A new seawater low-head turbine for the OBREC

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Abstract— **OBREC is a wave energy conversion system that utilizes the overtopping phenomenon. It operates by allowing waves to run over a ramp and enter a reservoir located above sea level within a breakwater. The wave energy is then converted into potential energy before being directed through a turbine to generate electrical energy. OBREC prototype is located in Naples harbour, Italy. The primary goal of the pilot project was to demonstrate the system's high-capacity factor, showcasing its ability to generate electricity even in a low-energy wave climate. Over the past 42 years, the average wave power at the site was found to be 1.8 kW/m. The system has proven to be reliable under severe wave conditions, with recorded wave heights exceeding 5 meters in the last five years. In ongoing monitoring activities conducted in real marine environments, a new set of power take-off equipment was installed in 2021, consisting of a propeller-type pico-turbine that was finalized in 2022. The performance and reliability of the entire structure were closely monitored during various stress tests, including start-stop cycles in the marine environment with different combinations of flow rate and hydraulic head.**

This paper focuses on the OBREC design including the development of the new turbine, task performed by means of numerical simulations. It also deals with the optimization of the hydraulic system and with the control of the electric generator, presenting some field results.

Keywords— **Overtopping Wave Energy Converter; Low head axial-flow turbine; Seawater hydro-turbine.**

I. INTRODUCTION

Exploitation of marine wave energy as a power source is now widely practiced worldwide. Numerous countries are investing significant resources in planning, installing, and/or enhancing structures dedicated to converting wave energy into electricity [1,2]. Among the various types of devices and converters for energy production, the OBREC (Overtopping Breakwater for Energy Conversion) represents a particularly advantageous technological solution. OBREC combines the exploitation of renewable wave energy with the protection of the anthropized environment behind the breakwater, by capturing incident waves. In terms of construction and subsequent management of the structure, greenhouse gas emissions are significantly reduced, and the environmental impact of such devices is negligible since the OBREC is fully integrated into existing or new breakwaters (Figure 1). The human perception of the OBREC presence could be therefore minimal.

However, it should be noted that most technologies developed for capturing and harnessing wave energy within coastal protection systems are still in the prototype phase and thus far from industrialization. This is due to a series of challenges, including adverse weather conditions that can pose a threat to the stability and the operation of such structures, as well as system maintenance and management, that can be demanding. In this context, the OBREC's technological development activities come into play. The innovative device, in its prototype form, is installed at the San Vincenzo pier in the port of Naples [3].

One crucial aspect to be considered in the design of a OBREC converter is its strong suitability for contexts characterized by limited access to the electrical grid, particularly in coastal areas. In such cases, technologies for energy production utilizing small water heads and flow rates (in the range 0.1-10 m^3/s) are few and often expensive. The OBREC solution can efficiently harness the available natural energy source under these specific conditions at a low cost.

In typical hydroelectric applications, Archimedes' screws are used for flow rates below 6-8 m^3/s and hydraulic heads below 6 m, generating a power typically below 100 kW [4]. When the expected power exceeds 50 kW, reaction turbines such as micro-Kaplan and micro-Francis turbines are employed. It is evident that, unlike natural riverine hydroelectric applications, the boundary

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conditions governing the operation of wave energy converters, including the OBREC, severely limit the range of potentially usable turbines, primarily due to the reduced available hydraulic head. Consequently, the engineering problem of selecting the best turbine for the installation in an OBREC-type device represents a crucial stage in designing such arrangements. Moreover, the management scenario is further complicated by the big variability of the operating conditions. Unlike typical hydroelectric applications, the hydraulic head in wave energy converters depends on the wave height incident on the structure. As a result, the water flow passing through the hydraulic system and processed by the turbine can vary significantly within limited time frames. Furthermore, it is worth considering that, unlike conventional hydroelectric solutions along natural watercourses, the service life of a turbine used in OBREC for energy production is reduced due to the particularly severe environmental conditions, requiring frequent maintenance.

The design of some major structural components of the OBREC (reservoir, ramp, engine room), encompassing their sizing, typological characteristics, and respective materials, is implemented based on purely hydraulic and structural considerations depending on the meteo-marine conditions, expected flow rates, reduction of the rear side overtopping, loadings on the entire structure. Conversely, the same cannot be said for the turbine selection.

