Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

The integration of a hybrid Wave Energy Converter in port breakwaters

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Abstract—**The integration of Wave Energy Converters (WECs) in harbour breakwaters represents a realistic solution to set these infrastructures on the right track in terms of commitment to sustainable development goals and move the harbour development and operations in a more sustainable and environment-friendly direction.**

The project SE@PORTS, acronym of '*Sustainable Energy at Sea Ports*', developed by International Marine and Dredging Consultants (IMDC) based in Belgium with different partners from Portugal and Spain under the second Joint Call of Ocean Energy ERA-NET Cofound initiative, addresses those challenges. More specifically, the project goal is to assess the suitability of existing WECs to be integrated in port breakwaters. The goal of the project is achieved through the design and development of a novel hybrid-WEC concept, consisting in a combination of an Oscillating Water Column and an OverTopping Device, specifically designed to be embedded into existing port breakwaters. Ultimately, it will bring the selected concepts to the next TRL. This paper presents an overview of the SE@PORTS project with a description of the several phases and tasks developed by the different international partners involved in the project.

Keywords—**Hybrid-WECs, innovative breakwaters, SE@PORTS project.**

I. Introduction

THE integration of Wave Energy Converters (hereafter WECs) into port defence structures represents a relevant advance in coastal engineering, aiming at changing the traditional design approach of conventional maritime structures. The integration would likely put these port infrastructures on the right track for their commitment to sustainable and environment-friendly development and operations.

The aim of the paper is to present a wide overview of the project SE@PORTS. The principal goal of the project is to assess the suitability of existing WECs for integration in port infrastructure, bringing the selected concepts to the next Technology Readiness Levels (TRLs). This can be achieved through an innovative Hybrid-WEC concept, specifically designed to be embedded into breakwaters at the Ports of Leixões in Portugal and Las Palmas in Spain. By combining the main current and well established principles in harnessing wave energy, the novel technology will enable to exploit the strengths and overcome the individual limitations and weaknesses of each technology separately, while presenting a breakthrough and efficient approach to harness the wave energy at ports.

The paper is organized as follows: Section I introduces the SE@PORTS project and the main goal of the present work; Section II is devoted to a short introduction on the difference between conventional port breakwaters and the novel technologies, consisting of the introduction of Hybrid-WEC devices into port defence structure; the detailed description of the SE@PORTS project is presented in Section III; two case studies of the application of Hybrid-WEC in port breakwaters are described in Section IV; in Section V the assessment tools for the correct design of Hybrid-WECs integrated into breakwater are described. Finally, the main conclusions are drawn in the last section.

II. Conventional and innovative port breakwaters

A. Traditional port breakwaters

Traditional harbour breakwaters are constructed to create sufficiently calm waters for safe mooring and loading operations, handling of ships, and protection of harbour facilities. These structures are also built to improve manoeuvring conditions at harbour entrances and to help regulate sedimentation by directing currents and creating areas with different levels of wave disturbance. Despite the different typologies and specific performance, and despite the effort made by engineers on the innovation in this field, the basic concept design of

ID number: #1724 - Wave hydrodynamic modelling.

SE@PORTS (Sustainable Energy at Sea PORTS) was supported under the OCEANERA-NET COFUND, Second Joint Call 2016 (proposal ID 325).

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coastal and harbour defence structures has remained almost unchanged, since the principal function of these structures is to protect the harbour or coastline simply by dissipating the energy of the incoming waves.

B. Innovative port breakwaters

Over the last two decades, one relevant innovation in the coastal engineering field was aimed at modifying the traditional design approach in coastal structure design. In detail, engineers and researchers operating mostly on maritime and coastal structure design proposed a solution to significantly reduce the costs of the WECs, integrating them into port breakwaters [1]. It is worth pointing out that wave energy technologies are still at the initial stage of research and it is difficult to correctly estimate the costs and performance of the devices as well as the rest of the installation. The largest part of current economic studies is often oversimplified, which consequently creates uncertainty and diffidence for investors. Due to these reasons, an extended part of the entire wave energy sector heavily relies on incentives and public financial support.

A solution to decrease the cost of these technologies consists of the development of WEC devices that can be totally integrated into existing or new port infrastructures. These innovative structures still have their principal function of sheltering a location from the action of waves, i.e. the coastal and harbour protection, but with important benefits for the energy production due the inclusion of a WEC.

