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Preliminary design of a hybrid wave energy converter integrated into a rubble mound breakwater

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Abstract – **Sea ports are highly exposed to ocean waves, being often necessary to protect them with breakwaters and other sheltering solutions. Also, ports are infrastructures with substantial energy demands and major sources of air pollution and other environmental impacts. By using renewable energy, in particular electricity harvested from ocean waves, ports would be able to convert some of the disadvantages associated with the harsh ocean environment into a potential solution for the problem of large energy demands and pollution. In fact, many ports worldwide already started the transition to cleaner energy sources in order to decarbonize their activities and meet their future renewable energy targets. The high potential of port breakwaters for the integration of Wave Energy Converters (WECs) triggered the European SE@PORTS project (OCEANERA-NET), which aims to assess the suitability and viability of existing energy conversion technologies to be integrated into such infrastructures. The present paper introduces the preliminary design of a hybrid WEC solution that combines the concepts of Oscilating Water Column (OWC) and Overtopping Wave Energy Converter (OWEC). This hybrid WEC was developed taking into consideration the characteristics of the north breakwater of the Port of Leixões, Portugal, and the proposed plan for its extension. In order to simulate the physical phenomenon behind the OWC, a wave-to-wire model was developed in MATLAB SIMULINK. The performance of the OWEC was estimated resorting to the code WOPSIM (Wave Overtopping Simulation). Both tools were used to assist in the optimization of the hybrid WEC design. Some of the preliminary results are presented in this paper.**

Keywords—**hybrid WEC; wave overtopping; oscillating water column; concept selection; wave-to-wire model**

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I. Introduction

THE development of the wave energy sector is expected to benefit significantly from the creation of synergies with other sectors, as pointed out by the International Renewable Energy Agency [1]. Hence, opportunities must be found for the multi-purpose use of already existing or proposed marine and harbour infrastructures.

This can be achieved, for instance, by integrating wave energy converters (WECs) into breakwaters, which are designed to promote the dissipation of wave energy, creating sheltered conditions for port activities. It is also pertinent to consider that ports are infrastructures with substantial and quantifiable energy demands, often being a major source of air pollution and other environmental impacts.

Many ports worldwide already started the transition to cleaner energy sources in order to decarbonize their activities and meet their renewable energy targets. The high potential of port breakwaters for the integration of WECs, due to their high exposure to ocean waves, triggered the European project SE@PORTS (OCEANERA-NET), which intends to demonstrate that this approach is a win-win solution for both breakwaters and WEC solutions. Despite the lack of investment in the application of WECs at ports, such concepts have already been proposed and some onshore pilot projects exist, although most of them are based on the application of an Oscillating Water Column (OWC) only, e.g., Mutriku in Spain [2], REWEC3 in Civitavecchia [3] or Overtopping Devices as presented in [4]–[6].

The present paper discusses the development of a cost-efficient and versatile hybrid WEC concept to harness energy at sea ports, while ensuring their functionality, reliability and robustness. In this work the preliminary design of this novel solution, integrated into the proposed extension of the rubble-mound breakwater of the Port of Leixões, Porto, Portugal [7] (one of the case studies of SE@PORTS), is presented. The hybrid WEC combines the overtopping and oscillating water column principles, taking into consideration the characteristics of the harbour infrastructure. A preliminary wave-to-wire model in MATLAB Simulink was developed to estimate the performance of this innovative concept and to assist in the improvement of its design. An overview of this numerical model is presented in this paper.

II. State of the Art in WEC-Breakwater Integration

This section presents a review of the state-of-the-art of WECs integrated into breakwater (or similar structures), such as oscillating water column, overtopping converters, hinged point absorbers and flexible membranes. The devices presented in this section have been developed and tested in real environment or at model scale. This review has been done to learn from the experiences, to obtain reference values from typical device dimensions and to assess the individual advantages and disadvantages of each of the following WEC technologies.

A. Oscillating Water Column (OWC)

The OWC comprises a partially submerged concrete or steel structure, with an opening below the water surface, and an air column confined between its inner walls and the free water surface. The oscillating motion of the internal free surface, induced by the incident waves, forces the air to flow through a turbine that drives an electrical generator. The most commonly used turbine is the Wells turbine, due to its ability to provide rotation in one direction for both suction and blowing effects [8].

The world's first OWC-Caisson breakwater integration, in 1989, was located at Sakata Port in Japan. Between 1995 and 1999, the Pico OWC power plant was installed at the Azores Islands, Fig. 1 (a). The Pico OWC used an horizontal-axis Wells turbine generator [9].

More recently, in 2008, a multi-turbine facility, consisting of 16 chambers, has been successfully installed on a vertical breakwater at the port of Mutriku, Spain, Fig. 1 (b), becoming the first facility in Europe to integrate such a concept into a breakwater. The OWC principle was chosen as it would require only a few changes to the original breakwater design. In addition, it was the most tested technology. In 2012, the biggest OWC–breakwater integration device, and the first in the Mediterranean Sea, the Resonant Wave Energy Converter 3 (REWEC3) [10], [11], was successfully installed at the harbour of Civitavecchia, Italy, Fig. 1 (c).

The advantages of this technology are: its simplicity, as it consists of only two elements (a reinforced concrete structure, which acts as an oscillating chamber, and turbine generators), and the absence of moving parts in the water, thus minimizing maintenance. The main disadvantages include high initial costs and potential negative visual impact.

