Assignment Wave Energy

OFFSHORE RENEWABLES TECHNOLOGIES /
MARINE RENEWABLE TECHNOLOGIES

OE44170/CIEM4305

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Contents

1 Task 1

All relevant parameters are computed in our Python file. In this section, you find the numerical results.

Given Constants

Wind speed at $10\,\mathrm{m}$	$U_{10} = 30\,\mathrm{m/s}$
Fetch length	$F = 178\,760.4\,\mathrm{m}$
JONSWAP parameters	$a = 0.0016,\ b = 0.2857$
Gravity	$g = 9.81\,\mathrm{m/s^2}$
Water density (sea water)	$\rho = 1025\,\mathrm{kg/m^3}$

Conversion of wind speed to friction velocity

Empirical relation:

$$U_a = 0.71\,U_{10}^{1.23} \tag{1}$$

$$\boxed{U_a = 46.57\,(m/s)}$$

Dimensionless variables (JONSWAP)

$$\hat{F} = \frac{F\,g}{U_a^2} \tag{2}$$

$$\boxed{\hat{F} = 808.55}$$

$$\hat{H}_{m0} = a\,\hat{F}^{\,0.5}, \tag{3}$$

$$\boxed{\hat{H}_{m0} = 0.05\,(m)}$$

$$\hat{T}_p = b\,\hat{F}^{\,0.33} \tag{4}$$

$$\boxed{\hat{T}_p = 2.6\,(s)}$$

Dimensional significant height & peak period

Invert the non-dimensionalization:

$$H_{m0} = \hat{H}_{m0}\,\frac{U_a^2}{g}, \tag{5}$$

$$\boxed{H_{m0} = 10.06\,(m)}$$

$$T_p = \hat{T}_p\,\frac{U_a}{g} \tag{6}$$

$$\boxed{\hat{T}_p = 12.36\,(s)}$$

Energy period For the irregular-wave flux, it is used the relation for the energy period T_e. $T_e \approx 0.9\,T_p$:

$$\boxed{T_e = 11.12\,(s)}$$

Wave-energy flux

Regular waves

$$P_{\text{reg}} = \frac{\rho\, g^2\, H_{m0}^2\, T}{32\,\pi}$$ with $T = T_p$ for a regular wave at the spectral peak.

$$\boxed{P_{\text{reg}} = 1104.04 \;\; \text{(kW/m)}}$$

Irregular waves

$$P_{\text{irr}} = \frac{\rho\, g^2\, H_{m0}^2\, T_e}{64\,\pi}$$

$$\boxed{P_{\text{irr}} = 613.35 \;\; \text{(kW/m)}}$$

Results Summary

Quantity	Symbol	Value (SI units)
Significant wave height	H_{m0}	10.06 m
Peak wave period	T_p	12.36 s
Energy period	T_e	11.12 s
Wave energy flux (regular)	P_{reg}	1104.04 kW/m
Wave energy flux (irregular)	P_{irr}	613.35 kW/m

2 Task 2

All relevant parameters are computed in our Python file. In this section, you find the numerical results in Table 1. Equation 7 depicts the power produced from irregular waves. Similar to task 1, $T_e \approx 0.9 \cdot T_p$.

