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Ocean Wave Energy Converters: Analysis, Modeling, and Simulation. Some case studies.

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Abstract. Wave energy has much more potential and benefits than other forms of renewable energy. It is more predictable, consistent, and controllable than wind or solar energy. In this way, an adequate infrastructure can be an alternative and also sustainable system for power supply. In this paper, different wave energy conversion mechanisms (buoys, Pelamis, and oysters) have been described. These models are implemented and simulated using the Design Modeller, ANSYS-AQWA, and WEC-SIM applications. The purpose has been to develop a complete simulation of the wave energy converter and discuss its operation. The analysis has been developed in Matlab-Simulink and both regular and irregular waves have been considered. For this, an approximation to the linear waves theory has been used. The results obtained indicate the energy absorbed from the sea waves and also the energy supplied to the power grid. The simulation results estimated with the different WEC models are comparable to the results shown by other research papers.

Keywords. Ocean wave energy converter; power take-off design; multi-degree of freedom; numerical simulation; raft-type converter; oscillating buoy; oyster; technical principles.

1. Introduction

In the last decade, the interest in renewable energies has grown rapidly, reaching, in some cases, a prosperous market with excellent prospects. Marine energies have the capacity and potential to play an important role in the world's future. Thus, marine energy is considered the renewable energy source that is going to evolve the most in this 21st century. Despite its high potential worldwide, currently, the production of electricity from these marine renewable energies is negligible. In general, because its level of maturity is much lower than other renewable energies such as photovoltaic or wind.

As renewable energy with immense development potential, ocean wave energy has abundant energy capacity. In recent years, several devices have been developed to convert marine energy into electricity with relatively low efficiency and very different results. For devices to be efficient, the wave energy converter (WEC) must be designed to capture much of the energy over a wide range of ocean wave frequencies. Thus, a detailed study is required, both in the direction and wave crest height in the time. Furthermore, most of the ocean wave energy exits at relatively low frequencies, which are more easily accessed by relatively large WECs.

Currently, numerous studies support the analysis and investigation of different WECs in order to extract energy from ocean currents, waves, and tides. Thus, in [1], [2] different power take-off (PTO) systems are described and their basic operating principles are defined. This includes an analysis and comparison of the advantages and drawbacks of each WEC presented [3]. Mechanical direct drive systems and hybrid power take-off systems are considered important development for the future.

The absorption points, simply called buoys, are relatively small devices compared to other types of WEC, although it is an evolved technology. Thus buoys could be a potential option for harvesting energy from highly energetic sources in locations around the world's oceans. Some authors [4], [5] present different floating-point absorber buoys describing these mechanisms in detail. They also provide a rough estimate of the kinetic energy obtained. Meanwhile, Liu et al. [6] propose a combined hydrodynamic and hydraulic power take-off unit model to optimize the performance of the raft-type WEC. Based on this combined model, the comparison of performances with the hydraulic power take-off unit and a linear power take-off unit is also presented in this paper.

Researchers around the world have designed many wave energy converters with varied structures and based on different energy capture technologies [7], [8]. In this way, its scalability has been studied and the energy harvested has been quantified. Likewise, other authors [9] introduce some WECs with multiple degrees of freedom, describing their operation. Other authors propose floating platforms technologies as an effective solution for harvesting wave energy [10]. Another drawback is the incorporation of marine energy into the power-grid. Power fluctuations generated by the wave energy converters can significantly modify the power quality [11], [12]. IPOS converters with modular storage are a good choice for high voltage power distribution (HVDC).

2. Modelling and Simulation Process

In this section, the modelling and simulation process of the different wave energy converters (WEC) is described. For this, the ANSYS software has been used, which allows us to analyze the computational fluid dynamics and develop the hydrodynamic simulation by the boundary element method (BEM). The different forces and moments are calculated numerically by discretizing the geometries of the bodies and mechanisms into smaller elements.

BEM solutions are obtained by solving Laplace's equation for the velocity potential, which assumes that this flow is indivisible, incompressible, and irrotational. Subsequently, the WEC-Sim simulator imports the non-dimensional hydrodynamic coefficients from a data structure for the AQWA BEM solver.

