# Resonant Wave Energy Converters: Small-scale field experiments and first full-scale prototype

**The Resonant Wave Energy Converter 3 (REWEC3) is a device belonging to the family of Oscillating Water Columns (OWCs), that can convert the energy of incident waves into electrical energy via turbines. In contrast to classical OWCs, it incorporates a small vertical U-shaped duct to connect the water column to the open wave field. This article shows the results of a small-scale field experiment involving a REWEC3 designed for working with a 2 kW turbine. Then, the next experimental activity on a REWEC3 installed in the NOEL laboratory with the collaboration of ENEA is presented. Finally, the first prototype of ReWEC3 under construction in Civitavecchia (Rome, Italy) is shown. The crucial features of the construction stage are discussed and some initial performances are provided.**

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## Introduction

The Resonant Wave Energy Converter 3 (REWEC3) is an Oscillating Water Column (OWC) device, already described in Part I. The modeling of the REWEC3 is different from that of OWCs, as the equation of motion of the water column includes non-linear terms associated to the head losses in the vertical duct. A holistic view on the design process has been given by Boccotti [1], while the modeling and the experimental validation have been discussed by Boccotti [2], Boccotti *et al*. [3], and Arena *et al*. [4].
In 2013 a novel U-OWC was installed at the Natural Ocean Engineering Laboratory (NOEL) of the Mediterranea University of Reggio Calabria. Such a plant is equipped with a 2 kW turbine (Figs. 1-2). The best conditions for conducting the experiments occurred on September 1st, 2014, when a storm allowed to record optimal sea state conditions for the plant, for testing the power converted by the device (Fig. 3). The preliminary results of this activity are shown in Arena *et al*. [5].
On the basis of the existing experiences, a new small-scale filed experiment is planned to be carried out on a REWEC3 devices installed in the NOEL laboratory with the collaboration of ENEA (Fig. 4 shows a 3D view of the ENEA caisson; Fig. 5 shows the actual ENEA caisson). Some specific aspects related to the optimization of the device and on hydrodynamics inside the plant will be investigated.
Finally, the first prototype of REWEC3 is under construction in Civitavecchia (Rome, Italy). The device is embodied in a vertical breakwater, so that the plant can be employed both for protection purposes and for energy harvesting. The crucial features of the construction stage are discussed and some initial performances of the plant are provided.

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FIGURE 1 The REWEC3 plant installed in the breakwater in reinforce concrete at NOEL laboratory

FIGURE 2 Wells turbine installed at the REWEC3 breakwater at NOEL laboratory. The turbine has been designed within the POSEIDONE project by the team of the University of Rome La Sapienza and manufactured by Faggiolati Pumps SpA. Experimental activities are managed by Mediterranea University and Wavenergy.it

## Recent experiences on fully equipped REWEC3 plant and future development stages

One of the main research activities on the REWEC3 plants are related to small-scale experiments carried out in the field. Indeed, the possibility of implementing a fully equipped plant requires specific investigations on the joint turbine-REWEC3 dynamics.

FIGURE 3 The Wells turbine installed at the REWEC3 breakwater at NOEL laboratory, during the storm of September 1st, 2014

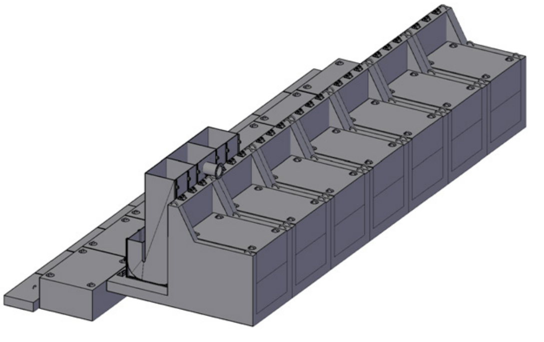

FIGURE 4 The 3D view of the REWEC3 caisson at NOEL laboratory realized in collaboration with ENEA

FIGURE 5 The REWEC3 caisson realized in collaboration with ENEA, during the installation stage at NOEL laboratory