(a) (b) (c)

Fig. 1. Examples of OWC: (a) Isolated OWC (Pico, Azores) [9], (b) Mutriku OWC plant [2], (c) REWEC3 3D representation.

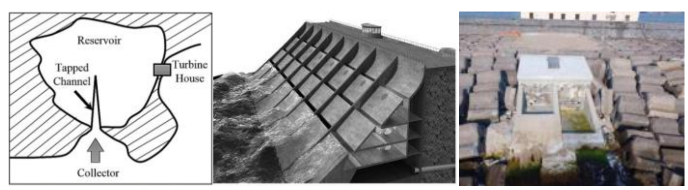
B. Overtopping Wave Energy Converter (OWEC)

OWECs are designed to extract energy from ocean waves based on wave overtopping into a reservoir, which is emptied into the ocean through a set of low-head hydro turbines. These converters typically feature a low crest freeboard and a smooth impermeable steep slope (ramp).

The earliest invention of overtopping concept is a tapered-channel wave power device, also known as TAPCHAN. This fixed WEC type has been developed in 1980, in Norway [12]. The concept used in TAPCHAN is similar to the traditional hydroelectric power plant as shown in Fig. 2 (a).

The use of the overtopping principle in breakwaters started with the Sea-Wave Slot-Cone Generator (SSG) invention in 2002, Fig. 2 (b), and, later, with the Overtopping Breakwater for Energy Conversion (OBREC), in 2013.

Currently, the one of the prototypes under development is the OBREC, which has been embedded into the rubble mound breakwater of the Port of Naples (Italy) [13]. The reason for choosing the overtopping concept was the compatibility aspect, along with the existing horizontal composite caisson breakwater design Fig. 2 (c).



(a) (b) (c)

Fig. 2. Examples of OWEC: (a) Top view of TAPCHAN [12], (b) Cross-section of SSG WEC [30], (c) Frontal view of the OBREC [13].

The slope of the ramp in the breakwater front is designed to minimize the dissipation of wave energy during the run-up phenomena. As the water depth reduces, waves start to break in several forms (spilling, collapsing, plunging or surging), depending on the bottom slope and the wave steepness. For overtopping devices, the slightly breaking surging waves are preferred since energy dissipation is small and, consequently, the wave run up and overtopping is higher. The overtopped water is collected in reservoirs and re-used to generate electricity through low head hydro-turbines. This integrated concept enhances the ability of stand-alone breakwaters with a dual-function as wave absorption and wave energy harnessing devices.

The main advantages of this device are the simple and low cost operation and maintenance requirements. Furthermore, the gates controlling the water flow are virtually the only moving parts. On the other hand, this device has the potential to induce strong reflections, which may trigger seabed scour.

C. *Point Absorbers*

Point absorbers are oscillating bodies which produce energy by reacting against a fixed structure (like a breakwater) or against another oscillating body. Their horizontal dimensions are much smaller than the incident wavelength. Point absorbers devices can be classified according to the degree of freedom from which they capture the ocean energy, e.g., heaving systems (PowerBuoy), pitching systems (SEAREV) etc. [9].

In most cases, the point absorber WEC system consists of a large set of floaters reacting against a common frame and sharing the same PTO. This is the case of the Wave Star device, developed in Denmark, Fig. 3 (a), which consists of two rectilinear arrays of closely spaced floaters located on both sides of a long bottom-standing steel structure. The WEC system is aligned with the dominant wave direction and houses a PTO consisting of a high-pressure oil hydraulic circuit and a hydraulic motor [14].

The Brazilian hyperbaric device is based on a similar concept, Fig. 3 (b), the main difference being that the reference frame about which the buoys oscillate is a breakwater, and water is pumped to feed a Pelton turbine in a circuit that includes an air accumulator [15].

(a) (b)

Fig. 3. Point absorbers prototypes: (a) Wave Star, with 2 floaters of 5 m diameter, rated 25 kW each, being tested at Hanstholm, Denmark, 2009 [31], (b) hyperbaric device installed at a breakwater in São Gonçalo do Amarante, Brazil, 2012. [15]

Point absorbers are efficient devices; however, they have high PTO maintenance costs and survivability issues. They may also interfere with berthing.

D. *Flexible Membranes*

This type of WEC exploits the flexible properties of its elements to generate energy. The inflatable membrane covers a concave cell, creating an air-filled volume. As waves pass over the flexible membrane, the air inside is compressed and driven into a duct and finally passes through a turbine. The turbine spins a generator to produce electricity. The air is recycled to re-inflate the membranes for the next wave [16].

One of the projects in progress is the AWS-III, developed by AWS Ocean Energy, Scotland. The AWS-III is a multi-cell array of flexible membranes. The cells are inter-connected, allowing interchange of air between cells in anti-phase. A typical device comprises an array of nine cells, each measuring around 16 m wide by 8 m deep, arranged around a catamaran structure. This device is capable of producing an average of 2.4 MW from a rough sea, weighing less than 3500 t. The AWS-III is slack-moored in water depths of around 100 m [17].

In November 2014, AWS completed the large-scale installation of a single AWS III power-generating cassette at Lyness quay, Orkney, Fig. 4. The purpose of the test was to demonstrate the concept in a real sea environment.

Fig. 4. AWS-III Absorber Saddle and Installation at Test Site in Scotland [32].

The flexible membranes are made of reinforced industrial grade rubber. Similar materials are already in use in a range of marine applications with good performance and durability. The flexible absorbers are highly efficient and are the only moving part of the power train exposed to the sea. The use of air as a transmission medium removes end-stop issues. However, there are not many studies regarding the use of flexible membranes due to the difficulties in characterizing the non-linear behaviour of the materials and their deformation due to wave action.