Function	Program	Application	Input		Output	
			File Name	File Format	File Name	File Format
3D Design	ANSYS	DesignModeler		-	"CaseStudy"	.stp
Change design formats	Rhino5	-	"CaseStudy"	.stp	"CaseStudy"	.stl
Hydrodynamic Diffraction Analysis	ANSYS	AQWA	"CaseStudy"	.stp	ANALYSIS ANALYSIS	.AH1 .LIS
bemio	MATLAB	-	bemio ANALYSIS ANALYSIS	.m .AH1 .LIS	ANALYSIS	.h5
Model Design	MATLAB	Simulink	-	-	"CaseStudy"	.slx

Fig. 1. Methodology, process, and software used during the development of the different WEC models analyzed.

The analytical methodology used for the development of the different models and the study of the wave energy converters is described in Fig. 1. The diagram represents the different basic steps for the development of the WEC simulation. In all cases, the same procedure has been followed to obtain the geometric optimization of the model. Thus, ANSYS and Matlab/Simulink have been the main software used for model simulation and drawing conclusions.

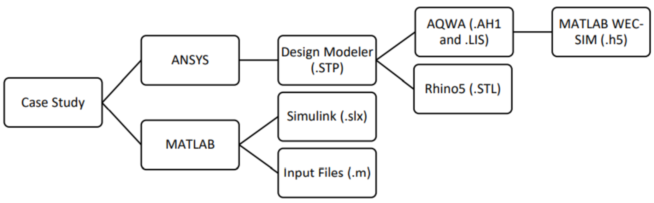

Fig. 2. Detail of the procedure followed.

The diagram in Fig. 2 describes the general simulation procedure for each case study. The file format used by each application is also displayed. The main objective has been to study the behavior of some wave energy converters while obtaining the estimated power produced in each device. To achieve this purpose, a wave energy converter simulator (WEC-Sim) is used, which allows us to fully simulate and analyze its own design.

3. JONSWAP wave spectrum

In the sea, the waves are produced by the wind. The JONSWAP wave spectrum (Joint North Sea Wave Project) can be used to describe a wave system in which there is an imbalance in the flow of energy. In this case, the JONSWAP spectrum is similar to the Pierson-Moskowitz spectrum, except that the waves continue to grow with distance (or time). This detail is specified by the "α" parameter. Also the peak in the spectrum is higher, see Fig. 3, as specified by the "γ" parameter. This latter coefficient is important because it leads to enhanced nonlinear interactions and a time-changing spectrum in accordance with Hasselmann's theory. Thus, an additional factor was added to the Pierson-Moskowitz spectrum to improve the fit to its measurement. In short, the JONSWAP spectrum is thus a Pierson-Moskowitz spectrum multiplied by an additional peak enhancement factor γ^r. Figure 3 shows a comparison of JONSWAP and Pierson-Moskowitz spectrum.

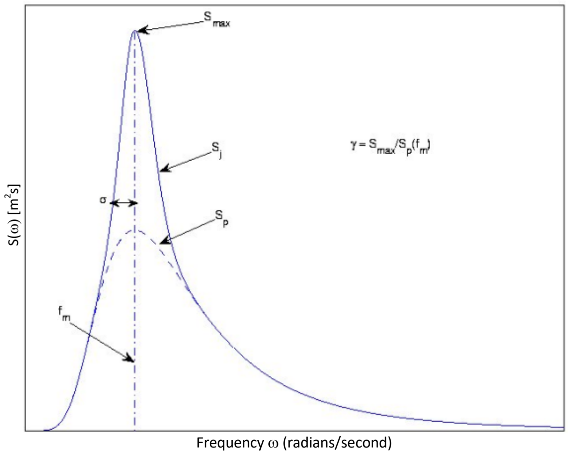

Fig. 3. JONSWAP and Pierson-Moskowitz spectrum.

JONSWAP curve S_j (m^2s) is used to determine the values for the coefficients in the equations. The gamma γ and alpha α parameters together with the peak frequency ω_p (frequency value where the energy spectrum is maximum) are determined empirically [13]. Therefore, the value of Sj(ω) at a given frequency ω (rad/s) will be given by,

$$S_j(\omega) = \frac{\alpha g^2}{\omega^5} exp\left[-\frac{5}{4}\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^r \qquad (1)$$

$$r = exp\left[-\frac{(\omega-\omega_p)^2}{2\sigma^2\omega_p^2}\right] \qquad (2)$$

where $\omega = 2\pi f$ (rad/s) and f is the wave frequency in Hz, while g is acceleration of gravity in m/s^2, γ is the non-dimensional peak-shape parameter and r is the exponent of the peak shape parameter, while σ is the scaling factor in the JONSWAP spectrum, see Fig. 3, and has values corresponding to,

$$\sigma = \begin{cases} 0{,}07 & \omega \le \omega_p \\ 0{,}09 & \omega > \omega_p \end{cases} \qquad (3)$$

A wave spectrum S(*f*) or S(ω) can be represented with different empirical spectral relationships, such as Scott, Torsethaugen, Pierson-Moskowitz, Bretschneider, Ochi-Hubble, etc. In [13] the commonly used spectra are described, as well as their mathematical relationships.

