Journal of Newviews in Engineering and Technology (JNET)
Volume 5, Issue 2, June 2023
Available online at http://www.rsujnet.org/index.php/publications/2023-edition
e- ISSN: 2795-2215

Numerical Simulation of the Effect of Wave Height and Wave Period on Point Absorber Wave Energy Converter

Oyegbemi K. Olayinka*, Ibiba E. Douglas, and Charles U. Orji
Department of Marine Engineering, Rivers State University, Port Harcourt, Nigeria.
*Corresponding Author Email: olayinka.oyegbemi@nmu.edu.ng

ABSTRACT
This paper discusses a simulation study that explores the impact of wave height and wave period on the power output of a point absorber wave energy converter (WEC). The investigation was conducted using MATLAB's open-source code WecSim. The study examines the device's efficiency and power output under various wave conditions and provides insights into their optimal design and operation. Results show that the power output of the WEC increases significantly with increasing wave height but decreases with increasing peak period. However, efficiency reduces as the wave height and peak period increase. At a wave height of 1 meter, the study recorded a maximum efficiency of approximately 16.4%, while at a peak period of 11 seconds, a maximum efficiency of about 21% was observed. The analysis revealed a bilinear behavior when comparing constant significant wave height and constant peak period, indicating that power output improves with lower peak periods and higher significant wave heights. The study's findings provide valuable insights for optimizing the design and operation of point absorber WECs under different wave conditions, thus enhancing their performance and accelerating their deployment in the renewable energy market.

KEYWORDS: Wave energy converters, Point absorber, Simulation study, Renewable energy, Sensitivity analysis.

Cite This Paper: Olayinka, O. K., Douglas, I. E. & Orji, C. U (2023). Numerical Simulation of the Effect of Wave Height and Wave Period on Point Absorber Wave Energy Converter. *Journal of Newviews in Engineering and Technology*. 5(2), 1 – 7.

1. INTRODUCTION

Wave energy is a highly promising form of renewable energy because of its plentiful supply, predictability, and high energy density. Wave energy converters (WECs) are devices that transform the kinetic energy of ocean waves into electrical energy. In recent years, there has been a surge of interest in point absorber WECs, which are known for their simplicity, versatility, and potential for scalability. A typical point absorber WEC is compose of a buoyant structure that is connected to a power take-off system through a mooring line. As the buoyant structure moves up and down with the waves, the mooring line stretches and contracts, producing motion that can be converted into electrical energy by various types of power take-off systems, including hydraulic, pneumatic, or electromagnetic mechanisms (Falcao, 2010).

Point absorber wave energy converters (WECs) have an advantage in that they can capture wave energy from all directions, making them suitable for deployment in open water. Their small size and flexibility also make them easy to deploy and maintain, with less environmental impact compared to other WECs. However, their performance is heavily influenced by wave characteristics, specifically wave height and wave period. Wave height refers to the vertical distance between a wave's crest and trough, while wave period refers to the time it takes for a wave crest to travel a distance equal to one wavelength. Despite several studies investigating the impact of these parameters on point absorber performance, the results have been inconclusive

Journal of Newviews in Engineering and Technology (JNET)
Volume 5, Issue 2, June 2023
Available online at http://www.rsujnet.org/index.php/publications/2023-edition
e- ISSN: 2795-2215

due to variations in experimental setups, data analysis methods, and wave conditions.

Ye *et al*. (2017) conducted a study to explore the impact of wave height on the power output of a point absorber WEC, they employed a scaled-down model of the WEC and varied the wave height between 0.1 m to 0.3 m. The results revealed an increase in power output with increasing wave height up to a certain threshold, beyond which the power output remained constant or decreased. The outcome was explained as a consequence of the nonlinear nature of the wave-mooring system. Similarly, Farzaneh and Domel (2019) conducted a study to examine the influence of wave period on the power output of a point absorber WEC. They performed experiments using a model that simulated the response of the WEC to waves with different periods.

The power generated by point absorber wave energy converters (WECs) is greatly influenced by wave height and wave period. A resonance phenomenon between the wave and mooring system is responsible for the peak in power output at a specific wave period. Although point absorber WECs offer numerous benefits over other types of WECs, their performance is heavily dependent on these two parameters. Several studies have investigated the impact of wave height on the performance of point absorber WECs. In their numerical study, Smith *et al.* (2018) found that an increase in wave height led to an increase in the absorbed power by the point absorber. This is primarily due to the larger potential energy available in higher waves, resulting in increased motion and power generation. However, the relationship between wave height and power absorption is not linear. Van Buren et al. (2020) conducted experiments on a point absorber WEC and observed that beyond a certain wave height, the absorbed power started to saturate. This saturation effect is attributed to the limited capacity of the device to capture and convert the wave energy efficiently. Hence, while an increase in wave height initially enhances power absorption, there exists a threshold beyond which the device's performance reaches a plateau.

