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Italian wave energy: state of the art and challenges of exiting full scale pilots

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Abstract— **In this review, the experience made during the last decade by Italian researcher and engineers of full-scale pilots of wave energy device is described. Focus is on the development of three prototypes called REWEC3, ISWEC and OBREC. The REWEC3 (REsonant Wave Energy Converter) is the first worldwide application in the Med Sea (and one of the biggest in the world) of an innovative WEC, which improves the classical "Oscillating Water Column" technology. The full-scale prototype has been installed at the Port of Civitavecchia. The ISWEC, Inertial Sea Wave Energy Converter, is a device based on a floating body slack-moored to the seabed, using a gyroscope as a reference frame to produce electric power. The real scale pilot was installed offshore of Pantelleria Island (South Italy). The OBREC, Overtopping Breakwater for wave Energy Conversion, represents the world's first overtopping WEC totally integrated in an existing breakwater. The full-scale pilot is operative at the Port of Naples.**

The research of low marginal cost and low marginal environmental impact coupled with very high potential for electricity production represents the distinguishing feature and the most important challenge of the Italian research on the marine energy. The three pilots correspond to three different ways of solving such trilemma.

Keywords— **full scale prototype, real wave climate, wave energy converter**

I. Introduction

THE efforts of Italian engineers and researchers in the wave energy sector have been very revealing during the last decade. Navigating the landscape of Italian wave energy, several technologies have been conceived and developed. Despite the effort to improve these technologies, one of the greatest issues remains the economical aspect and the reliability. The lack of knowledge of the behaviour under real storm condition, as well as of the actual impacts and benefits of the various options and scenarios leads to conflict, negative stakeholder perceptions, and project abandonment for a lot of projects.

Nowadays, very few wave energy converters (WECs) are developed in full scale, but no one in the final commercial stage.

In this work, three real-scale prototypes are highlighted: the REWEC3 (REsonant Wave Energy Converter), the OBREC (Overtopping Breakwater for wave Energy Conversion) and the ISWEC (Inertial Sea Wave Energy Converter). The three pilot plants are located in the Tyrrhenian Sea (Fig. 1). Thanks to these prototypes, Italy is establishing a leading position on the world stage.

The relevance of these technologies stems out after more than 10 years of analytical, numerical, laboratories experimental research and field monitoring campaigns conducted by the three proposing research units.

The main purpose of the three pilots is carried out experiments in order:

- to verify and quantify the predicted energy production capability;
- to quantify the technically acclaimed and universal indicators of energy production;
- to assess their feasibility, industrialization and standardization;
- to assess their applicability and economical convenience, in a comparative manner.

Indeed, often "more commercial" devices developers do not disclose their real energy production data with proper scientific methodology and transparency. It is intention of the proposing each research units to pursue a pure academic approach by publishing and sharing production data and indicators clearly defined and fully explained. The global efficiency of the systems will be provided by systematically reconstructing:

- capture factor: ratio of produced electricity to incoming wave energy;

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• power matrix: energy rate production as a function of the sea state main parameters (ensemble height and period measures);

• reflection coefficient: ratio of reflected to incident wave (hydraulic performance).

All of the above main indicators will be compared with theoretical predictions and numerical simulations. Hence, the robustness of the modelling tools will be established, a fundamental step in the industrialization process. Finally, investments, maintenance costs and feasibility of each prototype will be evaluated and compared among other existent devices, whereas available.

In this paper, Section 2 is devoted to the description of the REWEC3 and OBREC devices, falling within category of "breakwater-integrated wave energy converters". Section 3 provide an overview of the ISWEC, the most advanced prototype for offshore application. Finally, some conclusions are drawn.

Fig. 1. Tyrrhenian Sea map showing the location of REWEC3, OBREC and ISWEC pilot plants.

II. BREAKWATER-INTEGRATED WITH WEC

Coastal engineers design coastal defences and harbour breakwaters with the purpose of dissipating incoming wave energy. Dissipation is obtained mainly by wave breaking and porous flow in the mound and/or partly reflecting the wave back to the sea and transmission into the harbor due to penetration and overtopping. Innovation in coastal engineering design is starting to move from this traditional approach to a new concept of capturing the wave energy [1]. In the following, two innovative breakwaters integrated with wave-energy converters, representing the state of the art of Oscillating Water Colum and Overtopping Device respectively, are presented.

A. ReWEC3

The construction of the first prototype of the ReWEC3 (Resonant Wave Energy Converter) [2,3] device, denominated also U-OWC, started in 2012 in Italy. The device was integrated into the vertical breakwater of the Civitavecchia Port (Fig. 2). This prototype represented, at present, the first full-scale WEC-integrated breakwater in the Mediterranean Sea and one of the biggest in the world [4]. The Civitavecchia works involved the construction of 17 caissons with 124 multiple independent active chambers available for the exploitation of incident wave energy, for a total length of about 495m. A view of part of the new breakwaters built in Civitavecchia with the REWEC3 caisson technology is shown in Figure 2, where the status of the works in May 2014 and September 2016 are shown. The cost of the caissons was funded to the Port Authority of Civitavecchia by the Italian Government via CIPE, "*Legge Obiettivo*" [5] with the main objective of absorbing the incident sea waves for reducing the amplification of the wave motion in front of the vertical breakwater and realizing a low-reflective structure. This is a relevant aspect of the ReWEC3 caisson because the technology was proposed as a valid alternative of a traditional caisson. Furthermore, adding a ReWEC3 to a breakwater during the design stage would increase the cost for the structural change of about 5% of the total cost [6].