4. WEC-Sim Simulator Tool

Wave Energy Converter Simulator (WEC-Sim) is an open-source wave energy converter simulation tool. The software is developed in MATLAB/Simulink using the

Simscape Multibody dynamics solver. This WEC-Sim tool is a collaboration between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories. The model of a wave energy converter (WEC) has to include the interaction between the incident waves, the device movement (bodies, joints, elements, etc.), the power take-off (PTO mechanism), and the mooring system. The WEC-Sim tool can model rigid bodies and flexible bodies. Figure 4 shows the schematic block diagram of a point absorber model developed with WEC-Sim.

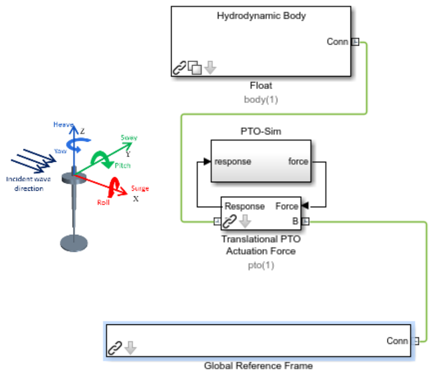

Fig. 4. Schematic block diagram of the Buoy model and WEC-Sim reference coordinate system.

As represented in Figs. 4 and 5, the Simulink models are based on a hydrodynamic body that is connected to a PTO (Power Take-Off) system. The system is then connected to a global reference frame that acts as the ocean floor. WEC-Sim can be used for regular and irregular wave simulations, although they are estimated differently for sinusoidal steady-state response scenarios and random sea simulations.

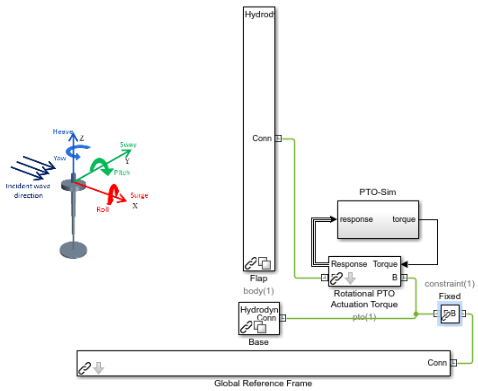

Fig. 5. Schematic block diagram associated with the Oyster mechanism and WEC-Sim reference coordinate system.

In buoy-type WEC devices, the power take-off mechanism is modeled as a direct drive linear generator system, where the reaction force of the F_{PTO} is given by:

$$F_{PTO} = \frac{\pi}{\tau_{pm}} \lambda_{fd} i_{sq} \ [N] \quad (4)$$

where τ_{pm} is the magnet pole pitch (m), λ_{fd} is the stator d-axis winding flux link (V×s), while i_{sq} is the stator q-axis current (A).

Whereas in hydraulic WEC devices, the PTO mechanism is modeled as a hydraulic system, where the reaction force of the F_{PTO} is given by:

$$F_{PTO} = \Delta P_p A_p \ [N] \quad (5)$$

where ΔP_p is the hydraulic piston differential pressure, and A_p is the piston area.

Likewise, the maximum power P_{PTO} that can be harvested by these systems can be expressed as a function of the relative speed $\dot{X}_{rel}$ as,

$$P_{PTO} = -F_{PTO} \dot{X}_{rel} \ [W] \quad (6)$$

where $\dot{X}_{rel}$ it is caused by motion between two bodies. The PTO system is important as it affects the conversion efficiency of wave energy. It also contributes to the mass, size, and structural dynamics of the wave energy converter used.

A. Modelling Ocean Waves

Regarding linear wave theory, both regular and irregular surface waves can be considered in the analysis of WEC systems. In general, a regular wave is sinusoidal and is caused by a constant wind over a long period of time. Now, sea waves consist mainly of regular overlapping waves, because the speed of the wind varies. Thus, an irregular wave is defined as the superposition of a range of regular waves with variable amplitude.