This concludes the review of WEC technologies integrated into breakwaters or fixed platforms. Next, several conceptual ideas of hybrid WECs using these technologies are presented.

III. HYBRID WEC CONCEPTS AND SELECTION

Possible combinations of the already proven WEC technologies are described in this section, with their conceptual 2D designs. Moreover, several criteria for the evaluation and selection of these concepts will be discussed to facilitate an equivalent comparison amongst them.

E. *Oscillating Water Column and Overtopping Wave Energy Converter*

An innovative hybrid WEC concept based on the oscillating water column and the wave overtopping converter technologies is presented in Fig. 5. The overtopping converter, with three reservoirs (similar to the SSG device [4]), is installed on the front wall of the OWC chamber.

F. *Flexible Membranes and Overtopping Wave Energy Converter*

This hybrid WEC concept is the result of the integration of flexible membranes on the reservoir ramps of the overtopping wave energy converter, as shown in Fig. 6. The flexible membranes are installed at an angle to the incoming waves as to enhance the vibration of the flexible material and increase the airflow in the membranes.

It is possible to generate energy in two ways – (i) energy generated from the airflow through the turbine (e.g., Wells turbine) due to free surface oscillations inside the chamber, and (ii) converted potential energy of the stored water in the reservoirs, passing through low-head hydro turbines (Kaplan turbine [12]).

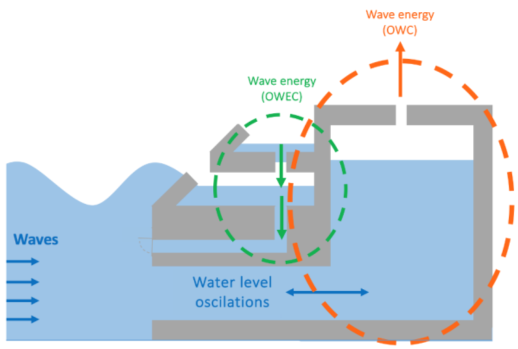


Fig. 5. Hybrid WEC concept – OWC and OWEC.

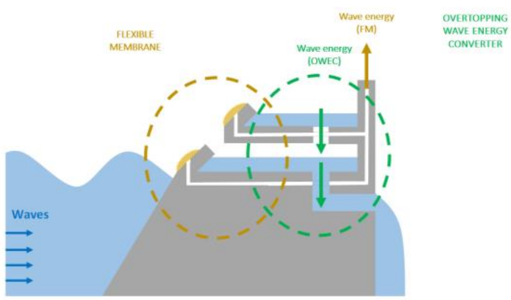


Fig. 6. Hybrid WEC concept – Flexible Membranes and OWEC.

G. *Flexible Membranes and Oscillating Water Column*

This concept combines flexible membranes and an OWC, Fig. 7. The flexible membranes are installed on the outer walls of the OWC chamber. Thus, energy will be generated by compression of air inside the OWC chamber and compression of air inside the membranes.

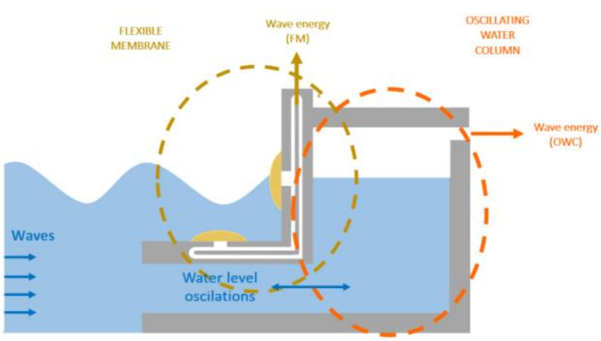


Fig. 7. Hybrid WEC concept – Flexible Membranes and OWC.

Combining Flexible Membranes and an OWC can also be made using Dieletric Elastomer Generators (DEG; a deformable polymeric transducer that can be utilized to provide direct electrical energy generation). In this setting, the air inside the OWC deforms the DEG, generating electricity. Experiments using this technology have been performed in sea condition by the Natural Ocean Engineering Laboratory, Italy [18].

It is important to recall that the main goal of the project is to develop a cost-efficient and flexible hybrid WEC concept while meeting reliability standards and robustness of the system, in order to instil the confidence of various port authorities worldwide (the primary stakeholders of this technology). Moreover, parameters such as WEC modularity/scalability, ease of maintenance, breakwater installation and structural change, among others, must be taken into account, apart from the hydraulic performance and energy production. It is crucial to compare the various proposed hybrid WEC concepts, in order to have a clearer picture of the most suitable or favourable technology to be integrated into the breakwater at a specific sea port location. A brief summary of these important criteria, which will be used to evaluate the proposed hybrid WEC concepts before proceeding to the detailed model design and wave tank testing, is presented in Table 1. The more important and relevant the criterion is to meet the goals of this project, the higher the weight it would represent on the final decision.

In the next section, the infrastructure of the Port of Leixões is described, which will include the design and dimensions of the proposed north breakwater. This will help in making a decision to choose a hybrid WEC concept for further analysis.

IV. Port of Leixões

H. *Port infrastructure*

With the biggest harbour infrastructure in the north of Portugal, the Port of Leixões is a key centre of commercial and economic shipping activities with privileged access to one of the most important navigation routes in the world: the Atlantic Ocean. Thus, the Port of Leixões plays a relevant role in terms of national economic development. This port is located on the northwest Portuguese coast at a latitude of 41º11' north and a longitude of 8º42' west, and nearly 4 km north of the mouth of the Douro River.