The integration of a WEC into a new breakwater has several advantages [2]-[3] such as the low construction costs, considering that the breakwater would be built regardless of the inclusion of the WEC device (cost-sharing). Furthermore, the access for the construction, installation and maintenance are much easier compared to other standalone WEC devices located offshore. On the other hand, the amount of energy extracted with these new technologies is small compared to those located in deep sea. Moreover, not all breakwaters are appropriate and feasible for the integration, depending on their type, geographical location and orientation with respect to the incident waves.

C. Typologies of WECs integrated into breakwaters

Although several different types of WECs are under development, only two typologies are currently considered appropriate to be entirely embedded into traditional coastal defence structures: the Oscillating Water Column (hereafter OWC) and the OverTopping Device (hereafter OTD).

The OWC is one of the oldest WEC concepts and one of the few devices that reached the prototype development stage. It consists of a chamber submerged in the seawater and opened below the water surface such that waves can enter into the box. An air duct with an air turbine connects the chamber to the atmosphere (see Fig. 1). Under the wave motion, the air in the chamber is alternately compressed and decompressed, creating a bi-directional flow in the duct. This flow drives a self-rectifying turbine connected with a generator for the electricity production. This class of WEC is the most extensively studied with the largest number of existing developed devices. This represents one of the main reasons for integration into breakwaters.

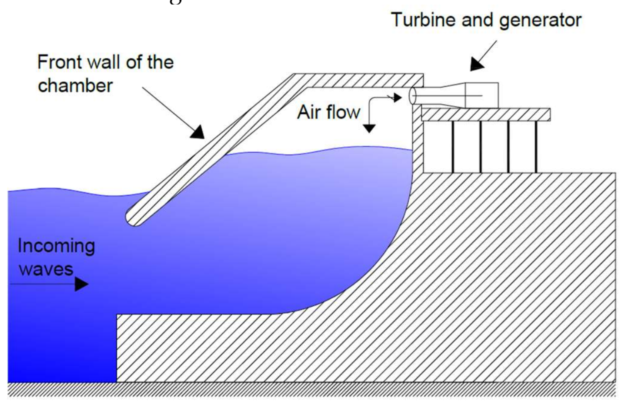

Fig. 1. Cross section of a generic shoreline OWC device [4].

An advantage lies in its relative simplicity, being a rigid structure with the only moving part represented by the rotor of turbines. Moreover, it is not actually the seawater itself that moves the turbines, thus the latter is never exposed to water, which considerably extends the service life of the equipment. Finally, the integration is probably the easiest solution from the economical, constructional and operational point of view. In order to promote the diffusion of this technology, it is important to maximize both the conversion efficiency of the device and its survivability/operability in severe wave conditions. The OWC device could have a limited operability in highly energetic sea states, due to the possible problems (loss of efficiency or damage) with the air turbine caused by both excessive air pressure in the chamber and green water droplets/jets reaching it. Relief valves are sometimes deployed to regulate excessive air chamber pressure in OWC devices [5]-[6], thus dissipating this excess of energy. It has to be stressed that the use of OWC into existing breakwaters might change the original cross-section of the breakwater, which may have a relevant impact on the global hydraulic performance of the structure in terms of wave reflection, wave overtopping and wave stability. For instance, at the Port of Mutriku (Spain) [16]-[17], despite the original indication, a significant difference in cross-section was introduced to accommodate an OWC system. The original project was a rubble-mound with a concrete wall running along the entire length, while the installed pilot plant consisted of a vertical caisson-type. Therefore, the hydraulic performance of the cross-section with the OWC could be highly different compared to the remaining section of the breakwater with conventional structure.

Contrary to the OWC, a breakwater-integrated OTD device utilizes a frontal sloping plate that leads the incident waves to overtop into one [7]-[8] or more reservoirs [9], placed at a level higher than the seawater level. Fig. 2 shows the cross-section of an overtopping device named OBREC (Overtopping Breakwater for Energy Conversion) with one ramp and a reservoir behind it [4].

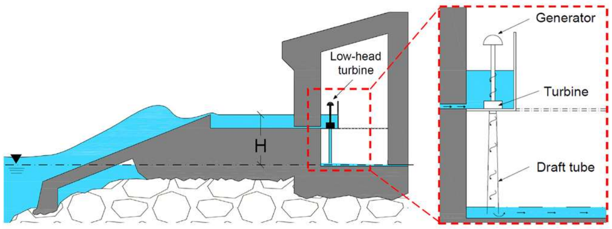

Fig. 2. Cross section of the OBREC device installed in Italy [4].

Due to the hydraulic head between the reservoir level and the seawater level, the potential energy of the stored water is converted into mechanical and electrical energy, passing through very low head hydraulic turbines coupled with generators, located in a machine room behind the structure.