As wave height increases, the dynamic loads on the device also increase, potentially leading to structural fatigue and damage. Li *et al.* (2022) conducted a numerical study and highlighted the importance of considering the structural response and design criteria to ensure the safe and reliable operation of point absorber WECs under varying wave heights. Several studies have investigated the effect of wave period on the performance of these devices.

In their study, Chen and Yu (2019) found that an increase in wave period led to increased power absorption by the point absorber WEC. This is because longer wave periods provide more time for the device to respond and capture the wave energy effectively. The resonant frequency of the device also plays a crucial role in determining the optimal wave period for power absorption.

However, the relationship between wave period and power absorption is not straightforward. Jensen *et al*. (2021) conducted experiments and numerical simulations and observed that there exists an optimal wave period range for maximum power absorption. Beyond this range, the power absorption decreased due to a mismatch between the device's resonant frequency and the incoming wave period. Therefore, while longer wave periods generally favor power absorption, an optimal range must be considered to achieve maximum performance.

The objective of this paper is to modify the operating performance of an existing model of point absorber wave energy converters and conduct sensitivity studies on power output and efficiency, by carrying out these objectives, this research addresses the existing research gap in point absorber WEC studies by providing further simulation-based investigations on the effect of wave height and peak period. These studies aim to optimize power absorption, predict device performance, and foster technological innovation. The insights and data-driven guidelines derived from these studies will contribute to the design, deployment, and operation of point absorber

Journal of Newviews in Engineering and Technology (JNET)
Volume 5, Issue 2, June 2023
Available online at http://www.rsujnet.org/index.php/publications/2023-edition
e- ISSN: 2795-2215

WECs in various wave climates, facilitating the advancement and widespread adoption of wave energy conversion as a renewable energy source.

2. MATERIALS AND METHODS

A two-body point absorber with a cylindrical shape, model adopted and replicated in Auto-CAD. One body, known as the floater, rests on the water surface, while the other body, called the spar, houses the coil. These two bodies are connected through a permanent magnet, which is supported by a metal structure. The oscillation of the permanent magnet within the coil generates power. Table 1 provides the structural specifications of the Point Absorber Wave Energy Converter (PAWEC).

Table 1: Structural Data of the Model

	Mass(kg)	CG	Moment of Inertia (kg m$^{2)}$
Float	727.01	-0.72	21,306,91
Spar	878.30	- 21.29	94,407,091

The added mass and damping coefficient was obtained in Ansys softwere and it was imported in WecSim, WecSim is an established open sourced MATLAB code for Wave Energy Converters. The Equation 1 and Equation 2 present the equation of motion in the study

$$m_1\ddot{X}_1 = F_{exc1}(t) + F_{rad1}(t) + F_{pto1}(t) + F_{v1}(t) + F_{me1}(t) + F_{B1}(t) \quad (1)$$

$$m_2\ddot{X}_2 = F_{exc2}(t) + F_{rad2}(t) + F_{pto2}(t) + F_{v2}(t) + F_{me2}(t) + F_{B2}(t) \quad (2)$$

Where

$\ddot{X}$= Transitional or ratatiotional acceleration of the device as the case may be

m = Mass Metrx

$F_{exc}(t)$= Wave Excitation force and torque vector

$F_{rad}(t)$ =The force and torque vector resulting from the wave radiation

$F_{pto}(t)$ = PTO force and torque vector

$F_v(t)$ = Damping Force and Torgue

$F_{me}(t)$ = Morison element and Torque vector

$F_B(t)$ = Net bouyancy term

The radiated force equation for a floating body is given by Eq. 3. The positive force of wave excitation is given by Eq. 4.

$$F\_rad(t) = -A(\omega)\ddot{X} - B(\omega)\, X \quad (3)$$

$$F_{exc} = R\,(t)\left[R_f(t)\frac{H}{2}\, F_{exc}(\omega,\ \boldsymbol{\theta})e^{i\omega t}\right] \quad (4)$$

2.1 Convolutional Integral Formulation

The Convolutional Integral approach using the Cummins equation is explained. This method accounts for the impact of fluid memory on WEC dynamics when dealing with non-uniform wave spectra. The equation for the radiated force, as stated in Eq. 5, is also provided.

$$F_{rad}(t) = -\, A_\infty\ddot{X} - \int_0^t K_r(t-r)\,\dot{X}\,(r)dr \quad (5)$$

Where;

A∞ = weighted mass matrix at infinite frequencies

Kr = A radiated pulse response function.