The geographical location of the port implies that it is subjected to a severe local wave climate. During storms, significant wave heights may easily exceed 8 m. Tides are of the semi-diurnal type with amplitudes ranging between 2 and 4 m.

The Port of Leixões has undergone major changes since its initial construction in 1890, with the innermost facilities being mostly protected by the north breakwater as shown in Fig. 8, which spans more than 2000 m and is protected at the head by a detached submerged breakwater.

TABLE 1. CRITERIA FOR CONCEPT EVALUATION

Selection Criteria	Description
Cost effectiveness	The WEC technology with a lower levelized cost of energy (LCOE) as stated in the literature.
Breakwater Construction and Integration	The functional and structural performance of the breakwater must not be affected by the WEC, hence the selected concept must fit into the breakwater making as few changes in the original design as possible.
Technology Readiness Level (TRL)	The higher the TRL of the individual WEC concept, the more tried and tested the technology and higher its level of maturity is.
Scalability/Modularity	This is a relevant parameter as arrays of hybrid WEC will be installed along the length of the breakwaters at different locations.
Maintenance	They form a large part of the WEC operation costs, hence lower and easily accessible maintenance is desirable.
Reliability	Preference will be given to the WEC technology that possesses minimum risks and thus higher potential of attracting the stakeholders' confidence.
Innovation	The most innovative hybrid WEC concept, which utilizes the individual strength of each technology, will score the highest in this criterion.

(a) (b)

Fig. 8. Port of Leixões (a) Location on the Iberian Peninsula (source: Google Maps), (b) aerial view of the harbour entrance and its breakwaters (source: APDL).

It is expected that the port will continue to improve and to enlarge its facilities in the future to accommodate larger ships and efficiently handle increasing quantities of cargo. The port development is frequently linked to energy consumption. From 2014 to 2016, for instance, the electricity demand increased by 14.8% [19]. The sustainable development of the port activities will require the use of clean and renewable energy sources in order to meet the increasing electricity consumption. This can be achieved through the integration of innovative WEC technologies into the port sheltering structures.

I. *Evolution of the North Breakwater*

The Leixões North Breakwater, due to its characteristics and exposure to waves, is the structure of the Port of Leixões with the best conditions for the implementation of the hybrid WEC concept being developed in the SE@PORTS project. Hence, it must be described with a higher level of detail.

The analysis of the development stages of the north breakwater reveals a record of both successes and failures that had to be corrected in order to fulfil the sheltering and safety requirements of the Port of Leixões, as it expanded over the years. The experience gathered is relevant for the design and development of a breakwater incorporating a wave energy converter.

Currently, one of the most relevant projected interventions in the Port of Leixões is the extension of the north breakwater. The solution designed is intended to not only provide enhanced sheltering in the harbour basin, but also an improvement of the conditions for the ships entering the port. An additional goal could be the integration of a WEC into the proposed structure, either during the construction phase or even at a later stage.

The initial study [20] considered an extension length of 200 or 300 m, with two different orientations: one aligned with the existing north breakwater and the other oblique to it. Simulations for ship manoeuvrability on approach to the port favoured the 300 m extension with a non-aligned orientation.

Seabed surveys demonstrated that the water depth would reach about 18 m at the head of the future breakwater extension. The provisional layout is presented in Fig. 9. It can be seen that the bathymetry is almost perpendicular to the breakwater alignment.

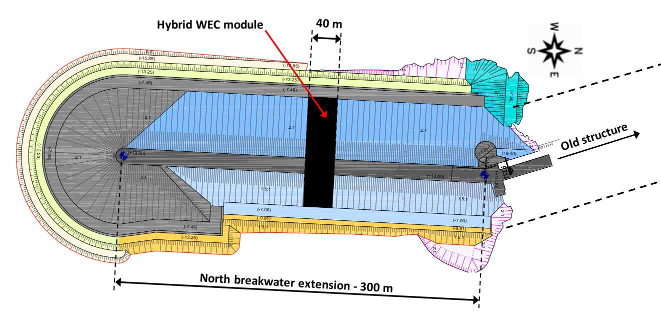


Fig. 9. Provisional layout of the North breakwater [21].

The present design of the North breakwater extension [21], consists of a rubble mound structure with an armour layer made of blocks of high density concrete. The superstructure's crest level, the armour layer and the cross-section characteristics are presented in Fig. 10.

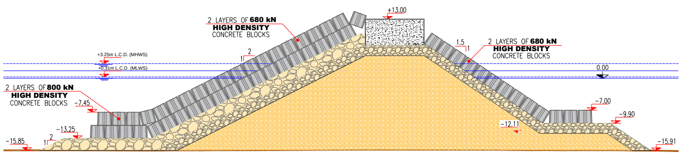


Fig. 10. Cross-section of the north breakwater extension [21].

J. *Marine Environment*

The highly energetic wave climate to which the Port of Leixões is subjected has the NW octant as the dominant wave direction, with a small contribution from the other components. Moreover, the most frequent offshore significant wave heights occur between 1 and 2 m, with about 70% of the occurrences ranging between 1 and 3 m. The maximum wave heights often surpass 8 m. The peak wave period values are commonly from 6 to 12 s (about 84% of occurrence), and the maximum value is around 20 s. This analysis is supported by the data provided by the authorities managing the Port of Leixões, the APDL (the Port Authority of Douro, Leixões and Viana do Castelo) [19].