WECs based on the overtopping principle have some well-recognized advantages:

- they offer the possibility to store the wave energy, discontinuous in its availability, in the form of relatively stable static energy, which is easier to use;
- the low-head hydraulic turbines used for the energy conversion, such as the Kaplan turbines, have the benefit of being a mature technology used for many decades for power generation.

However, it is worth mentioning that the energy production occurs only when the waves overtop the frontal ramp and fill the reservoir, which means that the energy production occurs only during relatively high energetic sea state characteristics.

Furthermore, regarding the instrumental apparatus adopted for the energy conversion, currently only limited tests have been carried out on a pilot plant in order to evaluate the performance of low-head turbines applied to this technology [4]. Consequently, the studies carried out on the different overtopping devices [10] to investigate their performance in terms of energy production have been conducted assuming a theoretical efficiency of the Power Take-Off (PTO) system.

D. *Existing full-scale devices*

Because of the complex geometry of the WEC-integrated breakwater, research on full-scale prototypes exposed to real environmental conditions is required in order to increase the knowledge of the hydrodynamic wave-structure interaction and carry out a reliable study of the energy production. It is clear that the commercialization step of these non-conventional breakwaters can be reached only when the reliability of the structure can be demonstrated via field monitoring under extreme wave conditions.

Although the first example of this technology has been proposed in the early 1990’s in Japan at the port of Sakata [15], only three WECs integrated into breakwaters are currently in operation, all of which are located in Europe. The first two devices consist of OWC systems integrated into breakwaters situated at the port of Mutriku in Spain [16]-[17] and the port of Civitavecchia in Italy [18]. It is worth noting that, despite the relatively low efficiency, the Mutriku plant is the only commercial OWC-integrated breakwater that regularly supplies electricity to the grid, reaching a milestone in 2015 with its first GWh of electricity supplied to the national grid [19].

The most recent full-scale WEC embedded into a rubble-mound breakwater has been installed at the port of Naples in Italy [20]-[21]. This prototype represents the first non-conventional breakwater at full scale that exploits the overtopping phenomenon in order to capture energy from waves and to convert it into electricity [22]. The pilot plant is under monitoring since 2016. The first year of monitoring (2016-2017) was aimed at demonstrating the ability of the PTO system to produce electricity. In the machine room, three low head turbines were located in order to convert potential energy (water stored in the reservoirs) into kinetic energy and then in electrical energy by means of a generator. The total nominal power installed was 2.5 kW [4]. Currently the monitoring activity is focused on the wave-structure interaction study with pressure transducers installed on the different parts of the prototype.

III. THE SE@PORTS PROJECT

E. *General description*

Seaports are infrastructures with substantial energy needs – e.g. for crane operation, lighting, ship demands – and responsible for air pollution problems and other relevant environmental impact. The commitment to sustainability motivates many ports all around the world, and particularly in Europe, to harness renewable energy resources. For instance, in 2017 the International Association of Ports and Harbors (IAPH) decided to set up a World Ports Sustainability Program (WPSP) [25]. This program is intended to enhance and coordinate future sustainability efforts of ports worldwide and foster international cooperation with partners in the supply chain, and is guided by the 17 United Nation Sustainable Development Goals (SDGs) [27]. The WPSP aims at empowering port community actors worldwide to engage with business, governmental and societal stakeholders in creating sustainable added value for the coastal communities and wider regions in which their ports are embedded. More specifically they will focus on five practical areas:

- developing robust infrastructure, ready to face the challenges of the future;

- climate and energy, with the emphasis on initiatives that contribute to achieving the objectives of the Paris climate agreement [27];
- societal integration, by improving relations between ports and cities;
- safety and security, including cyber-security;
- rolling out transparent, ethical policies and management.

In this vein, the integration of WEC devices in port breakwaters might be a realistic solution to put these critical infrastructures on the right track in terms of commitment to the SGDs and move port development and operations in a more environment-friendly direction.

The project SE@PORTS, acronym of '*Sustainable Energy at Sea Ports*', is developed by International Marine and Dredging Consultants (IMDC) based in Belgium, with international partners from Portugal and Spain under the 2nd Joint Call of Ocean Energy ERA-NET Co-fund (OCEANERA-NET COFUND) initiative. The latter represents an initiative of national and regional government agencies from across Europe, which has received funding from the European Union under the Horizon 2020 Programme for Research and Innovation. The aim is to coordinate support for research and development in ocean energy and to encourage collaborative projects that tackle some of the key challenges identified for the sector as it progresses towards commercialisation.