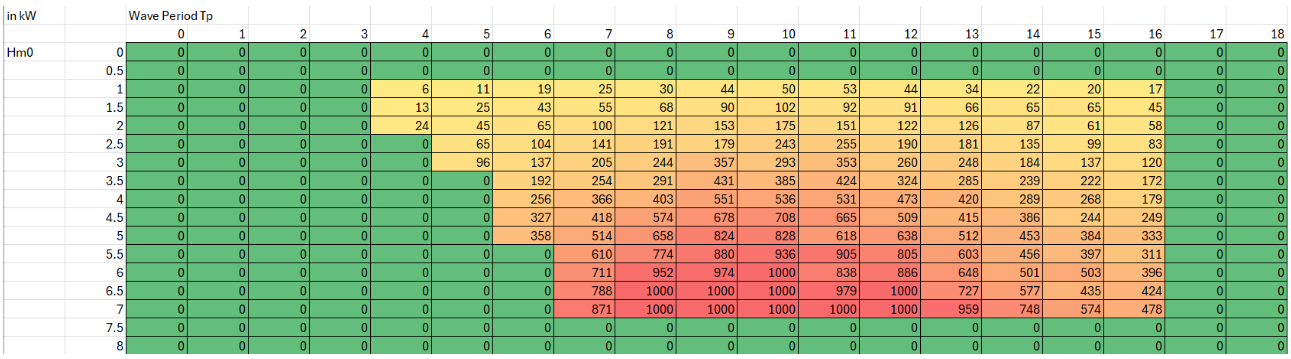
$$P_{\text{wave}}(t) = \frac{\rho\, g^2\, H_{m0}(t)^2\; 0.9\, T_p(t)}{64\,\pi} \qquad [P_{\text{wave}}] = \mathrm{W/m} \tag{7}$$

Table 1: Statistical values of wave data

Parameter	**Mean**	**Std**	**Max**	**Min**
H_{m0} (m)	1.90	0.92	6.31	0.45
T_p (s)	10.83	2.84	19.19	3.14
$P_{\text{wave, irreg}}$ (kW/m)	24.36	31.44	306.63	0.54

3 Task 3

For task 3, the used power matrix is depicted in Figure 1.



in kW		Wave Period Tp																		
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hm0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	6	11	19	25	30	44	50	53	44	34	22	20	17	0	0
	1.5	0	0	0	0	13	25	43	55	68	90	102	92	91	66	65	65	45	0	0
	2	0	0	0	0	24	45	65	100	121	153	175	151	122	126	87	61	58	0	0
	2.5	0	0	0	0	0	65	104	141	191	179	243	255	190	181	135	99	83	0	0
	3	0	0	0	0	0	96	137	205	244	357	293	353	260	248	184	137	120	0	0
	3.5	0	0	0	0	0	0	192	254	291	431	385	424	324	285	239	222	172	0	0
	4	0	0	0	0	0	0	256	366	403	551	536	531	473	420	289	268	179	0	0
	4.5	0	0	0	0	0	0	327	418	574	678	708	665	509	415	386	244	249	0	0
	5	0	0	0	0	0	0	358	514	658	824	828	618	638	512	453	384	333	0	0
	5.5	0	0	0	0	0	0	0	610	774	880	936	905	805	603	456	397	311	0	0
	6	0	0	0	0	0	0	0	711	952	974	1000	838	886	648	501	503	396	0	0
	6.5	0	0	0	0	0	0	0	788	1000	1000	1000	979	1000	727	577	435	424	0	0
	7	0	0	0	0	0	0	0	871	1000	1000	1000	1000	1000	959	748	574	478	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 1: Power matrix of the wave converter

The wave converter as illustrated in Figure 1, starts generating wave energy between $1 < h_{m0} < 7$ & $1 < T_p < 16$. Part of the retrieved data, is a list with H_{m0} values and their corresponding T_p values.

To obtain the total power produced of this wave converter, we compared the set $\{h_{m0}, T_p\}$ to the power matrix. We took the sum of all values in the power matrix that were closest to the set $\{h_{m0}, T_p\}$. Thus, our bins were centered around the data points given for h_{m0} and T_p. For example, if we have a value of $T_p = 2.48$, we put it in a bin of 2, and if we have a value of $h_{m0} = 2.26$, we put this in the bin of 2.5. The probability of occurrence is computed in a similar manner. Furthermore the capacity factor $C.F$ is computed as follows:

$$C.F = \frac{AEY}{P_{rated} \cdot 8760} \tag{8}$$

We divide the annual energy yield by the annual rated power production. In our case, we simply divide the total power produced by the rated power produced in the same time period. We obtained the following values for the total power produced and the capacity factor:

$$\text{Total Power Produced} = 1049\ MWh \tag{9}$$

$$C.F = 0.12 \tag{10}$$

Figure 2 illustrates the bivariate probability of the occurrence of h_{m0} and T_p. Similarly, the distribution of power and the sea state matrix are illustrated in Figures 3 and 4.