For the study of the hybrid WEC it was necessary to transfer the offshore wave climate to the region of interest, which is at the toe of the breakwater. This has been performed using a SWAN (Simulating Waves Nearshore) spectral wave model, developed by the Delft University of Technology, [21], and the input data is obtained from two offshore sources: measurements of the Leixões offshore wave buoy (Latitude - 41º19'N and Longitude - 8º59'W) and ECMWF's (European Centre for Medium-Range Weather Forecasts) wave forecast model (Latitude - 41º10'N and Longitude - 8º59'W) covering a period of 10 years (2004-2013) and 38 consecutive years (1979-2016), respectively. The joint distribution of the significant wave height with the mean wave direction at the vicinity of the breakwater is presented in Fig. 11.

The irregular sea states which will be used as an input to the numerical model of the chosen hybrid WEC concept are shown in Table 2, which gives a fair representation of the wave climate at the north breakwater. A significant wave height H_s of 0.5 m covers the range of H_s between 0 and 1 m, and the same goes for all the other values of H_s and T_p.

TABLE 2. SEA STATES FOR THE WEC NUMERICAL SIMULATION AT THE PORT OF LEIXÕES.

Sea State	$H_s\ (m)$	$T_p\ (s)$	$Prob(\%)$
1	0.5	6.5	16.8
2	1.5	7.5	45.9
3	2.5	8.5	23.7
4	3.5	9.5	9.4
5	4.5	10.5	3
6	5.5	11.5	1.2

K. *Energy demand*

Energias de Portugal (EDP) is the main energy supplier to the Port of Leixões. The evolution of the total energy consumption of the Port of Leixões from 2014 to 2016 is presented in Table 3. The individual contributions of the consumption sources are presented in Table 4 [19].

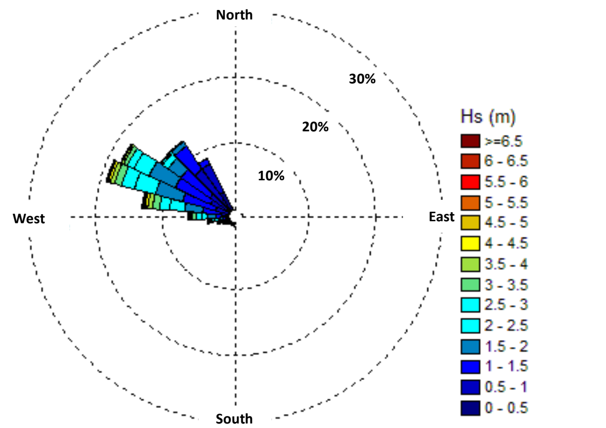


Fig. 11. Joint distribution of the significant wave height with the mean wave direction - toe of the proposed north breakwater [21].

TABLE 3. TOTAL ENERGY CONSUMPTION OF THE PORT OF LEIXÕES IN THE PERIOD 2014-2016.

	2014	2015	2016
Consumption (MWh)	25 270	27 918	29 015

TABLE 4. CONTRIBUTIONS FROM THE DIFFERENT CONSUMPTION SOURCES IN 2016 (IN %).

Consumption Sources		
Total Direct Energy	Diesel Fuel	49.85%
	Natural Gas	0.45%
Total Indirect Energy	Low-voltage Electrical Grid	4.93%
	Medium-voltage Electrical Grid	44.7%

V. PRELIMINARY DESIGN OF THE INTEGRATED HYBRID WEC

The design of the proposed rubble mound structure for the extension of the north breakwater is ideal to incorporate an OWEC, as has been done in the case of the OBREC prototype, requiring the fewest structural changes to the proposed breakwater structure amongst the considered alternatives. Hence, an OWEC should be chosen as the first subcomponent of the hybrid WEC. In terms of selecting the second technology, the combination of OWC with OWEC is favourable and advantageous as compared to the flexible membranes in terms of a number of criteria, as described in Table 1. The OWC has a much higher level of maturity and reliability, as it is the most experienced WEC technology. The OWC technology is cost effective, whereas the lack of experience and confidence in modelling flexible membranes discourages its choice for the scope of this project.

A preliminary design of the hybrid OWC-OWEC integrated into the proposed rubble mound breakwater at the Port of

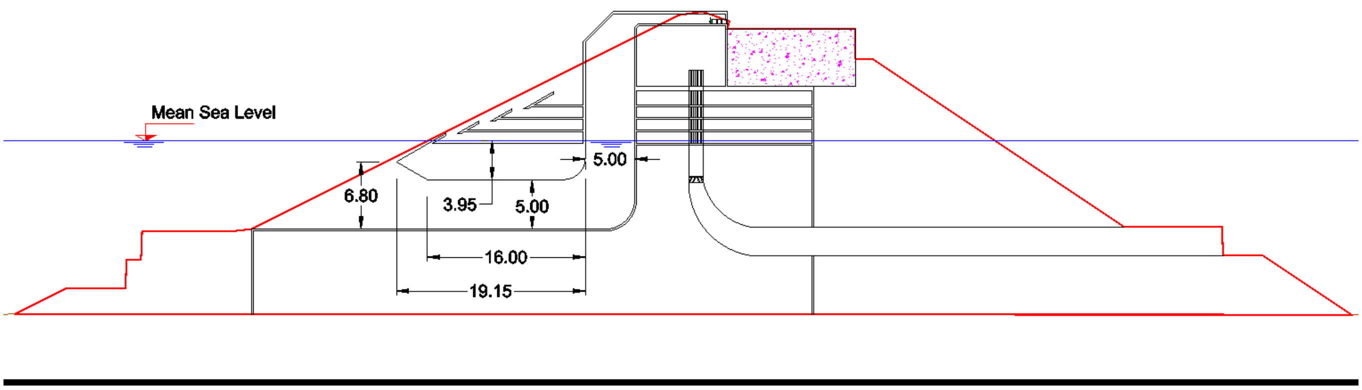


Fig. 12. Proposed hybrid OWC-OWEC WEC integrated into the structure proposed for the north breakwater extension.