In the last years, a monitoring system was installed in two REWEC3 chambers of the plant, within the activities of the project "Study for the development of the green mobility in the port of Civitavecchia through the implementation of the pilot technology REWEC3 - 2013-IT-92050-S" funded by the EU's TEN-T Programme. The chambers were equipped with sensors measuring water and air pressures. The instrumentation allows investigating the ReWEC3 dynamics pressure, fundamental for calculating the average absorbed wave power, and obtaining all the essential information for the energy performance. Results show that the device absorbs about 50-70% of the average incident wave power, with some specific records where the absorption coefficient ranges from 70% to the 90% [7, 8]. Only one traditional Wells turbine, without any optimization for the specific location, was installed on one chamber. The monitoring activity, conducted for about 2 years, provided an estimate of energetic performance of the device in term of wave energy absorption and a validation of the dynamic response of the plant [8, 9]

Assuming that the device is fully equipped with Wells turbines of around 20 kW for each chamber, a preliminary study [6] indicates that the expected annual average electrical power per unit length delivered by the ReWEC3 in Civitavecchia Port is about 0.55 kW/m, being the annual average power for unit length in front of the Civitavecchia breakwater is 2.1 kW/m [4]. Direct comparison between performance indicators of the Mutriku OWC installed in the North of Spain and the ReWEC3 plant in Civitavecchia shows that the ReWEC3 device might be able to convert a significantly larger percentage of the incident wave power into electrical power. Indeed, the annual average power for unit length in front of the Mutriku breakwater is about 11 kW/m per year and the annual average delivered electrical power is estimated about 0.68 kW/m [10].

New investigations are carried out with the objective to select and optimize a turbine/generator set coupled with a

ReWEC device installed in breakwaters located in the Mediterranean Sea [11], such as the Port of Civitavecchia, where the first prototype of U-OWC has been realized, or the Port of Salerno or Porto delle Grazie of Roccella Jonica (Italy), that will be the next realizations of the technology.

Fig. 2. REWEC3 prototype at Civitavecchia port. First panel (on the top): May 2014. Second panel (on the bottom): September 2016

B. OBREC

The full-scale of the OBREC was installed in 2015 in the San Vincenzo breakwater in Napoli (Italy), substituting a part of the seaward armour layer for a total area of ~75 m2 [12]. The prototype consists of a prefabricated frontal ramp, a basin and machine room cast in situ, whose bases are located above the sea water level. The prototype consists of two different geometrical configurations, as shown (Figure 3): OBREC_RS-Lab (Real Scale laboratory) and OBREC_NW-Lab (Natural Waves Laboratory). The value of crest freeboard, Rr, for the OBREC_RS-Lab was intended to capture the higher power generated by the higher waves. In fact, considering that the lowest nominal hydraulic head for commercial low head Kaplan turbine is 1.4-1.5 m, a ramp crest of 1.78 m (values referred to the Mean Low Water) has been selected. In the definition of Rr for the OBREC_NW-Lab, the mean runup of the most frequent wave (i.e. Hs=0.79 m) has been considered.

Fig. 3. OBREC prototype in the port of Naples.

The name Real Scale indicates the site-specific considerations made for that ramp crest; Natural Waves Laboratory indicates the intention to test a more general cross-section providing results easily exportable for more energetic sites [12]. These two configurations are similar except for the crest height of the ramp and, consequently for the values of reservoir width.

The intention is to investigate the hydraulic performances and loading on the prototype, using it as a large-scale model in order to gather field data for estimation of energy performances on more energetic coastal area [13, 14]. The estimated annual wave power per meter length in front of the device is relatively low (less than 2.5 kW/m), with a very long period of calm sea state and high seasonal variability of the wave conditions. Despite what one may think, these features are positive considering the field monitoring requirements, for which calm conditions are necessary to allow safe installation and maintenance of instruments (e.g. pressure transducers, overtopping tank, accelerometers, etc.).

The challenge of the two years of monitoring was to demonstrate the feasibility and structural reliability, evaluating the overall performances, particularly during the occasional storm conditions [15, 16]. Please note that, contrary to existing OWC devices developed in full-scale, the OBREC installed in Naples is entirely integrated into an existing rubble mound breakwater, having the same crest height and frontal slope. The relations proposed by Iuppa et al. (2016) [17] for the hydraulic response of the device, those proposed by Contestabile et al. (2017a) [14] for the loading acting on the structure and Allsop et al. (1997) [18] for a conventional structure, were used to design the full-scale device. The OBREC is supplied with an instrumental system designed to measure the wave pressure on the device, and to evaluate the performances in terms of electricity production. Moreover, a modern wave buoy, based on GPS technology [19], is installed in front of the prototype, at a distance of 100 meters, in order to measure incident waves acting on the device.