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The POSEIDONE project, funded by the Italian Ministry of Environment (G.U. – Serie V n. 150 del 21/12/2009), has involved the installation of a REWEC3 plant with a 2 kW turbine. The experimental activity has been pursued at the NOEL laboratory of the Mediterranea University. The novelty of this experiment relates to the installation of a turbine with such a remarkable power (consider that the experimentation is conducted at a laboratory with sea states having significant wave height of no more than 1.2 m). The project was proposed and conducted jointly by the Mediterranea University, the University of Rome La Sapienza, Faggiolati Pumps S.p.A. and Wavenergy.it S.r.l. (the licence of the REWEC3 patent by Professor Paolo Boccotti). The data of the experimentation are still under investigation. Therefore, the results will be disseminated at a later stage. However, here a confirmation about the favourable performance of the device can be given. Specifically, during the occurrence of sea states with significant wave height of 1m, the average converted power of about 500 W and peaks of 1.5 kW were recorded. This result has confirmed previous theoretical estimates and, to our knowledge, similar (scale-wise) experimentations were not able to reach these values of electrical power.

The next experimentation was conducted in collaboration with ENEA, which contributed to the installation of a new caisson that is going to be used for investigating problems on the optimization of the REWEC3 device. It is composed by one REWEC3 structure, equipped with 2 inner partition walls. The walls can be removed, so that different configurations of the inner part of the plant can be investigated. In this experimentation, the objective is to identify an optimal configuration of the REWEC3 and define criteria useful at the design stage, when the width of each REWEC3 cell must be designed. In addition, this experimentation is expected to provide a better insight into the REWEC3 dynamics. The mathematical models used for describing the REWEC3 dynamics will be reviewed and possibly improved, in order to define design tools even better.

In parallel to these activities, the problem of forcing an optimal turbine behaviour is faced. If the REWEC3 is exposed to the desired sea states, then resonance occurs. But, in other situations, the coupled REWEC3 – turbine behaviour must be improved by implementing adequate control strategies. The objective of a control strategy is to maximize the performance of the system in a variety of wave conditions. This is a crucial element of a full-scale prototype. It is worth noting that, at a fixed rotational speed, turbines such as Wells turbine are able to operate with good efficiency values only within a limited range of flow conditions around the peak efficiency point [6]. In this context, the choice of the optimal rotational speed of the turbine for a given sea state and a given turbine, as well as the determination of an effective control algorithm, are the key issues. This problem was investigated by Falcão and Justino [7] and Falcão [8] for a conventional OWC in random sea waves. Regarding the U-OWC, specific investigations on the PTO performance coupled to the active part are at their first stage of development.

The first approach to this problem was performed within the context of a MARINET project (Marine Renewable Infrastructure Network for emerging Energy Technologies) [9], which has allowed to access the test facilities of Tecnalia R&I, in Bilbao (Spain), providing an effective instrumentation for coupling the available numerical codes to the test-bench required for pursuing pertinent experimental measurements. A number of experiments have been carried out for a given geometric configuration and turbine characteristics. The determination of an optimal reference rotational speed for a fixed sea state and the differentiation of the system behavior in case of wind-generated waves and swells were the key findings of the project. Numerical models have been implemented to simulate the physical behavior of the designed plant. This process required the modelling of the hydrodynamic system, the PTO components, the electrical system and the control strategy. The electrical testing included two systems: a real part and a simulated part. The former is composed by both the emulated and the real component, meaning the numerical model featuring the behavior of the device (from the wave energy resource to the generator shaft) and the physical equipment of the test bench. The latter represents the behavior of the whole device used for validations and comparisons of the experimental testing. Results pointed out that there is a relevant connection between the spectral shape of the incident wave field and the optimal working conditions of a REWEC3. In this context, the activity performed at MARINET was crucial as it led to the determination of the future steps for developing a fully optimized REWEC3 plant. Actually, a Maximum Power Point Tracking (MPPT) method is under development for optimizing the performance of the plant in a variety of sea states. Considering the relevance of the sea state parameters, the proposed strategy relates to the identification of an optimal rotational speed given the significant wave height of the sea state.