Leixões is presented in Fig. 12. The width of the OWC is smaller than the width of the overtopping reservoirs, which allows the stored water to pass around the OWC chamber. In this preliminary design, the OWC and the OWEC can be modelled individually, and the final results for the average power will be the superposition of each component. The preliminary design parameters for both the OWC and the OWEC are shown in Table 5 and Table 6. These parameters are necessary to carry out the first numerical simulations presented in the next section. The dimensions were chosen respecting the breakwater cross-section and in an attempt to obtain a first estimation of the system's performance. The crest levels of the OWEC's reservoirs are relative to the mean sea level (MSL).

TABLE 5 DESIGN PARAMETERS FOR OWC.

Chamber length	24.15 m
Chamber width	5 m
Water depth	17.5 m
Turbine rotor diameter	1 m
Turbine generator inertia	200 $kg\ m^2$

TABLE 6 DESIGN PARAMETERS OF OWEC.

Reservoir front angles	30^0
Ramp angle α_r	30^0
Crest level Reservoir 1	0.75 m
Crest level Reservoir 2	2.00 m
Crest level Reservoir 3	3.25 m
Crest level Reservoir 4	5.00 m
Reservoir width	20.0 m
Reservoir 1 length	38.40 m
Reservoir 2 length	34.90 m
Reservoir 3 length	31.50 m
Reservoir 4 length	28.15 m
Reservoir 1 height	1.00 m
Reservoir 2 height	0.90 m
Reservoir 3 height	0.85 m
Reservoir 4 height	1.40 m

VI. NUMERICAL MODELLING RESULTS

The hybrid WEC has been modelled numerically in the time domain using the mathematical formulation found in the literature for each of the technologies. Firstly, the mathematical formulation of the OWC is presented [22] with relevant numerical results and then the procedure for the OWEC follows.

L. *Oscillating Water Column (OWC)*

The equation of motion for an OWC in heave is given by:

$$(m + A^{\infty})\ddot{x} = -\rho_w g S_c x - p_{at} S p^* - F_{rad} + F_{ext} \tag{1}$$

$$\dot{p^*} = -\frac{\gamma \dot{m}_t}{\rho_{at} S_c (h_0 - x)}(p^* + 1)^{\frac{\gamma-1}{\gamma}} + \gamma \frac{\dot{x}}{h_0 - x}(p^* + 1) \tag{2}$$

$$\dot{\kappa} = P_t - P_g \tag{3}$$

where,

$$p^* = \frac{p}{p_{at}} \tag{4}$$

$$f_{\kappa} = P_t - P_g \tag{5}$$

$$P_t = \eta_t\, p_{at}\, p^* Q_t \tag{6}$$

In Equations (1) to (6), m is the mass of the water displaced by the OWC chamber, A^{∞} is the a added mass at infinite frequency, x is the vertical displacement of the free surface of the water (positive in the upward direction), ρ_w is the density of water, S_c is the cross section area of the OWC, p_{at} is the atmospheric pressure, F_{rad} is the radiation force and F_{ext} is the wave exciting force. In addition, γ is the specific heat ratio of the air, $\dot{m}_t$ is the mass flow through the turbine, h_0 is the water height inside the OWC chamber in calm water, p is the gauge pressure inside the OWC chamber, κ is the kinetic energy of the turbine, Ω is the turbine rotation speed, η_t is the turbine efficiency and Q_t is the volume flow rate through the turbine. Finally, I is the inertia of the turbine-generator set, P_t is the instantaneous turbine power output and P_g is the generated power.

A simple speed control law for the generator that has been proposed and tested numerically is of the form [23]:

$$P_g = a\Omega^b \tag{7}$$

a and b can be optimized to maximize the power output of the OWC at a specific location.

The hydrodynamic coefficients of added mass, radiation damping and exciting force have been obtained using ANSYS AQWA. However, modelling OWC devices using BEM codes is especially challenging due to the very particular behaviour of the free-surface in the OWC chamber, where non-linear effects appear to be particularly relevant. The traditional method for modelling the free-surface inside the OWC chamber is either with a thick piston with a given height or an infinitely thin massless disk to represent the free-surface [24]

The hydrodynamic coefficients for a simple heaving cylinder, obtained from AQWA simulations (Fig. 13) were used to run preliminary tests of the time domain simulations in the wave-to-wire model developed in MATLAB SIMULINK [25], Fig. 16. This wave-to-wire model is divided into several sub-components, which represent the stages of the conversion of wave energy into electrical generator output, employing the OWC principle.