In detail, the partners involved in the project are currently investigating the integration of WECs in port breakwaters with three main objectives:

- assess the suitability of existing WECs (proven concept TRL 3) to be integrated in port infrastructure and bring the selected concepts of WEC's to the next TRL;
- demonstrate the win-win solution of incorporating WEC devices into port infrastructure;
- provide end users with key technical requirements and tools to best reduce and assess the risks and barriers of that incorporation.

The project includes various Work Packages (WPs) focused on both research as well as commercialisation. To realize the SE@PORTS ambition, it was necessary to characterize the case-study sites (WP2). As case studies sites, the Port of Las Palmas in Gran Canaries (Spain) (Fig. 3) and Port of Leixões in Porto, (Portugal) (Fig. 4) have been chosen. The present research consisted of:

- the detailed offshore site characterisation of the Port of Las Palmas in Spain and the Port of Leixões in Portugal;
- the characterization of the wave conditions at the toe of the structures with the use of advanced numerical modelling for wave transformation from deep to shallow water,
- assessment of the efficiency (wave-to-wire efficiency) of the WECs related to the available wave energy in the specific site;
- physical and numerical modelling in small scale for the evaluation of the hydraulic and structural performance of the various alternatives examined.

Fig. 3. View of the Port of Las Palmas in Gran Canaries (Spain).

The obtained results are then integrated into a work package dedicated to commercial aspects, including the preparation of a structured framework for end users to best reduce and assess the risks and barriers of the technology for the integration within port infrastructure, and the design assessment and engineering evaluation.

Within the SE@PORTS project, IMDC is also developing an assessment tool to predict the energy production of these Hybrid-WECs when integrated within a port breakwater. The aim is to apply the energy yield assessment tool to the two case study site ports, the rubble-mound north breakwater of the port of Leixões and the Nelson Mandela vertical breakwater of the port of Las Palmas. As described in the following section, the Hybrid-WEC represents a concept that combines an OWC device [2] with either a Seawave Slot-Cone Generator (SSG) [23] or the OBREC device [24], depending on the number of ramps and reservoirs considered for the OTD device.


Fig. 4. View of the Port of Leixões in Porto, (Portugal).

F. *The Hybrid-WEC systems*

This section describes and includes the design of innovative solutions of Hybrid-WEC systems, derived from the combination of the existing and already proven WEC technologies. In detail, various alternatives of hybrid systems are analysed. In this paper only two of these alternative are analysed in detail.

The first innovative Hybrid-WEC concept is based on the combination of a frontal OWC and an internal OTD, as shown in Fig. 5.

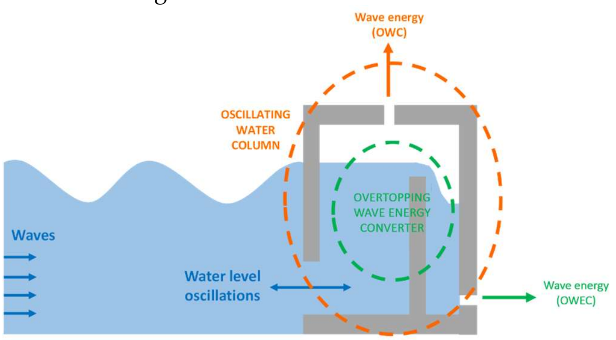

Fig. 5. HWEC concept based on the combination of a frontal OWC and internal OTD.

The OWC chamber is modified by placing a vertical wall inside. The OWC works in the conventional way, but when the water level inside the chamber crosses the wall height, the water overtops it, flowing into a reservoir where it is temporarily stored. When it reaches a certain level, this stored water is sucked by low head turbines coupled with generators in order to convert energy into electricity. The electricity is generated in two different ways: electricity generated because of the air compression due to water level oscillations inside the chamber (OWC), and electricity generated from the water stored in the reservoir (OTD). Moreover, since it is not a complex structure, this concept might be easily adaptable to existing breakwaters. It is worth mentioning that a similar concept has been recently proposed by [28], which investigated the effectiveness of this kind of WEC carrying out physical scale model tests under regular wave conditions and different wave heights, periods and steepness.

An alternative to the above design is presented in Fig. 6. The multiple-reservoir overtopping structure is integrated in front of the OWC chamber. Consequently, as in the first alternative, it is possible to generate energy in two different ways. For the case of the OTD device with multiple chambers, the water stored in the reservoir, after passing through the turbine, flows through a duct and is then discharged in front of the hybrid structure. In order to prevent the incoming wave from entering inside this duct, the flap opens only in one direction.