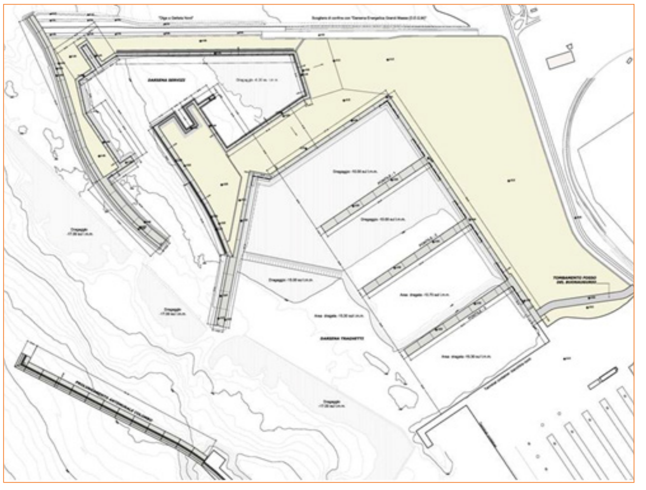

FIGURE 6 Layout of the new structures in the Port of Civitavecchia

## The first prototype of REWEC3 caisson under realization in the Port of Civitavecchia

The small-scale experimentation in the field on REWEC3 plants proceeds parallel to the activities of implementation of the new device at full scale. The Port of Civitavecchia (Rome, Italy) will host the first full-scale prototype of the REWEC3 device incorporated in a caisson breakwater, within the works planned for improving the services of the port and the quality of the infrastructure. Specifically, the construction of two new basins of about 50 ha, devoted to ferries and cruises (extension of quays of about 1.4 km) and to naval services (extension of quays of about 1.7 km), and the extension of the breakwater "C. Colombo" (the main breakwater of the port) to a total length of 400 m are mentioned. The new structures will be built by utilizing reinforced concrete cellular caissons (over 120 reinforced concrete caissons of different sizes). An overall view is given in Figure 6, which shows the layout of the port. In the outlined context, the embodiment of 17 REWEC caissons was proposed by the Constructor for reducing the reflection coefficient in front of the structure. Indeed, in a first instance, the caissons were designed for absorbing wave energy, without employing devices for exploiting wave energy. Then, the use of the REWEC3 technology was conducted by Wavenergy.it (www.wavenergy.it).

The contract on the extension of the Port of Civitavecchia was awarded in spring 2012. The time schedule has been planned for completing the works about at the end of 2015. The construction started in July 2012.

Obviously, the novel configuration of the REWEC3 breakwater has been designed for harvesting as much energy as possible (Figs. 7 and 8). In this context, the crucial change pertains to the inclusion of the pneumatic chamber, which has been utilized into all the REWEC3 caissons, for a total length of 510 m, at a water depth of 15 m.

Each REWEC3 caisson is 33.94 m long and includes 8 independent absorbing cells (vertical duct and pneumatic chamber) 3.87 m wide. The vertical duct is 1.60 m wide and the U-duct opening is located at -2.00 m below MWL, so that the opening is not always below the free surface, while the pneumatic chamber is 3.20 m wide. The external walls of the absorbing part of the REWEC3 are 0.50-0.60 m thick while the inner walls are 0.35 m thick.

Some cells of the caissons are filled with concrete in order to ensure both the global stability and a monolithic behavior of the structure. The remaining

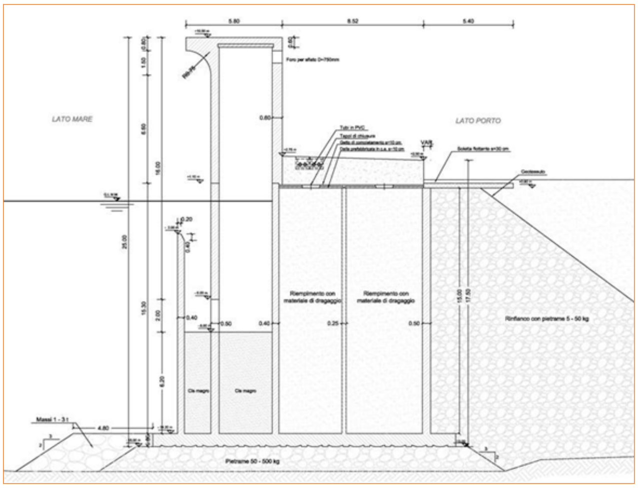


FIGURE 7 Cross-section of the REWEC3 wave energy converter in the Port of Civitavecchia