The radiated function of the pulse reaction is determined by Eq. 6.

$$K_r(t) = \frac{2}{\pi}\int_0^\infty B(\omega)cos\,(\omega t)d\omega \quad (6)$$

The irregular excitation force can be calculated by Eq. 7.

$$F_{exc}(t) = R\left[R_f(t)\sum_{j=1}^{N} F_{exc}\,(\omega_j,\ \boldsymbol{\theta})e^{i(\omega_j t+\emptyset_j)}\sqrt{2S(\omega_j)d\omega_j}\right] \quad (7)$$

Where;

N = The number of frequency bands selected for wave spectrum discreteness

Φ = The randomized phase angle. Eq..8

is used to calculate Kr for repeated modeling of irregular wave fields

$$K_e(t) = -\frac{1}{2\pi}\int_{0-\infty}^{\infty} F_{exc}\,(\omega,\ \boldsymbol{\theta})\,e^{i\omega t}d\omega \quad (8)$$

Eq (9) describes linear systems, with Ar, Br, Cr, and Dr representing the state, input, output, and

Journal of Newviews in Engineering and Technology (JNET)
Volume 5, Issue 2, June 2023
Available online at http://www.rsujnet.org/index.php/publications/2023-edition
e- ISSN: 2795-2215

feed-through matrices, respectively. The state vector, Xr, is used to depict the convolution kernel's progression over time..

$$\dot{X}r(t) = ArXr(t) + B_{ru}(t); \quad (9)$$

$$X_r(0) = 0$$

$$\int_0^t K_r(t-r)dr \;\; C_rX_r(t) + \; D_ru(t) \quad (10)$$

In Eq. (10), the impulse response of a state-space model with a single input and zero initial state is expressed in terms of u, which represents an impulse. Eq. (11) presents the solution when the initial state is set to x(0)=Bru, and Eq. (12) is used to calculate Kr

$$x(t)= e^{A_rt}x(0) + \int_0^t e^{A_r(t-r)}B_ru(r)dr \quad (11)$$

where Ar is the matrix exponential and the calculation of Kr follows:

$$Kr(t) = C_r \; e^{A_rt}B_r \quad (12)$$

2.2 Estimation of the Power Output

The Power output for the mechanical PTO can be calculated using equation 3.70 according to (R.So *et al*, 2015) this is valid for only mechanical PTO of the type used in this research.

$$P_{pto} = -C_{pto} \times \dot{Z}_R \quad (13)$$

Where.

C_{pto}= Force exerted by the PTO on the structure as discussed earlier,

$\dot{Z}_R$ = Difference in velocity between the two bodies i.e., the float and the spar.

2.3 Device Efficiency

The efficiency of the PAWEC is obtained using equation 2.

$$\eta = \frac{P_{pto}}{P_{pt}} * 100 \quad (14)$$

Where.

P_{pto} = Power Take off power output

P_{pto} = Theoretical power output

The power output is the maximum power generated by the WEC for a given wave height and period while the power input (P_{in}) is the total power available in the area occupied by the WEC. It is given according to equation 3 for irregular waves (Buckham 2019).

$$P_{in} = \frac{1}{64\,\pi} \; \rho \; g^2 H_s^2 T_e \;\; \text{(W/m)} \quad (15)$$

For regular wave, it is given as equation 16.

$$P_{in} = \frac{1}{32\,\pi} \; \rho \; g^2 H_s^2 T_e \;\; \text{(W/m)} \quad (16)$$

3. RESULTS AND DISCUSSION

The model was tested using regular wave condition, a wave height of 1 meter and a period of 12.20 seconds was used to test the model. Figure 1 presents the result. The simulation ran for several minutes, recording the power output. In order to enhance readability, averages were calculated at intervals of 100. The power output peaked at around 1.8 MW/m and reached a steady state at around 65 seconds. Since there is no abnormality in the performance result, it can be concluded the device will give accurate result in the analysis using the irregular wave condition.