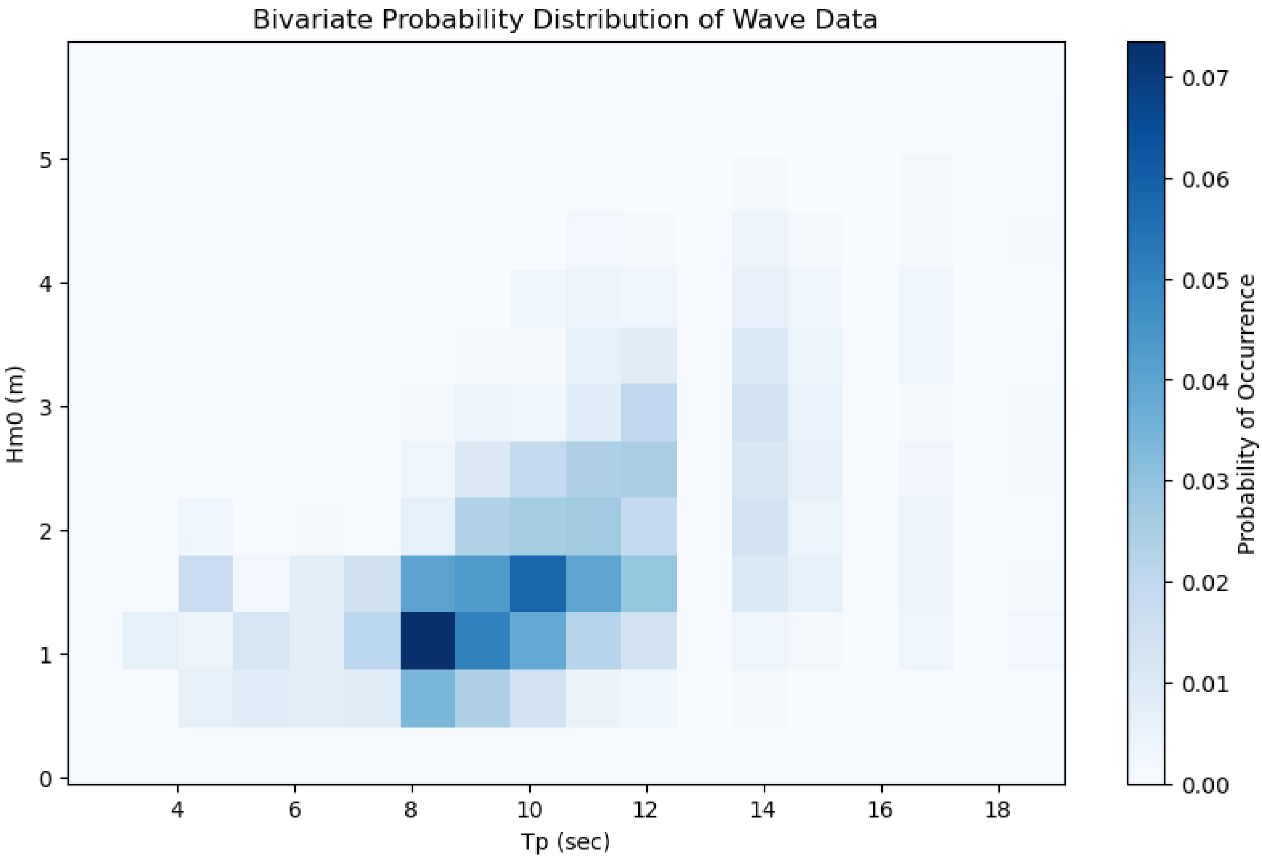


Figure 2: Bivariate Probability of Occurence

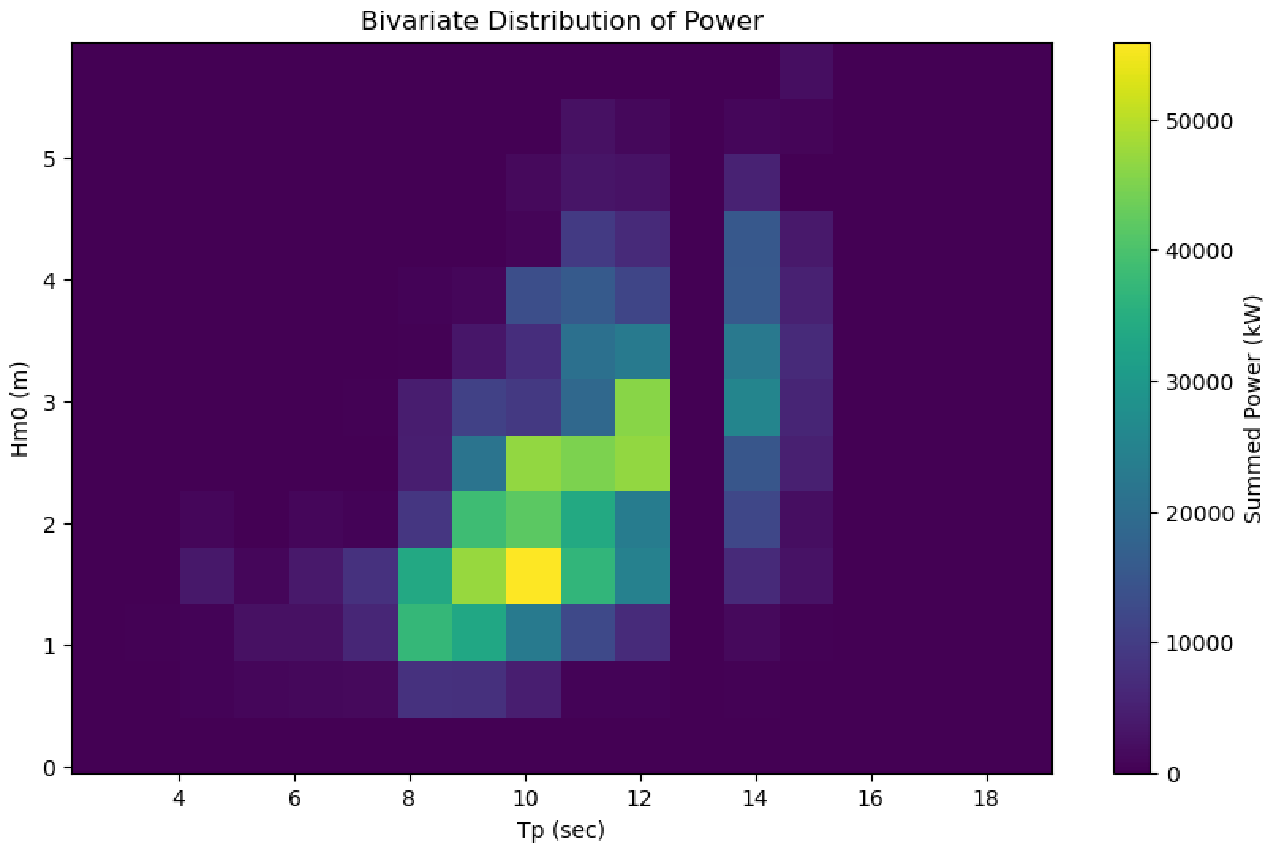


Figure 3: Power Distribution

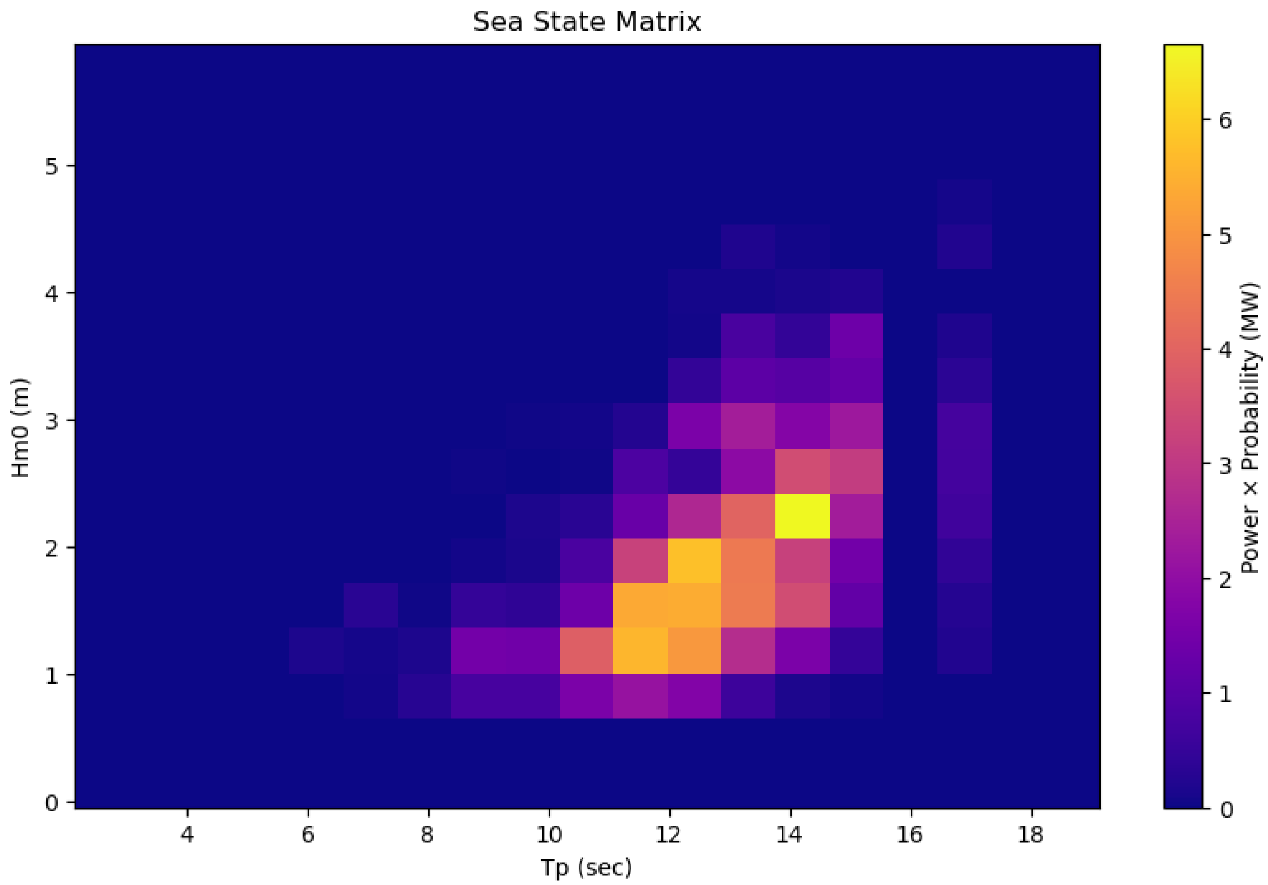


Figure 4: Sea State Matrix

4 Task 4

Mean significant wave height	$\overline{H}_{m0} = 1.90\,\mathrm{m}$
Wave amplitude (from mean H_{m0})	$a = \overline{H}_{m0}/2 = 0.95\,\mathrm{m}$
PTO linear damping	$B_{\mathrm{PTO}} = 300\,000\,\mathrm{N\,s/m}$
Device mass (sum of netID)	$m = 17\,876\,040\,\mathrm{kg}$
Drag coefficient	$C_d = 0.75$
Water Plane Area (R = 5 m)	$A_w = 78.54\,\mathrm{m}^2$
Water density / gravity	$\rho = 1025\,\mathrm{kg/m}^3, \quad g = 9.81\,\mathrm{m/s}^2$