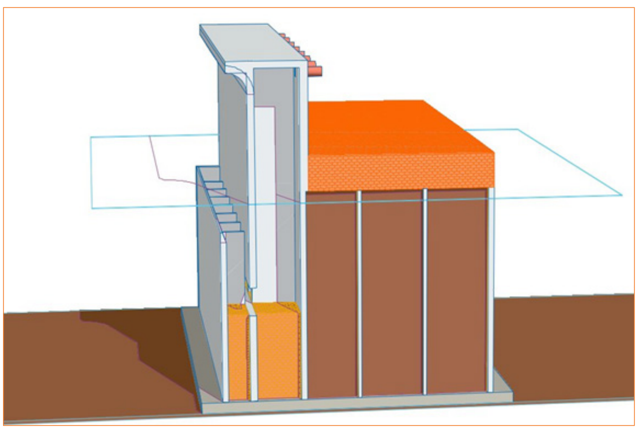

FIGURE 8 Perspective views of a single REWEC3 caisson, with independent cells, employed in the works of the Port of Civitavecchia

FIGURE 9 Progress of the construction of the REWEC3 caissons at the Port of Civitavecchia

FIGURE 10 4 REWEC3 caissons completed up to 10m above M.W.L. at the Port of Civitavecchia (Rome, Italy)

part is filled by using dredged materials. Some results have been shown on Arena *et al.* [10].
At present, 4 REWEC3 caissons have been completed up to 10 m above M.W.L. at the Port of Civitavecchia (Rome, Italy) (Figs. 9 and 10).

### *The caissons casting*

The construction of the reinforced concrete REWEC caissons consists of the following main steps:

- rubble layer foundation placement;
- casting up to 0,80 m SWL on a floating plant and launching;
- towing to preliminary site and sinking with water;
- towing to final site;
- filling with concrete and dredged material;
- backfilling;
- completion up to 10,00 m SWL on site.

The rubble mound foundation consists of a quarry rock layer of 50-500 kg and about 1 m thick, placed on the seabed and topped with a final levelling/

blinding layer of finer aggregate. The quarry material is placed and levelled by means of a crane pontoon, which discharges by means of a hydraulic grab on site.

Owing to its dimensions and weight, the caissons are cast in two different main phases. The first one considers the construction of the REWEC caissons for a total height of 15,80 m (down to +0.80 m under MSL) on a floating casting plant.

The bottom slab (0,80 m thickness) is cast in one single operation; during this phase the sliding formwork is hung up from the floating plant. Once the base slab is completed, the sliding formwork is lowered to start with the caisson body casting.

The concrete is cast in layers and in the meantime the horizontal reinforcement is positioned. Concrete is carried to the upper frame and distributed by means of a pump. The self-climbing formwork is raised by hydraulic jacks acting simultaneously on steel vertical bars, which stand on the caisson base slab and cause the formwork to rise slowly until the final level is achieved.

A series of mix designs were set at the beginning of the work, so the caissons are made with concrete, respecting the following requirements:

- cubic compressive strength 45 MPa;
- exposure class XS3;
- workability S4/S5;
- cement CEM III or CEMIV;
- w/cm 0.40-0.44;
- maximum diameter of aggregates 25-32 mm;
- concrete cover thickness value of 5 cm.

When the caisson body casting and concrete ballasting needed to ensure the caisson nautical stability are completed, the mobile upper frame with the formwork hung up is raised to allow the caisson launch. At the same time, the plant is brought down to the depth necessary for allowing the caisson floatation. Once floating, the caisson is moved out of the plant and towed, waiting for the final positioning. The placing phase consists in towing the caisson, by means a tugboat, to the placing site, where it is maintained in the right position by means of winches connected with some eyebolts on the caisson top at one end, and with other eyebolts on a crane pontoon or on the nearest caisson already sunk at the other end. Pumps are put on the caisson top slab and the seawater is pumped into the cells.