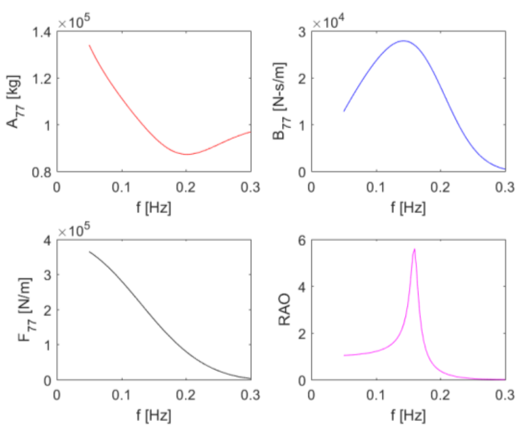


Fig. 13. Hydrodynamic coefficients from AQWA.

The time domain results, for the most probable sea state at the Port of Leixões, are presented in Fig. 14 and Fig. 15. From Fig. 14 the results of free surface elevation inside the chamber and the turbine outputs, namely the efficiency, air pressure and mass flow rate can be obtained. The characteristics of the Wells turbine were taken from the Pico plant.

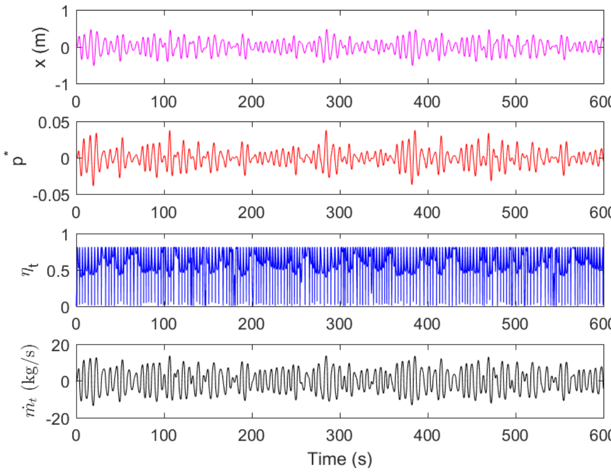


Fig. 14. From top to bottom: free surface elevation inside the OWC chamber; OWC turbine output – dimensionless relative pressure; efficiency; and mass flow rate.

M. Overtopping Wave Energy Converter (OWEC)

The overtopping converter has been simulated using the WOPSIM (Wave Overtopping Power Simulation) tool developed at Aalborg university [26]. WOPSIM is capable of simulating an overtopping structure with n reservoirs and was developed to test the different setups for the overtopping device SSG and improve its energy production. WOPSIM computes the power output of the SSG depending on a complete set of parameters, including wave climate, geometry of the device, turbine strategy, turbine characteristic curves and losses. The computation is based on the the overtopping formulas deducted from wave tank experiments. The same empirical formula is used for this case study. The program generates a random series of waves from the sea states description, and simulates the flow rates through the turbine and power production of the device in the time domain ([27], [28]). In this study, a multi-stage turbine was considered, in accordance with previous studies with the SSG device.

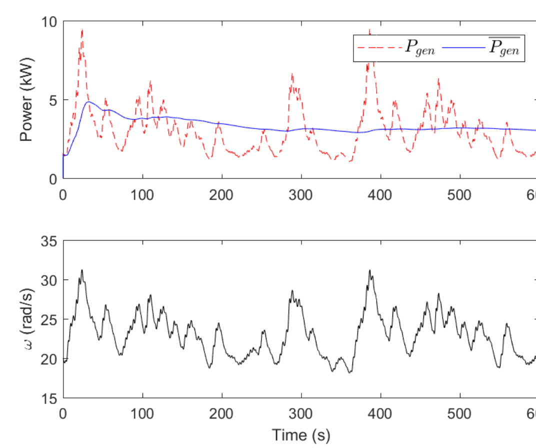


Fig. 15. Output power and turbine rotational velocity.

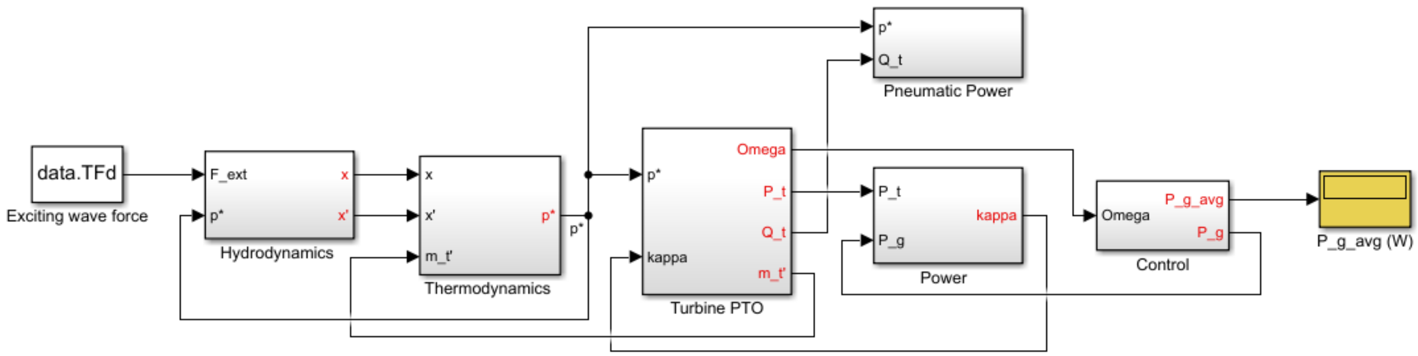


Fig. 16. SIMULINK block diagram for the OWC.

The snapshot of the WOPSIM simulation with all the required inputs is presented in Appendix A (Fig. 18) and the relevant results - the mean flow rate into the reservoirs, the mean overflow rate, the mean flow rate through the turbine and the mean produced power are shown in Fig. 17.