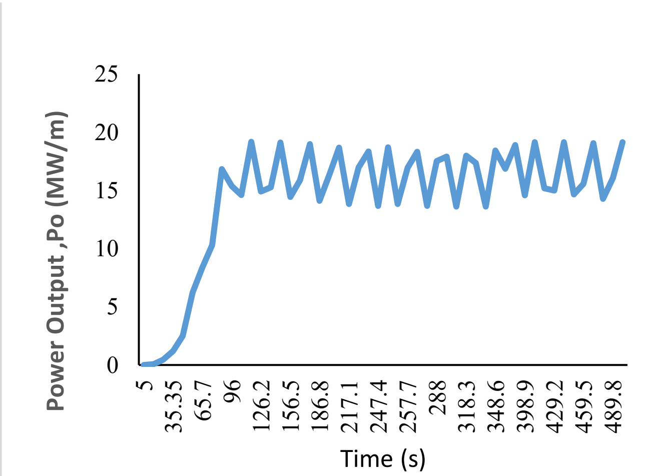

Figure 1: Power output in regular wave condition

3.1 Sensitivity Analysis at Constant Peak Period

The effect of a change in significant wave height at a constant peak period on the power output was examined. A five-step change from 1 m to 5 m was examined. The result summary is presented in figure 2. It was observed that the power output increases significantly as the significant wave height increases. At a significant wave height of 5 meters, the highest observed value peaked at about 7.4 MW/m and having an average power of 1.6 MW/m. The average peak power difference across the wave height is about 1.8 Mw/m. An average maximum power output of about 3.3

Journal of Newviews in Engineering and Technology (JNET)
Volume 5, Issue 2, June 2023
Available online at http://www.rsujnet.org/index.php/publications/2023-edition
e- ISSN: 2795-2215

MW/m was observed across the five steps under consideration.

However, the efficiency reduces as the wave height increases. A maximum efficiency of about 16.4% was recorded at a 1-meter significant wave height. An average efficiency reduction of 0.19% was observed across the range, i.e., from 1-meter significant wave height to 5 meters; Figure 3 presents the variation as the wave height increases.

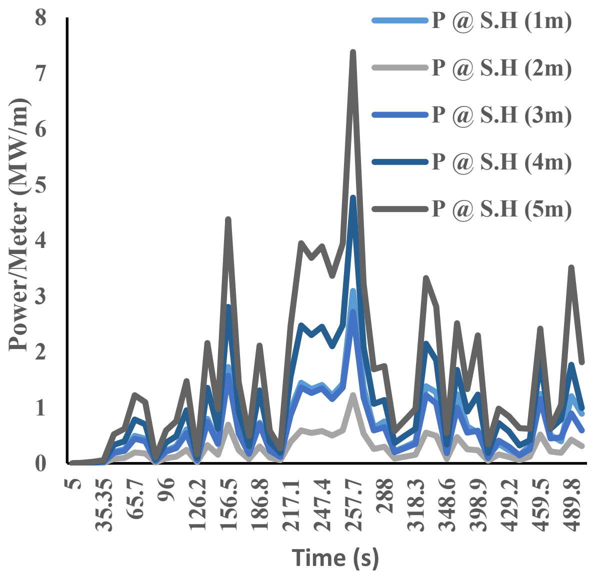

Figure 2: Variation in Power Output at Constant Peak Period and Increasing Significant Wave Height

3.2 Sensitivity Analysis at Constant Significant Wave Height

Sensitivity studies were also carried out to investigate the effects of varying the peak period at a constant significant wave height on the power output and efficiency of the device. A five-step change from 10 seconds to 15 seconds was considered, and the result summary is presented in figure 4. It was observed that the power output decreases significantly as the peak period increases. At a peak period of 10 seconds 0.33 MW/m having an average power of 0.08 MW/m was the observed highest power value. The average difference in peak power across the peak period is about 0.3 MW/m. An average maximum power output of about 0.27 MW/m was observed across the span considered. Efficiency also reduces as the peak period increases. A maximum efficiency of about 21% was recorded at 11 seconds the average efficiency reduction of 2.8% across Figure 5 presents the variation as the peak period increases.