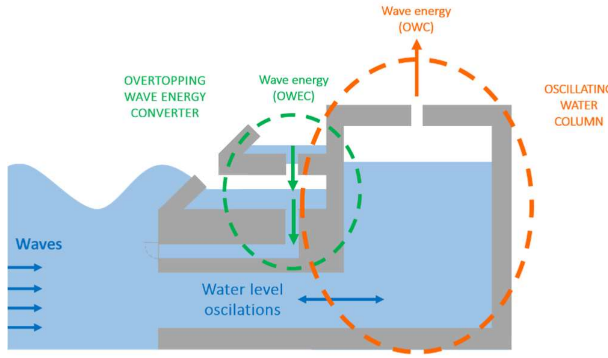

Fig. 6. HWEC concept based on the combination of a frontal multi-chamber OTD and internal OWC.

Other concepts evaluated were the result of the integration of flexible membranes with OTD and OWC devices.

G. *Selection of the technologies*

The main objective of the project is to develop a cost-efficient and flexible Hybrid-WEC concept for harnessing wave energy at seaport breakwaters, while ensuring system reliability and robustness adequate to address the needs of different locations and sea states.

Therefore, seven parameters has been taken into account and compared for different concepts presented in Section F, in order to have a clear picture of the most suitable concept:

- cost effectiveness
- breakwater construction
- level of maturity
- scalability/modularity
- maintenance
- reliability
- innovation

In order to decide which concept is the most suitable and meets the requirements of this project, a decision matrix has been developed with these parameters, which play a crucial role in the design and development of the Hybrid-WEC concept. These parameters are weighted: the more important and relevant to meet the goals of this project, the higher its weight in the final decision. The concept with the highest weighted average has been finally chosen for the next phase of the project. Eventually, the combination of the OTD and OWC devices appears as the most suitable to meet the objectives of the SE@PORTS projects and hence it has been further studied in detail to be integrated into the breakwater. It has to be stressed that the use of the flexible membrane combined with the OWC and OTD obtained the lowest score in terms of level of maturity and cost effectiveness when compared with the other alternatives.

IV. CASE STUDIES

H. Preliminary design

As already described, the SE@PORTS project is derived from the possibility of installing Hybrid-WECs in the Ports of Leixões (Portugal) and Port of Las Palmas (Spain). The intent is to extract wave energy in order to create a new supply source that can help tackle the port's energy demands. Therefore, a detailed wave characterization and wave energy assessment in the two specific sites has been carried out. The collected information was used to characterize the harbour's facilities and structures, as well as the local bathymetry and sediment transport patterns, wind regime, wave climate, currents, energy demand and relevant environmental parameters.

Understanding the environmental impact of the already existing structures and the results of the mitigation/compensation efforts that have been made by the port authorities represent an important source of knowledge for the SE@PORTS project. Providing a clean and renewable source of energy through the conversion of energy from waves must be a process that also contributes to an improvement of the local environmental conditions, otherwise it will have a negative footprint.

The Port of Leixões and the Port of Las Palmas were selected as case studies of the SE@PORTS project for several reasons. On the one hand, these ports are protected by structures with a good exposure to sea waves. On the other hand, the harbour facilities present high electricity consumption that can be, at least, partially ensured by the harnessed wave energy. In addition, the different characteristics of the breakwaters as well as their exposure to the marine environment make them representative of the main structures used in Europe to protect harbour infrastructure. Based on the information gathered after the detailed study of the overall characteristics at the two sites, a preliminary design of the Hybrid-WECs embedded into port breakwaters has been developed.

For the Port of Las Palmas (see Fig. 3), a vertical structure with a frontal OWC and internal multi-chambers OTD is designed, replacing part of the original cross-section of the Nelson Mandela vertical breakwater. As can be observed in Fig. 7, three overtopping levels have been defined for low, medium and high water level elevations. This allows the WEC to take advantage of a large range of spectral wave characteristics and water level conditions. The preliminary design of the device does not take too much caisson space or make any considerable changes in the caisson geometry, so the breakwater stability is not supposed to be considerably affected. This statement will be validated in the next step after the analysis of the data obtained with the numerical and physical model tests.

Regarding the Port of Leixões in Portugal (see Fig. 4), the detailed analysis of the port infrastructure combined with the characterization of the wave climate in front of the breakwater allowed to propose a preliminary design for the Hybrid-WEC integrated into breakwater, under the hypothesis of an extension of the North Breakwater. The original extension design is, as for the preceding structure expansions, based on a rubble-mound solution with two different sections for the trunk and the roundhead of the breakwater, representing the sections into which the new device is embedded.