Regular waves are defined as planar sinusoidal waves, where the incident wave is defined as $\vartheta(x, y, t)$

$$\vartheta(x, y, t) = \frac{H_m}{2} cos(\omega t - k(xcos\theta + ysin\theta) + \varphi_d) \quad (7)$$

$$k = \frac{2\pi}{\lambda} \quad (8)$$

where H_m is the wave height (m), ω is the wave frequency w=$2\pi f$ (rad/s), θ is the wave direction (rad), k is the wave number, λ is wave length (m), and φ_d.is the wave phase (rad).

Irregular waves are modeled as the linear superposition of a large number of harmonic waves with different frequencies and angles of incidence. In this case, the incident wave can be defined as $\vartheta(x, y, t)$

$$\vartheta(x, y, t) = \sum_{i=1}^{n} \left[\frac{H_{m,i}}{2} cos\left(\omega_i t - k_i(xcos\theta_i + ysin\theta_i) + \varphi_{d,i}\right) \right] \quad (9)$$

Now, the wave phase "$\varphi_{d,i}$" is a random coefficient for irregular waves.

Fig. 6. PB40 PowerBuoy wave energy converter manufactured for the WavePort Project. http://offshoreWID.biz.

5. Point Absorber (Buoy)

In the sea, the way a buoy works is simple. Waves are generated as a result of the transfer of wind energy on the ocean surface. So, big waves are generated when strong winds blow over long distances. The floating buoy moves up under the influence of a wave crest and moves down under the effect of a wave trough. This movement caused by the waves (mechanical stroke) allow us to drive an electric generator. Also, this wave energy can be distributed to onshore through an underwater power cable and then connected to the utility grid. The PB40 PowerBuoy wave energy converter prototype is shown in Fig. 6. This WEC device has an overall length of 43.5m, a float diameter of 11m, and a weight of 180t approx.

The techniques and steps of the simulation have been explained previously; in this section the parameters of this specific case study are defined. Thus the buoy model is described. No joints were considered in the analyzed case. The buoy is a single body and isn't connected to another body. This reason allows the Simulink model not to include any constraints. Table 1 describes the technical parameters (mass, diameter, area, etc.) of the proposed floating-point absorption model.

Table I. Technical parameters of the Buoy Model.

Model	Geometry				Water Depth
	Diameter	Height	Area	Mass	
Buoy	4,0m	1,0m	36,201m^2	6700kg	50,0m

The fluctuation of power from wave to wave occurs in the range of seconds and depends on seasonal variations. Thus, the power of the waves fluctuates with different time constants. In deep water, the harvested average wave power can be obtained using linear potential wave theory [10],

$$P = \frac{\rho g^2}{64\pi^2} H_{m0}^2 T_E \qquad (10)$$

where, P is the wave power per unit length of wave crest (W/m), ρ is the density of sea water ($\rho = 1025$kg/m^3), g is the acceleration due to gravity ($g = 9.81$m/s^2), H_{m0} is the significant wave height (m), and T_E is the average power period in the wave (s). The significant wave heights in the simulations can be chosen according to the equal energy transport theorem [14] [15],

$$H_{m0} = 2\sqrt{2}H_m \qquad (11)$$

where "H_m" is the amplitude of the regular wave with equal energy. In general, this wave resource is described in terms of power per meter of wave front (wave crest length).

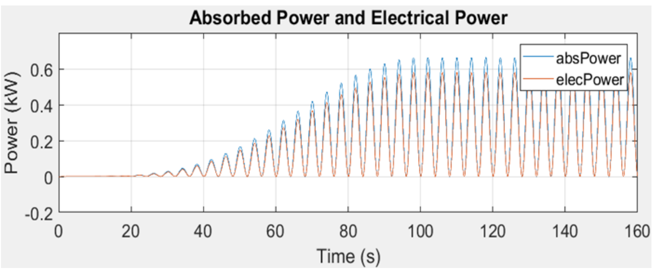

Fig. 7. Simulation results of the WEC-Sim buoy model. Power harvested from the sea.

A good valid numerical model can provide important information to estimate the power output of the system and predict its behavior. Figure 7 represents the simulation results of the power harvested by the WEC-Sim buoy model. It can be seen that in 90 seconds the system reaches the steady-state of power generation. It can be seen that the device absorbs a maximum power value of 0.61kW from the waves.

A. Wave propagation analysis with several buoys

Figure 8 shows the simulation developed with the ANSYS-AQUA software for the case of several buoys. The purpose has been to study the disturbances caused in the waves by the distance and position of the different buoys. In the figure it is also possible to observe, in colour map format, the movement of the buoys and the waves. The forces and moments have been calculated numerically by discretizing the different geometries of the bodies into multiple small elements. In this way, it is possible to more easily track the displacement of these elements as the body moves, and it also allows us to add the resulting forces and moments on each element around the gravity centre in the system.