Hydrodynamic forcing and coefficients (per period)

For each wave period studied T ($4\,\mathrm{s}$ to $20\,\mathrm{s}$):

$$\omega = \frac{2\pi}{T}, \qquad F_3 = \underbrace{\hat{F}_{ex}(T)}_{\text{excitation coeff. (N/m)}} \quad a$$

Radiation damping: $b_{33}(T)$, Added mass: $a_{33}(T)$, Hydrostatic stiffness: $c_{33}(T)$

Linearized viscous damping (from quadratic drag). Starting from $F_{\mathrm{drag}} = \frac{1}{2}\,\rho\,A_w\,|v|\,v\,C_d$ and linearizing for harmonic motion,

$$B_{\mathrm{visc}}(T) \;\approx\; \tfrac{1}{2}\,\rho\,A_w\,\omega(T)\,C_d \tag{11}$$

where A_w is the projected area normal to the heave velocity (for the given cylinder, the plane base area; was calculated as water plane area $A_w = \pi R^2$ based on the given radius R).

$$\text{Total linear damping: } B(T) = b_{33}(T) + B_{\mathrm{visc}}(T) + B_{\mathrm{PTO}}\,.$$

Heave equation of motion (frequency domain)

$$\left[-\omega^2\big(m + a_{33}(T)\big) + i\,\omega\,B(T) + c_{33}(T)\right]\,\zeta_3(T) \;=\; F_3(T) \tag{12}$$

Response amplitude operator (displacement amplitude)

From equation (12),

$$\zeta_3(T) \;=\; \frac{F_3(T)}{c_{33}(T) - \omega^2\big(m + a_{33}(T)\big) + i\,\omega B(T)}$$

$$\big|\zeta_3(T)\big| \;=\; \frac{|F_3(T)|}{\sqrt{\big[c_{33}(T) - \omega^2(m + a_{33}(T))\big]^2 + \big[\omega B(T)\big]^2}} \tag{13}$$

$$\boxed{\overline{\zeta_3(T)} = 16.59\,\mathrm{m}}$$

Mean absorbed power (via PTO)

With PTO damping B_{PTO}, the mean absorbed power in heave is

$$P(T) \;=\; \frac{1}{2}\,\omega^2\,B_{\mathrm{PTO}}\,\big|\zeta_3(T)\big|^2 \tag{14}$$

$$\boxed{\overline{P(T)} = 10.39\,(MW)}$$

Table 2: All used parameters for task 4

Wave period (s)	**Excitation force coefficient** (N/m)	**Radiation damping** (Ns/m)	**Added mass** (kg)	**Hydrostatic stiffness** (N/m)	**Amplitude of elevation** (m)	**Power** (MW)
20.0	705 314	8016	294 449	770 476	53.90	43.01
19.0	690 200	10 561	292 754	770 476	44.39	32.33
18.0	670 931	13 931	290 446	770 476	36.40	24.22
17.0	669 490	14 186	290 272	770 476	30.65	19.25
16.0	657 556	16 285	289 586	770 476	25.38	14.90
15.0	656 066	16 556	289 244	770 476	21.29	11.92
14.0	640 732	19 341	286 085	770 476	17.40	9.15
13.0	622 822	22 505	283 906	770 476	14.07	6.94
12.0	599 482	26 653	278 536	770 476	11.18	5.14
11.0	571 441	31 353	273 239	770 476	8.71	3.71
10.0	537 292	36 679	265 617	770 476	6.60	2.58
9.0	493 379	42 586	255 355	770 476	4.80	1.69
8.0	440 116	47 882	243 591	770 476	3.32	1.02
7.0	370 708	51 178	229 379	770 476	2.11	0.54
6.0	287 473	48 769	215 654	770 476	1.18	0.23
5.0	191 111	36 888	207 322	770 476	0.54	0.07
4.0	92 835	16 795	210 452	770 476	0.17	0.01