<=x<0.875	0,75		0,6	0,6	0,6	
0.875<=x<1.125	1,00			0,1	0,1	
1.125<=x<1.375	1,25				0,1	TOT 37,2

The most frequent wave heights will range between 0.125 m to 0.626 m covering roughly 33% of the total time but practically 89% (32.9% of 37.2%) of the time with waves. The most common period is expected to range between 1.75 s to 2.75 s.

3.1 Available Wave Power and expected power production

The scatter diagram was then used to compute various tables concerning wave power, wave power*probability, mechanical power, and the yearly energy production. The wave power was calculated with equation (4) and multiplied for the corresponding probability of occurrence of the wave (Table 6):

$$(4) \quad P_{wave}\,(kW/m) = \frac{1023 g^2 H_m^2 T_p}{1000 \pi \beta}, \text{ where } \beta = 64$$

The total available wave power at the intended location of installation resulted to be 0.074 kW/m.

*Tabel 6. Wave Power [kW/m]*probability*

Hm0 [m]\Tp [s]	2	2,5	3	3,5
0,25	0,01	0,00	0,00	0,00
0,50	0,00	0,03	0,01	0,00
0,75	0,00	0,00	0,00	0,01
1,00	0,00	0,00	0,00	0,00
1,25	0,00	0,00	0,00	0,00
TOT	0,074 kW/m			

For the mechanical power, the efficiencies used were estimated from the laboratory tests in Experimental Study of the WEPTOS Wave Energy Converter (DCE Contract Report No. 114). Additionally, values were only considered for wave heights and periods that correspond to less than or equal to 5% steepness. This is because above 5%, waves will break and this brings added uncertainty that will not be analyzed further. The last constraint comes from the generator capacity, which limits the mechanical power to 3kW maximum. The mechanical power is calculated as:

$$(5)\quad P_{mech} = P_{wave} * Eff. * b$$

Where Eff.= efficiency from DCE Contract Report No. 114 for the specific wave condition, Pwave is calculated with equation (4) and b is the width of the rotors = 21,12 m (Table 7). By applying the generator capacity of 3 kW, it seems that 5 of the 13 expected wave conditions will be limited.
The expected energy production is 4060 kWh/y.

Tabel 7. Power matrix [kW] for the WEPTOS prototype in selected wave conditions.

Reference Eff.	**0,53**	**0,33**	**0,21**	**0,14**
Hm0 [m] \ Tp [s]	**2**	**2,5**	**3**	**3,5**
0,25	0,69	0,53	0,41	0,32
0,5		2,13	1,63	1,27
0,75		3,00	3,00	2,85
1			3,00	3,00
1,25				3,00

Tabel 8. Estimated Contribution to energy production at Bransdø [kWh/y].

Hm0 [m]\Tp [s]	**2**	**2,5**	**3**	**3,5**
0,25	1297	61		0
0,5	0	1757	400	0
0,75	0	158	158	150
1	0	0	26	26
1,25	0	0	0	26
TOT	4059 kWh/y			

3.2 Estimation of wave heights during storm events

In order to estimate the wave heights in storm events three wind speeds were considered:
27 m/s, 30 m/s and 33 m/s. For these tree cases the wind stress factor was calculated for all the directions considered and resulted in what here we refer to the maximum wave height and maximum periods in tables 9 and 10.
The maximum wave height in storm events in case of 33 m/s wind speed is calculated to occur from the North direction and is 2.96 m. The corresponding wave period is also the maximum period calculated and is 5.40 s.

It must be noticed that 27-33 m/s winds correspond to Beaufort Scale > 8, 9. The percentage frequency of wind force 8, 9 BF and more at the station 6340 is 0.1% and 0.0 % over the year respectively. The months with higher frequency of occurrence are January-April (0.5%, 0.3%, 0.2%, 0.2%) and October-December (0.3%, 0.2%, 0.2%) for 8 BF, while for 9 BF and more the months are January and February (0.1%, 0.1%).

Table 9. max calculated wave heights for storm winds of 27 m/s (first column on the left), 30 m/s (middle column) and 33 m/s (column on the right).