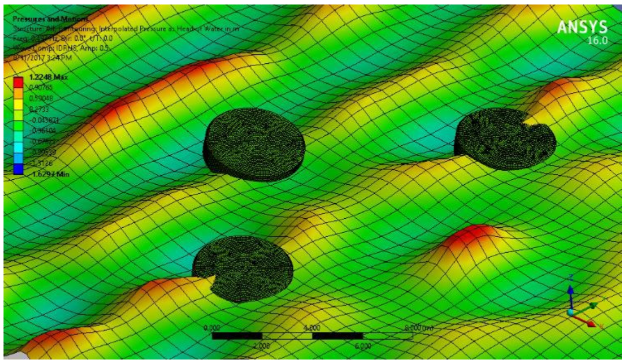

Fig. 8. Analysis of the disturbance caused between the different buoys. Image obtained from the ANSYS solver. It shows the pressures and wave motion of the waves.

To start the mechanical simulation, the environment parameters must be defined, as well as the dimensions of the study area and the parameters of the sea depth. Table 2 indicates the setting parameters in the 3D BEM simulation (ANSYS-AQWA software).

Table II. Configuration parameters in ANSYS-AQWA simulation with several buoys.

Water depth (m)	50
Water density (kg/m^3)	1025
Structure Fixity	it is free to move
Diameter/Width (m)	4
Wave type	Stokes 2nd order wave
Frequency (Hz)	0.497
Direction (degrees)	0
Incident Wave Amplitude (m)	0.5
Result Type	Phase angle
Wave position (phase)	1

Figure 9 represents a graph with the position of each buoy with regular wave. In this case, as can be seen in the graph, the displacement of buoys 2 and 3 coincide (lines B and C). It also highlights that there is a gap between the position occupied by the buoys at any given time. This displacement between the curves is associated with the separation distance of the buoys in the sea.

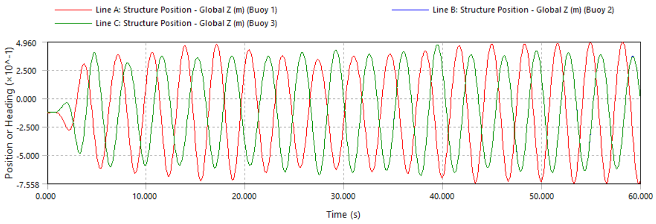

Fig. 9. Buoys position with regular waves.

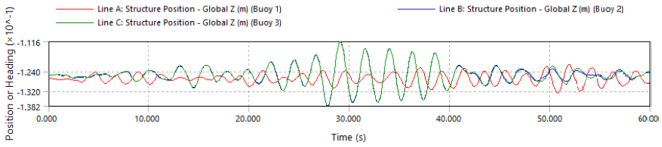

Fig. 10. Buoys position with irregular waves.

The analysis and simulation results performed with the irregular wave environment are not uniform (see Fig. 10), but it helps to show the difference between wave phenomena and disturbances and effects caused by buoys. Now the movement of the buoys within irregular waves will not be as smooth as before, but it allows us to observe the slight difference between each of the buoys. Irregular waves can be considered as a series of regular waves with different frequencies. In this way, it is possible to study the effect of the first buoy on the rest and vice versa. Likewise, the great difference in position between the buoys can be explained by the effect of the propagation of the waves and their irregularity.

6. Pelamis (Attenuator)

Pelamis device consists of several semi-submerged cylindrical sections, joined by articulated joints. In turn, the wave induces a relative movement in each section. Figure 11 shows the Pelamis wave energy converter. This system is capable of harvesting energy from wave-induced movement through its articulated joints. The angular displacement of this articulated joint activates the internal hydraulic system that pumps high-pressure oil to the hydraulic motor. In this way, the electric generator coupled to the hydraulic motor produces electricity.

Fig. 11. Pelamis is an offshore wave energy converter that uses the energy of ocean waves for electrical power. http://www.pelamiswave.com

Each module contains a complete electro-hydraulic power generation system. A single power distribution cable on the seafloor connects multiple devices to shore. Table 3 describes the technical parameters (mass, diameter, area, etc.) in the offshore wave energy converter (Pelamis model). The simulated device model consists of an articulated joint and two hydrodynamic structures. The Pelamis reached a maximum absorbed power of 60kW during the dynamic response period and 42kW in the steady-state.