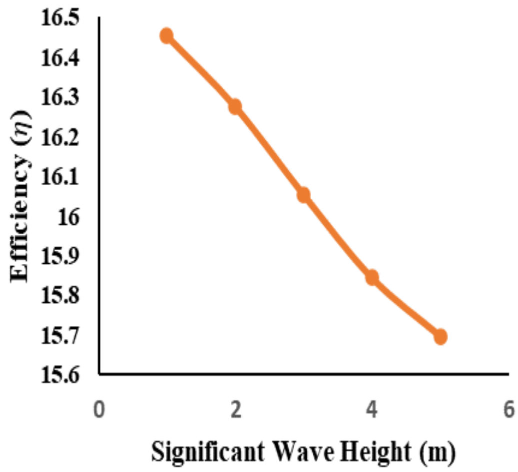

Figure 3: Variation in Efficiency at Constant Peak Period and Increasing Significant Wave Heigh

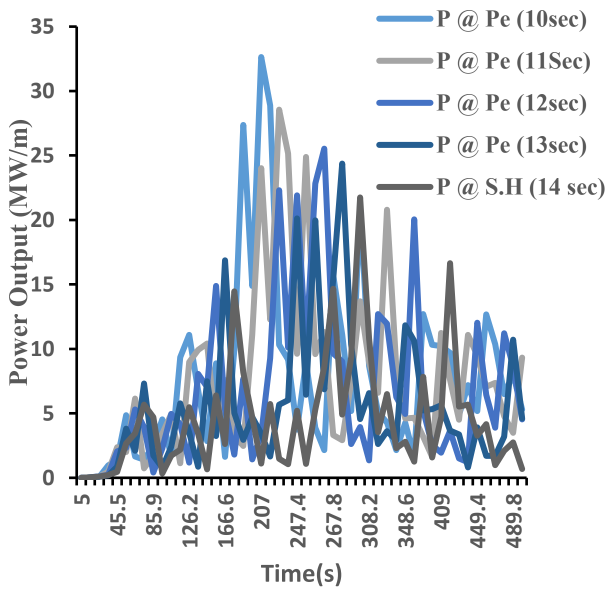

Figure 4: Variation in Power Output at Constant Significant Wave Height and Increasing Peak Period

Journal of Newviews in Engineering and Technology (JNET)
Volume 5, Issue 2, June 2023
Available online at http://www.rsujnet.org/index.php/publications/2023-edition
e- ISSN: 2795-2215

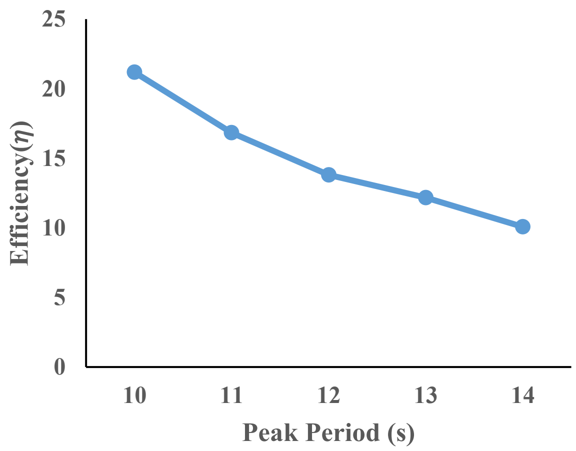

Figure 5: Variation in Efficiency at Constant Significant Wave Height and Increasing Peak Period

3.3 Comparison of the Two Cases

The efficiency and power output for the two cases considered in the sensitivity studies were compared. Figure 6 and Figure 7 present the comparison of the peak power output for both constant significant wave height and constant peak period. Figure 6 and Figure 7 show the significant power calculated.

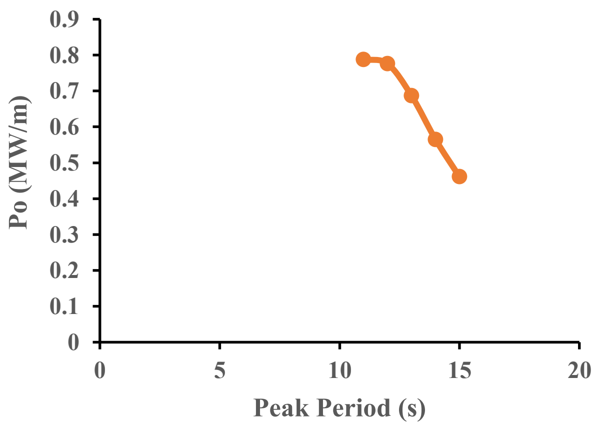

Figure 6: Variation in Power Output vs. Peak Period

The trend is characterized by a bilinear behavior that shows a decreasing power at constant significant wave height and an increasing power at constant peak period, it is consistent with the initial deduction that power output is improve at lower peak period and higher significant wave height. Also, in Figure 7 the significant power decreases as the significant wave height increases until 2 meters significant wave height, where it turns sharply and starts increasing. The 2 meters significant wave height is the second most efficient parameter of all the target parameter considered according to Figure 4. It can be deduced from the data that the power outputs deviate significantly from it average at this parameter, hence, efficiency improves at lower significant power output. A plausible explanation is that the range of wave height and period in the spectrum at 2 maters significant wave height is broad enough to include more resonance inducing force parameters (weave height and period) than the other parameters considered in the study.