The caisson position is constantly kept under observation by a topographic surveyor during the final step of the operation. A final check of the rubble mound levelling is made by divers, just before a complete sinking is reached. If it is acceptable, the caisson is completely sunk and filled with seawater to ensure it is stable until filling is complete.

The caisson filling is made of concrete and dredged material. The filling material will be unloaded on the caissons directly by lorries and then pushed into the cells by an excavator (from the placing of the first caisson a terrestrial connection has been realized).

Backfilling operation (when necessary) is started behind the caisson once it has been filled. The backfill material placed just behind the caisson consists of selected quarry material (5-50 kg).

The second phase of REWEC3 caisson casting considers the completion of the caissons with the construction of the upper part of the pneumatic chamber ("the seawall") by using a sliding formwork *in situ* in order to align the pneumatic chamber from the +0,80 m SWL up to +10,00 m SWL.

The final step of the construction involves the concrete demolition of the upper part of the vertical duct from -+2,00 m SWL up to +0,80 m SWL (the sea side row of cells) by cutting.

Behind the active part of the REWEC3, a superstructure of reinforced concrete will be built *in situ* including configurations for water, electricity and telecommunications services (see Fig. 8). The current design does not include the mechanical and the electrical parts to transmit energy into the port grid.

### *Wave climate description via available data (project TEN-T, annual programme 2013 - action 2013-IT-92050-S)*

The performances of the Civitavecchia plant took place by considering the wave data recorded since November 2012 by two buoys located in front of the breakwater. The monitoring system of the two buoys provides the statistical information on the sea states interacting with the structure. Specifically, the quantities of interest are: significant wave height; mean spectral period; and dominant direction. The

data are representative of 30-minute sea states and were recorded from November 16th 2012 to November 31st 2013. Totally, the available records are 17,218.
Then, the mean wave power available per unit width at Civitavecchia is calculated as,

$$\overline{\Phi} = \int_0^{\infty} \Phi(h) \left| \frac{dP(H_s > h)}{dh} \right| dh \qquad (2)$$

where the probability of exceedance of the significant wave height at a certain location $P(H_s>h)$ is given by Eq. (1). Then, the power per unit width associated with a certain sea state ($\Phi$) is estimated by the equation

$$\Phi = \rho g \int_0^{\infty} \int_0^{2\pi} c_g(\omega) S(\omega,\theta) d\theta \, d\omega \qquad (3)$$

where $\rho$ denotes the water density, $g$ is the acceleration due to gravity, $S(\omega,\theta)$ is the directional wave spectrum of the incoming waves and $c_g$ is the group celerity.
From the available data, the mean wave power per unit length $\overline{\Phi}$ in Civitavecchia has been estimated about 2.80 kW m$^{-1}$.
The results obtained have been compared to those achieved by the third order generation WAM model provided by ENEA [11, 12], showing a good agreement (see Tab. 1 and Fig. 11). In detail, Figure 11 shows the average wave power associated with