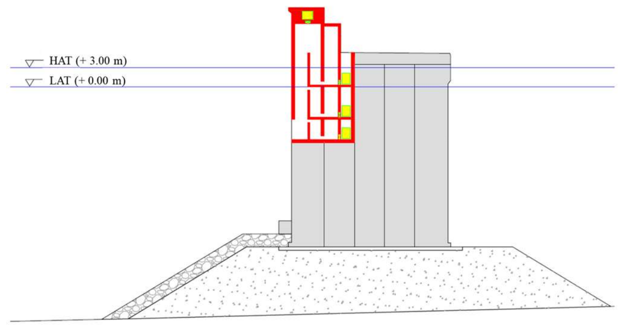

Fig. 7. Breakwater adaptation to incorporate the Hybrid-WEC in the Nelson Mandela at the Port of Las Palmas in Spain (preliminary design).

The integration of the Hybrid-WEC geometry into the Port of Leixões' North Breakwater extension solution involves an adaptation to the design of such solution, the local bathymetry and wave climate and the OWC/OTD concept selected for the SE@PORTS project. Taking into account the restrictions and limitations inherent to these conditions, a solution based on the design presented in Fig. 6 was selected and adapted to the case study, as shown in Fig. 8.

Several considerations were involved in the design process:

- the interior section of the breakwater is not changed after the integration of the Hybrid-WEC;
- multiple reservoirs are considered for the OTD devices mostly due to the considerable tidal range (around 4 m), and the high energetic wave climate in front of the structure.

It is important to note that the values of crest levels and dimensions presented in Fig. 8 serve as a reference only and are not definitive. In detail, they are based on the North Breakwater's extension project and the studies conducted by [29]. As shown in Fig. 8, the NM (Mean Sea Level) is located 9.75 metres above the base of the horizontal duct. The goal at this stage was to determine the optimal conditions of the multiple-chamber OTD and OWC, individually, for the local wave climate and, from the obtained results and conclusions, assess the optimization of the Hybrid-WEC solution in the next stage.

It must be stressed that the detailed design for the integration of the two proposed solutions into the Port of Leixões and Port of Las Palmas has required both numerical and physical modelling, considering different incident wave conditions and various geometries. More info on these test campaigns are described in the next section.

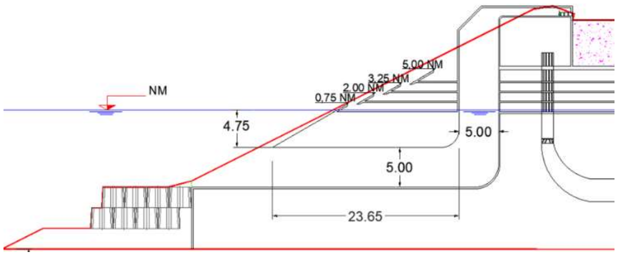

Fig. 8. Cross-section profile of the Hybrid-WEC proposal for the Port of Leixões' North Breakwater extension (preliminary design).

I. *Numerical and Physical Modelling*

The analytical studies on the different configurations served as a first approximation to the problem and a preliminary design of the Hybrid-WECs integrated into breakwaters. The next phase consisted of a detailed analysis of the performances of the innovative breakwaters using numerical and physical modelling.

In detail, a numerical study have been performed to analyse the problem more realistically and design the Hybrid-WEC for different geometries and sea states. The analyses have been carried out for two breakwater typologies: vertical breakwater in the case of Las Palmas Port, and rubble-mound breakwater in the case of Leixões Port. 2D numerical models were used for both analyses.

In the case of Las Palmas Port, the Spanish partner (the *Environmental Hydraulic Institute "IHCantabria"*) adopted two numerical models: IH2VOF [30]-[31], a CFD model for the analysis of the hydrodynamic performance of the OTD integrated into vertical caisson, and a Boundary Element Methods (BEM) solver, called NEMOH, to characterize and design the OWC, adopting a technique successfully used in the past [32]. The combined use of the two models has been used for the geometrical optimization of the innovative breakwater at the Las Palmas Port, considering the specific wave climate in front of the structure. The detailed analysis of the numerical investigation conducted by IHCantabria is going to be published.

In the case of Port of Leixões, the Portuguese partners, the *Instituto Nacional de Estadística y Geografía (INEGI)* and the *University of Porto (UPorto)*, used Ansys FLUENT [33] to investigate the performance of the innovative breakwater. From the numerical analysis, the dimensions of the integrated OTD and OWC devices have been defined, and the characterization of the breakwater overall behaviour has been analysed, considering the local wave climate in front of the Port of Leixões. The detailed numerical analysis that has been carried out, allowed to define every detail of the Hybrid-WEC performances, including the ones regarding PTO system of the energy conversion.