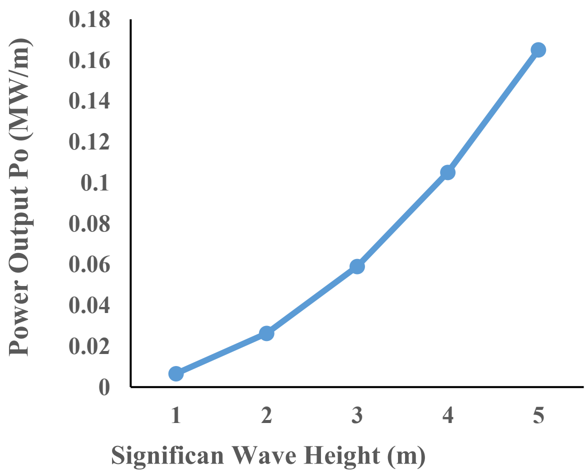

Figure 7: Variation in Power Output vs. significant wave Height

4. CONCLUSION

In conclusion, this simulation study investigated the effect of wave height and wave period on the power output and efficiency of a point absorber wave energy converter. The investigation was conducted using MATLAB open-source code WecSim. The results showed that the power output of the device significantly increased as the wave height increased, while the efficiency decreased. The power output also significantly decreased as the peak period increased, with a corresponding decrease in efficiency. The study revealed that the device is most efficient at a significant wave height of 2 meters and a peak period of 11 seconds. These findings provide insights into the optimal design and operation of point absorber wave energy converters under different wave conditions, which can enhance their performance and accelerate their deployment in the renewable energy market. Further research is recommended to investigate the performance of the device under real sea conditions and to optimize its design for improved efficiency and power output.

REFERENCES

Chen, H., & Yu, Y. H. (2019). Performance evaluation of a point absorber wave energy converter under different wave conditions. *Energies*, 12(16), 3042.

Falcao, A. F. de O. (2010). Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews*, 14(3), 899-918. Doi: 10.1016/j.rser.2009.11.003

Farzaneh, H., & Domel, A. (2019). Investigation of the effect of wave period on the performance of point absorber wave energy converters. *Ocean Engineering*, 188, 107953. Doi: 10.1016/j.oceaneng.2019.107953.

Jensen, B. R., Ferri, F., Troch, P., & Ruehl, K. (2021). Wave energy converters: A review of the technologies for renewable energy production. *Renewable and Sustainable Energy Reviews*, 137, 110707.

Li, C., Ma, Q., Sun, L., & Huang, Z. (2022). Numerical analysis of structural response of a point absorber wave energy converter under different wave conditions. *Ocean Engineering*, 249, 108690.

Smith, J. M., Driscoll, F., & Shay, L. (2018). A numerical study of the hydrodynamic performance of a point absorber wave energy converter. *Ocean Engineering*, 157, 223-238.

Vicente-Barrero, M., Ramos, V., & Rodriguez-Rodriguez, J. (2017). State of the art in wave energy technologies and marine renewable energy: A review. *Sustainability,* 9(2), 187. Doi: 10.3390/su9020187

Vicente-Barrero, M., Gómez-Moreno, F. J., Moreno-Ruiz, A., & Sánchez-Lizaso, J. L. (2017). Point absorber wave energy converters: State of the art and future challenges. *Renewable and Sustainable Energy Reviews*, 73, 887-901. Doi: 10.1016/j.rser.2017.02.054

Van Buren, T., Toxopeus, S., Pecher, A., & van der Hout, A. (2020). Experimental validation of a point absorber wave energy converter under varying wave conditions. *Renewable Energy*, 148, 951-961.

Ye, F., Babarit, A., He, Y., & Wei, G. (2017). Experimental investigation of the influence of wave height on a point absorber wave energy converter. *Ocean Engineering,* 131, 50-60. Doi: 10.1016/j.oceaneng.2016.12.028