| Data | Φ(Kw/m) |
|---|---|
| WAM data | 2,37 |
| TEN-T buoy | 2,80 |

**TABLE 1** Mean wave power per unit length $\overline{\Phi}$

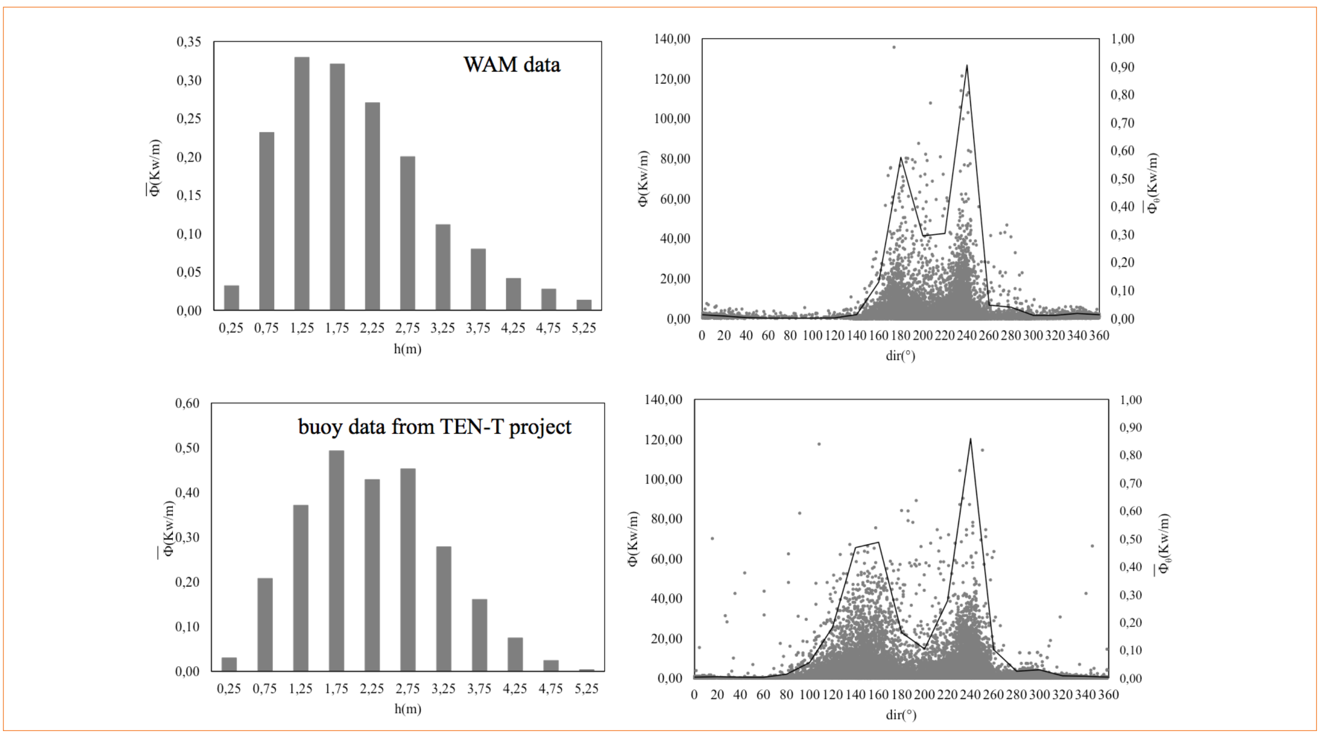


**FIGURE 11** Left panels: average wave power associated with certain significant wave height intervals; right panels: wave power calculated for each sea state with the related wave direction (dots) and mean wave power calculated for a certain directional sector (continuous line). The left vertical axis pertains to the wave power; the right vertical axis pertains to the mean wave power; the horizontal axis shows the wave direction

certain significant wave height intervals (left panels). It is seen that the largest amount of incident wave power is related to sea states with significant wave height belonging to the interval (1.25 m, 2.75 m), both with the WAM model and the measurements of buoys. Obviously, such a consideration is crucial for characterizing the performance of the plant. Indeed, the plant has to be designed to maximize the energy absorption for sea states with the occurrence of the largest incident wave energy. Then, in the right panels of Figure 11 the wave power calculated for each sea state with the related wave direction (dots) and mean wave power calculated for a certain directional sector (continuous line) are shown; the left vertical axis pertains to the wave power; the right vertical axis pertains to the mean wave power; the horizontal axis shows the wave direction.