The results of the numerical modelling adopted in this project are currently used to define the geometrical configurations tested in laboratory in the next phase. Therefore, the data gathered during the experimental campaigns have been used to firstly validate the results of the numerical model and then to extend their applications, for a better understanding of the wave-structure interaction and an accurate optimization of the Hybrid-WEC integrated into the breakwater at the two selected sites.

Recently, Rosa-Santos et al., [34] investigated the influence of the integration of a Hybrid-WEC module on the stability and functionality of a rubble-mound breakwater with a particular geometry proposed for the extension of the North breakwater of the Port of Leixões. Results indicated that the inclusion of a combined solution (OWC + OTD) into a rubble-mound breakwater can increase the hydraulic performance in terms of wave overtopping at the rear side of the structure when compared to a conventional geometry. In detail, the innovative breakwater seems to significantly reduce the mean wave overtopping, although this relevant reduction led to a slight increase of the reflection coefficient compared to a traditional structure. Additional tests with new wave conditions are desirable to confirm and extend the obtained results and conclusions, which seem very favourable to the integration of this kind of Hybrid-WEC into harbour breakwaters.

V. ASSESSMENT TOOLS FOR HYBRID-WEC INTEGRATION INTO PORT BREAKWATERS

The final stages of the SE@PORTS project (WP5) consist of the definition of assessment tools and guidelines for a correct integration of these innovative Hybrid-WECs into conventional breakwaters.

The principal goals of this work are to provide:

- technical requirements for integration of WECs in port breakwaters (D5.1);
- assessment tools to predict the energy production once operational (D5.2);
- an application of the tools and guidelines for the two test cases at the Ports of Leixões and Port of Las Palmas (D5.3);
- a market scoping exercise at European scale in order to find the optimum selection of the most suitable sites for these novel technologies (D5.4).

At the time of writing the present paper, only the Technical Requirements (D5.1) and the Market Scoping Study (D5.4) have been performed. The description of the results of these two sections will be briefly reported in the next two paragraphs.

J. *Technical requirements*

The aim of this work is to describe the different technical requirements for the integration of WEC systems into port breakwaters. Furthermore, rule-out criteria were identified based on technology, specific natural and socio-economic conditions, and infrastructure setting (existing vs. new breakwater or vertical caisson vs.

rubble-mound breakwater, etc.). These rule-out criteria aimed at guiding the end users in their quest to procure a win-win situation, cost-sharing and transition to a low-carbon energy source, through the implementation of a WEC device into a harbour breakwater.

The technical requirements can be summarized as follows:

- knowledge required for preliminary design;
- design requirements;
- construction requirement;
- operation and maintenance requirements;
- decommissioning and/or removal.

1) Knowledge required for preliminary design

Firstly, the knowledge required for preliminary design of these structures are analysed. In detail, functional requirements (performance indicators) are presented for the breakwater structure, the WEC integrated into it and the port infrastructure. It is clear that the most important goal for the integration of a WEC device into harbour breakwaters is to guarantee the functionality of the structures considered as harbour protection. The innovative breakwater still has the primary function of harbour protection, dissipating the wave energy and/or reflecting it back into the sea. Therefore, the principal functionality aspects and requirements are similar to the ones of a traditional harbour defence structure.

As a part of the knowledge needed for the preliminary and detailed design of a WEC integration into new or existing breakwaters, the required information regarding the physical conditions are investigated. It is important to stress that these requirements are very similar to the ones traditionally considered for conventional harbour structures, such as the climate and metocean analyses, the morphodynamic condition, the bathymetry, topography and soil condition, seismic activity and the presence of existing infrastructure [35].

2) Design requirements

Regarding the design of the innovative breakwater, due to the non-conventional geometrical characteristic of the WEC-breakwater system, generally speaking, the design formulas used for the traditional harbour defence structures need to be adapted. The presence of the WEC device might change the geometrical configuration of a traditional breakwater, which in turn affects the hydraulic and structural performance of the breakwater in terms of wave reflection, wave overtopping, wave loading as well as local and global stability [4]. Therefore the design requirements are investigated and divided into hydraulic performance, hydraulic stability, structural stability and geotechnical stability.

3) Construction requirements

The integration of the WEC into a new or existing infrastructure is a delicate task due to the lack of deep experience in this aspect. In fact, only few WEC prototypes have been integrated at real scale into harbour structures, and none of them was exempt from technical problems. Construction requirements are therefore investigated for the correct integration of a WEC into a breakwater. These requirements highly depend on whether the breakwater structure is newly constructed (i.e. construction or expansion of harbour) or it is existent and only adapted for the integration of a WEC. The integration is also function of the breakwater type (rubble-mound breakwater, vertical structure, horizontal or vertical composite breakwater, etc.).