Three fixed-Kaplan (propeller) low-head turbines equipped with permanent magnet generators, with a total power of 2.5 kW, and a maximum-power-point-tracking charge controller were located in 2015 in the machine room behind the reservoir, for stress test during storm events [16]. In February 2019 a new "S-type" turbine has been installed, which transform the wave energy into kinetic energy and then into electricity thanks to the presence of a generator. If future it is planned to install a set of low-head turbines, including a hybrid "multi-field turbine" obtained coupling different turbines typologies (Contestabile et al. 2016), in order to identify the best technology via cost-benefit analysis. The ongoing and future research will be focus on increase the OBREC Technology Readiness Level (TRL) from 6 to 7 (system demonstrated with turbines and electricity generation in an extended period - 1 year).

Since 2016, the OBREC device installed at the Naples harbour is part of the NAtural Wave Energy Lab (NAWEL) of University of Campania "Luigi Vanvitelli" (Italy). The natural laboratory consists of a full monitored 30-m traditional breakwater that include the full scale OBREC prototype. About 4000 m^2 of sea in front of the breakwater, in depth of about 25 meters, are available for testing different floating devices and it is used as multi-use space for new ecologically sensitive economy at sea (floating wind platform, bioreactor for microalgal growth, mineral accretion innovative applications). The next step to be achieved in the coming years is to enlarge the reservoirs size, to the right and to the left of the machine room.

III. Wave activated bodies

C. *ISWEC*

ISWEC (Inertial Sea Wave Energy Converter) is a device based on the technology developed by Politecnico di Torino and implemented by the company Wave for Energy Srl. It consists in floater anchored to the seabed with a loose mooring, allowing the pitching movement and orientation to follow the main direction of the front wave. Outside it looks like a completely closed hull, with the only electric cable that, through a joint, passes through the hull and connects with a static cable positioned on the seabed and reaching as far as the beach, in a transformer cabin to the island network.

The heart of the machine is the gyroscopic system: two flywheels of 10 tons placed in rotation generating the inertial reaction torques that arise from the interaction between their speed and the pitching motion of the hull on two internal precession shafts, on which the permanent magnet electric generators are keyed [20].

During the device operation the mechanical power contained in the movement of the waves is transferred to the hull, thus causing the motion of the latter, in particular in the pitching motion. The angular velocity of the hull, combined with the angular momentum of the flywheel placed in rotation, creates a gyroscopic moment that causes the transfer of mechanical power between the hull and the inner shaft of precession, on which the electric Power Take Off (PTO) is mounted. The flywheel speed is adjusted to adapt to the working sea conditions and maximize energy absorption. The angular velocity in working conditions and the regulation law of the absorption PTO is updated hourly, using the forecasts provided by ENEA. Every day in fact the sea state forecasts are transmitted and received automatically from the device for the next three days with hourly resolution.

The first ISWEC prototype was launched in August 2015 in the nearest of Pantelleria Island. The installed system presented some partitions: there was no connection to the network (therefore the machine was in stand-alone operation) with elements of dissipation of the energy produced, and the system only saw one of the two gyroscopic units installed. The decision to proceed with subsequent steps of experimentation was born with the aim of proceeding to intermediate checks of the design choices been made. In the first test phase of the system, the sea conditions encountered have become extremely challenging, with significant heights and peak periods characteristic of oceanic sites. This made it possible to test the tightness of the device and the mooring system [21-23].

Fig. 4. The ISWEC pilot in Pantelleria.

IV. Conclusion

This paper presents a concise collection of three innovative technologies representing the Italian state of art in wave energy sector. Indeed, ISWEC, OBREC and REWEC3 are the technologies with the highest technological readiness level.

The innovation introduced by the three devices is given by the solution of the main issues associated with wave energy production in the Med Sea:

• significant energy production even in mild seas: each WEC can be "tuned" to resonance based on the local wave climate, hence valorising the Mediterranean Sea Basin (see, for instance, the MED project founded by EU titled: "BLUENE - BLUe ENErgy for Mediterranean", http://www.medmaritimeprojects.eu/section/bluene);

• economic benefits, based on the fact that preliminary results show as these devices have a very low payback period, comparable to the offshore wind sector.

The pilots here presented are contributing to create a smart alternative in the next Italian energy market, expected to undergo substantial changes in the coming years.

Furthermore, a path of innovation is going to be created, due to the opportunity of use the prototypes as laboratories in large scale. The intention is to obtain information and data exportable for more energetic sites and to investigate others unforeseeable effects or risk factors, which could lead to results that are different from the expectations expressed herein. By its nature, in fact, the use extended in time of such innovative power technologies in the marine environment, remain still unclear for impacts produced on the device it self and on the environment. There's still some work but much road has been made.

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