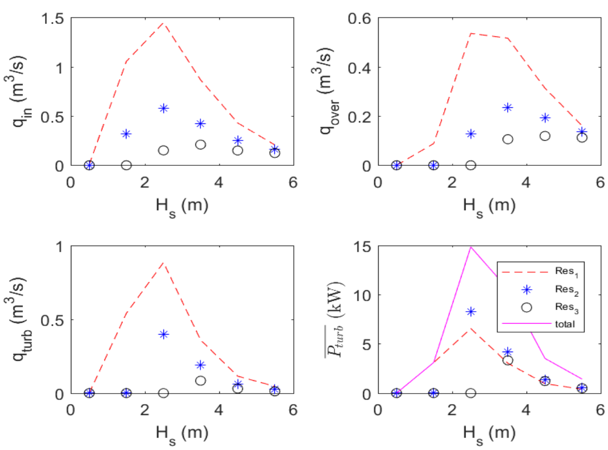


Fig. 17. WOPSIM simulation results.

VII. Conclusions and Future Work

A literature review of WECs integrated into breakwaters was presented. By learning from those experiences, a few conceptual ideas of hybrid WECs have been proposed. Based on several criteria, such as WEC reliability, scalability, TRL, etc, a combination of overtopping and oscillating water column principles were selected as the most suitable hybrid WEC concept to be integrated into the breakwater of Port of Leixões. A preliminary design of this solution has been included in the paper and the most important design criteria, needed to perform the numerical simulations that allow evaluating the performance of the system, were identified as well.

Numerical modelling approaches have been presented for both the selected concepts (OWC and OWEC), along with a few preliminary results. In an attempt to simulate the physical phenomenon behind an OWC (hydrodynamics, thermodynamics, PTO, generator, etc.), a wave-to-wire model was developed resorting to MATLAB SIMULINK. For this purpose, the hydrodynamic coefficients of a heaving cylinder, a typical test case, were obtained from ANSYS AQWA and inputted into the numerical model, together with the data for the most probable wave climate at Port of Leixões. Despite being at an early stage of development, this procedure allowed checking the functionality of the tool and generating preliminary results for power and efficiency. In the case of the OWEC, the WOPSIM tool was used to simulate the flow rates into the reservoirs and through the turbine.

The next steps of this work include further design optimization of each technologies. For the OWC, the wave-to-wire model, fed by the hydrodynamic coefficients of the actual OWC coming from ANSYS AQWA, will be validated against experimental results [29]. Furthermore, CFD simulations will be also carried out to analyse the water elevation in front of the structure and inside the chamber, as well as the overtopping component, thus obtaining the flow rates in each reservoir. Once more, the CFD results will be validated against experimental results [29].

Acknowledgments

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VIII. APPENDIX A

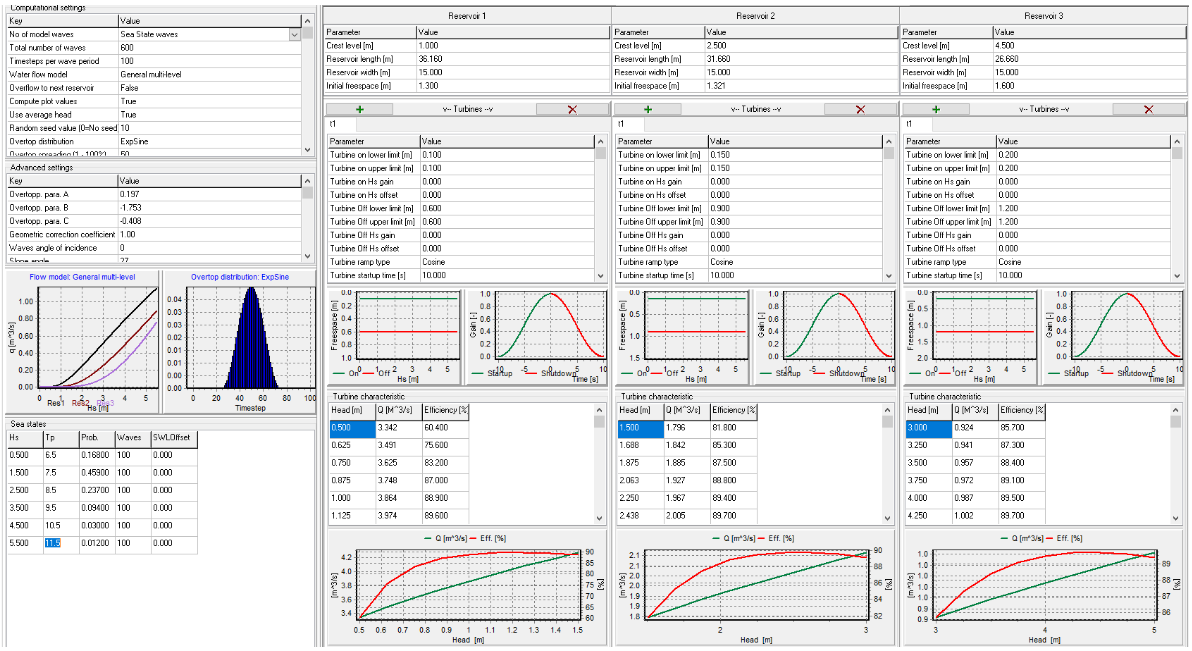

Fig. 18. WOPSIM Simulation Snapshot.