4) Operation and maintenance requirements

The work also includes the study of the requirements and procedure for the operation and maintenance activity necessary to recognize potential problems and to take appropriate actions to assure the project continues to function at an acceptable level. Due to the lack of a deep knowledge and experience of the wave-structure interaction and hydraulic behaviour of a WEC integrated into harbour breakwaters, an extensive and specific monitoring and maintenance plan needs to be planned.

The monitoring can be executed constantly or periodically, with particular attention during and after extreme events to provide information required for an updated evaluation of the WEC/breakwater integrity such that the appropriate maintenance action can be carried out. Based on the outcome of the inspection and monitoring evaluation, a decision for maintenance actions has to be taken. Therefore, an investigation of the possible damage reasons as well as the activities to carry out for the breakwater and WEC reparation and rehabilitation is included in the analysis.

5) Decommissioning and/or removal

Finally, several reasons that can suggest or lead to a decommissioning and/or removal of the WEC device from the breakwater are investigated, as well as the description of the uncertainties and rule-out criteria with several cases where the integration of a WEC system would not be feasible.

K. Market scoping

For the development of Hybrid-WECs and the optimum selection of the most suitable sites, the detailed assessment of the wave energy resource is one of the most important aspects to consider.

Over the last 20 years, many studies have been carried out aimed at assessing the global and local wave energy resource around the world. Based on a detailed review of recent studies dedicated to this field, information regarding the annual average wave power per unit length in kW/m, the seasonal wave power as well as the spatial and temporal variability of the available power are provided for most of the European countries. Based on the study, the most energetic regions in Europe are the ones with their coasts facing the Atlantic Sea, i.e. Portugal, the Northern part of Spain (Asturias, Galicia, Cantabria and Basque Country) and the western coasts of

France, Ireland and UK, where the annual average wave power ranges between 30 to 70 kW/m, from south to north. However, it is important to stress that the primary discriminating factor for the development of a Hybrid-WEC project is the intrinsic temporal variability of the available resource: it could be much more problematic to develop a Hybrid-WEC in a highly energetic environment characterized by a strong temporal variability rather than in an environment characterized by a medium energy content but showing a moderate inter- and intra-annual variability [12]. In this regards, the perspective of also developing WEC devices in particular areas (defined in literature [36] as "hot-spot") of the Mediterranean Sea or North Sea can still be considered very attractive, due to the relevant reduction of the initial cost of the structure.

Another relevant and complementary aspect to take into account for the study of a suitable location of a WEC along the European coastal areas is the accurate analysis of the proactive public energy policies, which can offer a substantial contribution to accelerate the innovation, increase the competitiveness and shorten the time-to-market of WEC devices. Nowadays, a new strategic European policy on waste management and reduction of emissions and the continuing increase of the oil price, has led the international community to invest in wave energy technologies, with several public energy policies. In the European Union, following the launch of the Ocean Energy communication in 2014 and the subsequent establishment of the Ocean Energy Forum [37], the industry has been asked to convene to identify common actions to support the technology for the final commercialization phase. More recently, the inclusion of ocean energy in the new Strategic Energy Technology Plan (SET-Plan) of the European Union has highlighted the European leadership in the sector and the need to improve the performance of WEC devices throughout the innovation, supply and value chain. In line with the SET-Plan communication, the European Commission, Member States and stakeholders have recently defined a "Declaration of Intent for Ocean Energy" [38] setting out ambitious targets for ocean energy technologies to make a significant contribution to the future European energy system. The Strategic Roadmaps developed by the Ocean Energy Forum and by the European Technology and Innovation Platform for ocean energy have identified key actions for making ocean energy a commercial reality in the EU and on a global stage [39]-[40].

VI. CONCLUSIONS

Over the last two decades, an original innovation in the coastal engineering field consisted of the integration of WECs into conventional breakwaters, modifying the traditional design approach in coastal structure design. This paper presented an overview of the SE@PORTS project. The aim of the project is to contribute on the design and development of novel Hybrid-WEC, consisting into the combination of existing WEC device, into existing or new port breakwater. The different phases of the project are described, with the inclusion of specific case studies at the Ports of Leixões (Portugal) and Port of Las Palmas (Spain).

ACKNOWLEDGEMENT

SE@PORTS (Sustainable Energy at Sea PORTS) was supported under the OCEANERA-NET COFUND, Second Joint Call 2016 (proposal ID 325).

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