Table III. Technical parameters of the Pelamis Model.

Model	Geometry				Water Depth
	Diameter	Length	Area	Mass	
Pelamis	3,5m	30,0m	349,11m^2	155tn	50,0m

7. Oyster

The Oyster is a hydroelectric wave energy device that uses the movement of ocean waves to generate electricity, see Fig. 12. The Oyster concept is an oscillating wave converter: a floating articulated flap attached to the seabed about 10m deep. The movement of the articulated flap drives two hydraulic pistons that supply high-pressure water to a hydroelectric turbine on the coast. In turn, the turbine drives an electrical generator to produce power. Oyster is stationed at the European Marine Energy Center (EMEC) in Orkney, Scotland.

Table IV. Parameters of the Oyster Model.

Model	Geometry				Water Depth
	Flap	Height	Area	Mass	
Oyster	1,8x18m	8,9m	423,02m^2	127tn	10,0m

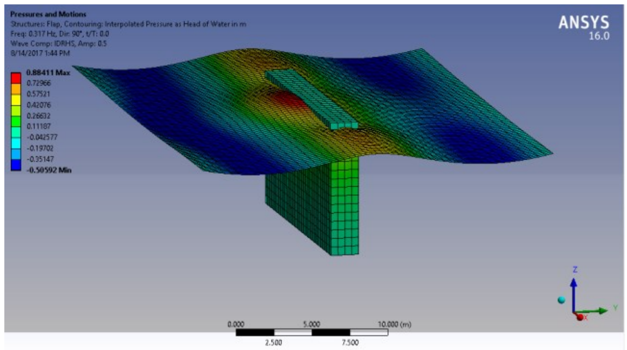

Fig. 12. Schematic block diagram associated with the Pelamis attenuator mechanism.

In the case of the buoy, the simulation results have been analyzed in the direction of the z-axis. Now in this new case, the device moves back and forth along with the wave, in the y-direction. Fig. 13 represents the device position result caused by irregular waves (y-axis direction). In this way, it is possible to observe the initial dynamic response of the Oyster converter.

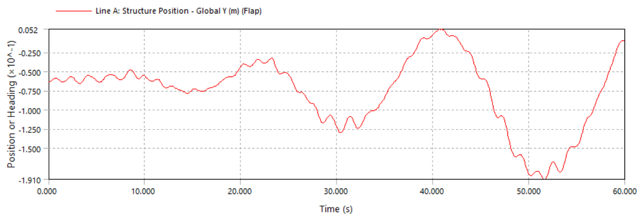

Fig. 13. Oyster position result with irregular wave.

While Fig. 14 represents the simulation results related to the energy harvested by the Oyster WEC-Sim model. It can be seen that this device absorbs a maximum power value of 210kW from the waves. An experimental prototype close to the Scottish coast is shown in Fig. 15.

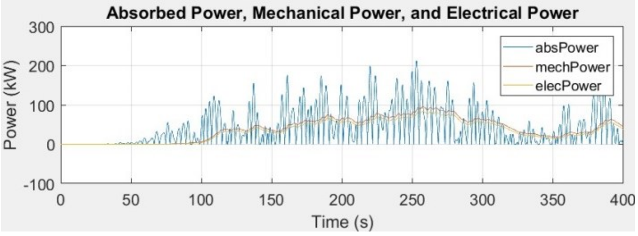

Fig. 14. Simulation results of the WEC-Sim Oyster model. Power harvested from the sea.

Fig. 15. Oyster device is a near-shore wave energy converter. https://www.offshorewind.biz/

8. Conclusion

In this paper, different wave energy converter mechanisms (e.g. point absorber buoy, raft-type WEC, and oyster) have been described. At the moment, the real implementation of these devices is difficult due to the investment costs, the high manufacturing costs of the mechanisms, and the robustness required in the energy harvesting system. However, these systems may represent the future in wave energy harvesting, and play an important role in the transition to sustainable energy systems. Thus, different PTO technologies were explored and explained. These models have been implemented and simulated using the Design Modeller, ANSYS-AQWA, and WEC-SIM applications. The analysis has been carried out considering regular and irregular waves and using an approximation to the linear wave theory. In this way, the same sea conditions have been applied to each of the models studied. In each case, the results obtained have been studied and the simulation data are presented as preliminary validation. The simulation results obtained with the different WEC models are comparable to the results shown by other authors [2], [16]. Parallel to the verification of the proposed WEC models, the power results have been compared with other simulation tools.

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