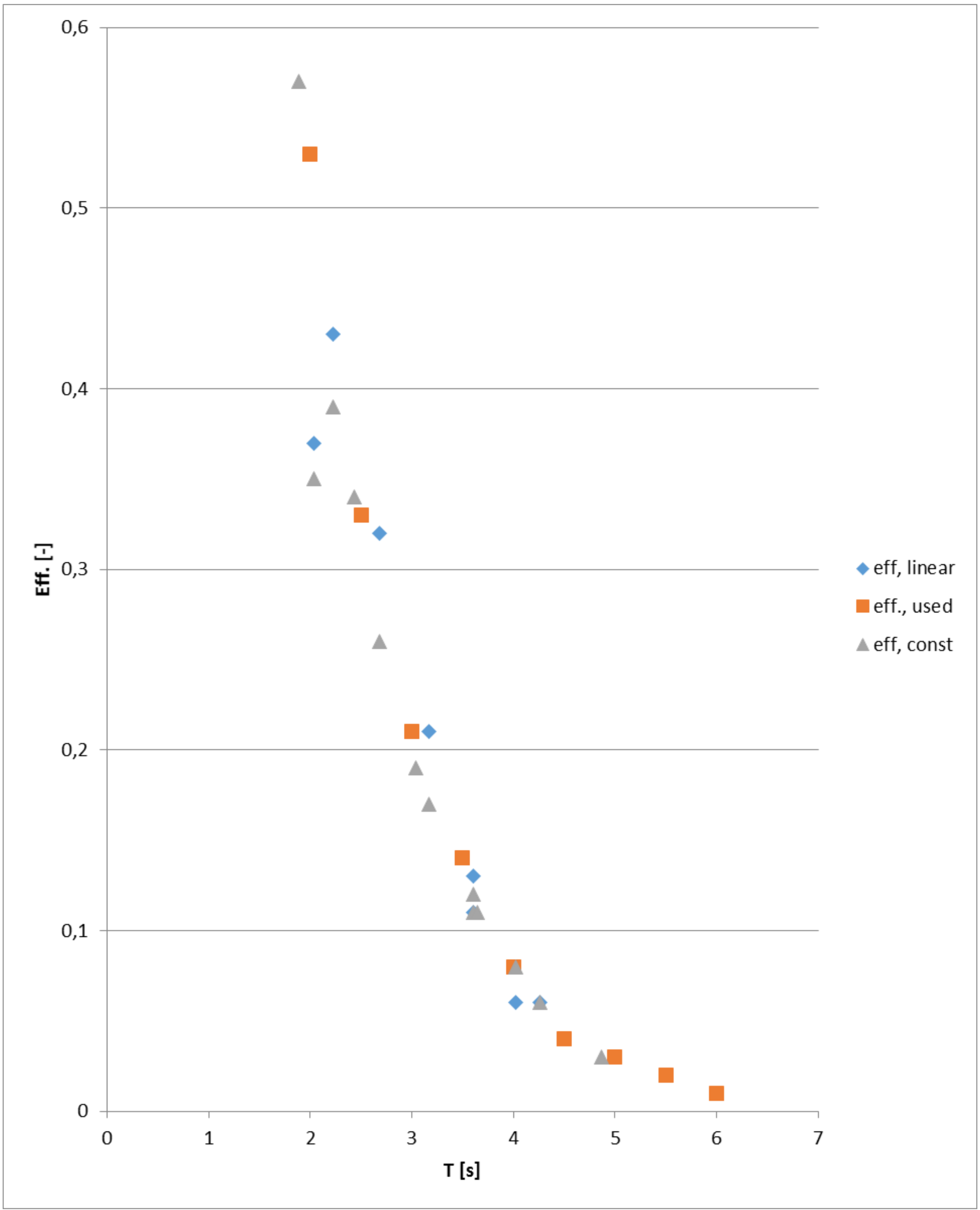
MAX Wave height [m] for a certain fetch, shallow water reviewed equation SPM 1984			
N	2,39	2,68	2,96
NE	2,21	2,48	2,76
E	2,17	2,45	2,72
SW	1,62	1,83	2,05
NW	2,16	2,44	2,71
W	1,63	1,85	2,07
min	1,62	1,83	2,05
max	2,39	2,68	2,96

Table 10. max calculated wave periods for storm winds of 27 m/s (first column on the left), 30 m/s (middle column) and 33 m/s (column on the right).

MAX Periods [s], shallow water reviewed equation SPM 1984			
N	4,98	5,20	5,40
NE	4,66	4,87	5,06
E	4,61	4,81	5,01
SW	3,72	3,88	4,04
NW	4,59	4,80	4,99
W	3,75	3,91	4,07
min	3,72	3,88	4,04
max	4,98	5,20	5,40

4. Considerations

In the Figure 2, the efficiency of the WOPTOS in Bransø is plotted against the wave period. The efficiencies have been calculated during laboratory tests in CCOB facilities in Spain. The efficiency curve was obtained for linear and constant loading. The orange dots in Figure 2 are the value we have used in this report as reference for expected performance.
We can notice that the max values of the efficiency correspond also to the most common periods in Brandsø, around T= 2 s. (Table 5).



Figur 2. Expected efficiencies

5. Conclusions

Wave heights above 0.125 m and periods above 1.75 s occur only 37.2% of total time. Therefore it is considered that 62.8% of conditions correspond to calm.

The most frequent wave heights will range between 0.125 m to 0.626 m covering roughly 33% of the total time but practically 89% (32.9% of 37.2%) of the time with waves. The most common period is expected to range between 1.75 s and 2.75 s. This range of periods corresponds to the max efficiency for the WEPTOS prototype #1.

The total available wave power at the intended location of installation resulted to be 0.074 kW/m. The expected energy production is 4060 kWh/y that would correspond to a load factor of 0.30)

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