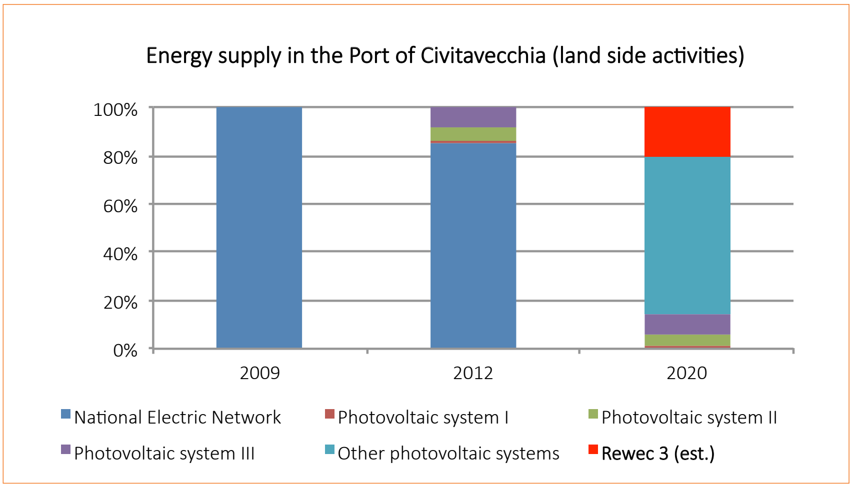


FIGURE 12 Electrical needs in the Port of Civitavecchia: the perspective of electricity supply from renewable sources up to 2020
*Source: TEN-T ANNUAL PROGRAMME 2013 - ACTION 2013-IT-92050-S*

### *Expected performances of the REWEC3 device in Civitavecchia*

The average wave energy absorbed by the REWEC3 in Civitavecchia is evaluated from the mean power of incoming waves estimated in the previous section. In this regard, the hydrodynamics of the REWEC3 is described via the theoretical model proposed by Boccotti [2] and [1], described in Arena *et al.* [10], and developed with a different approach by Malara & Arena [13].

Initial estimates of the wave energy absorbed by the REWEC3 in Civitavecchia have been shown in Arena *et al.* [5]. It is seen that the plant absorbs the largest amount of wave energy in the most significant sea states. Specifically, the absorbed mean wave power is 1,281 MWh/yr/km for sea states with $H_s$ ranging in the interval (2.5-3] m and $T_m$ in (5.5-6]s ($H_s$ being the significant wave height and $T_m$ the mean wave period). Whereas it absorbs 1163 MWh/yr/km with $H_s$ (2-2.5] m and $T_m$ in (5-5.5] s, for which the absorbed mean wave power is more than 80% the incident one. The REWEC3 plant in Civitavecchia is able to absorb about 12.1 GWh/yr/km.

Initial estimations of the electrical power given by the REWEC3 plant are provided by considering a monoplane Wells turbine. By considering classical laboratory studies for the estimation of head losses and the efficiency of a Wells turbine (Curran and Gato, [14]), a production of electricity of 20 MWh/yr for each cell of the REWEC3 device in Civitavecchia has been estimated.

Better energy efficiency is expected to be reached with turbines optimized for the working condition of the REWEC3 in Civitavecchia for different wave conditions, for which the system REWEC3+turbine could be suitably regulated to maximizing the production of electricity from the turbine.

The installation and the complete exploitation of the systems REWEC3 for the absorption of the energy produced by the waves will contribute for almost 20% of the total needs of the port (2,510,000 kWh per year), see Figure 12.

## Conclusions

The paper, in the first part, has shown the preliminary results of a field experiment on a REWEC3 model installed at the NOEL laboratory. The REWEC3 is a wave energy harvester belonging to the family of oscillating water columns. The key feature of the device is the ability of naturally reaching the resonance condition with the incident waves without the need of any phase control devices. This experimental activity has been pursued for testing in a relevant environment a REWEC3 equipped with a 2kW turbine. The best conditions for conducting the experiments occurred on September 1st, 2014, when a storm allowed to record optimal sea-state conditions for the plant. The first results of the research are: a U-OWC plant equipped with a turbine is able to reach the resonance condition with the incident waves; the turbine utilized at the NOEL is capable of producing an average power close to 500 W, with power peaks close to 1 kW. The results shown in this paper are preliminary and will be the basis for the next field experimental activity that will be executed on a new REWEC3 device installed at the NOEL laboratory with the collaboration of ENEA, for the investigation of some specific aspects related to the hydrodynamics onside the plant.
In the second part, the present work has dealt with the first caisson breakwater plant embodying a U-OWC device: the REWEC3. The plant is located in Civitavecchia (Rome, Italy). The construction stage of the REWEC has been described. Different phases have been described for highlighting the crucial steps involved in the construction of the structure. The details of the layout and of the cross-section of the plant have been shown, as well. Finally, the paper has dealt with the performances of the REWEC3 plant under construction in the port of Civitavecchia.

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