For this reason, it is necessary to combine hydraulic, mechanical, and economic evaluations for the optimal solution. This approach represents an advancement compared to the classical literature, as it considers not only the creation of a device capable of capturing incident waves and converting their potential energy into electricity, but it also transforms the engineering issue into a multi-variable optimization problem, to maximize electricity production [5-7]. In the case of OBREC with multiple reservoirs, the main objective is to determine the optimal number of storage reservoirs [8]. However, as also reported by Victor et al. (2011), the multi-criteria problem cannot be limited to the stand-alone geometric optimization of the structure, but it must also consider the turbine type selection. In this regard, an important work that contributes to the optimization of electricity production in an OBREC-type converter is the study of Cavallaro et al. [9], who demonstrated that the electricity generated in such a device (the study assumes its operation on the island of Pantelleria, Sicily) depends on three parameters: (1) the crest elevation of the free-surface outflow ramp, (2) the bottom elevation of the reservoir, and (3) the ramp height. It is worth noting the significance, as emphasized by Cavallaro et al. [9], of considering one of the components' positions (the ramp crest) relative to the free surface in the reservoir, which, in turn, depends on the operation of the mechanical parts (the turbine) responsible for electricity production.

For the reasons mentioned above, this study proposes a multi-parametric study of the OBREC operation aimed at maximizing the energy output. The variables affecting the produced electricity are the crest elevation of the ramp relative to the free surface, the turbine type and electric generator, the control strategy. The multi-criteria analysis illustrated in this paper is based on numerical simulations.

Fig. 1. Photo of the OBREC device integrated in the existing breakwater of the San Vincenzo pier in the port of Naples (Italy).

II. METHODS

Based on the multi-criteria analysis conducted by Williamson et al. [10], it was decided to consider three different types of hydraulic turbines, while keeping in mind that reaction turbines belong to the most common turbine category on the market: reaction turbines (axial flow), crossflow Banki Mitchell turbine and Archimedes screw.

A. *Description of the OBREC geometry and hydraulic system*

For the numerical applications, the OBREC structure was considered, Figure 2. The structure consists of a flat ramp (overtopping ramp) that directs breaking waves into a reservoir. This way, the water flow is channelled through an inlet device into the hydraulic system towards the turbine, which is installed inside the powerhouse. For water levels above the threshold of the inlet device, the hydraulic system is activated, allowing a certain flow rate (Q_{in}) through the turbine. Otherwise, the turbine remains inactive, and the reservoir empties. The filling-emptying rate of the reservoir is influenced not only by the turbine's capacity and the incoming water quantity but also by the reservoir volume. A larger reservoir has a greater storage capacity, resulting in better water storage and volume regulation.

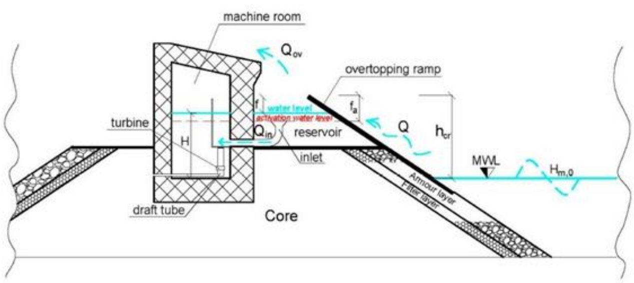

Fig. 2. Sketch of the OBREC arrangement (longitudinal view) with main notation.

As mentioned, one of the parameters considered in the multi-criteria analysis is the control strategy, which involves turning the hydraulic machine on and off a finite number of times based on the free surface water level in the reservoir and on the minimum and maximum activation and deactivation levels of the turbine.

In this case, the chosen control strategy consists of setting the minimum activation level, below which it is assumed that no water flows through the hydraulic system. The minimum activation level is constrained by the flow-limiting device. The water head variation for turbine operation is between the threshold level of the flow-limiting device and the crest level of the overtopping ramp. This variable is defined as activation free space (f_a) in Fig. 2.

B. *Numerical model*

The performance of the energy converter is typically estimated using a power matrix, which allows the characteristics of the wave (typically the significant wave height H_s and the peak period T_p) to be combined with the power output of the converter. However, since the OBREC prototype represents the world's first energy converter fully integrated into an existing breakwater [11], the power matrix is not available. Therefore, the only practical approach to solve the optimization problem is represented by numerical modelling of the system, considering parameter variations.

OBREC energy production was modelled using the software OBRECsim V01, developed in MATLAB® at the Università degli Studi della Campania, in Italy [12,13], Figure 3.

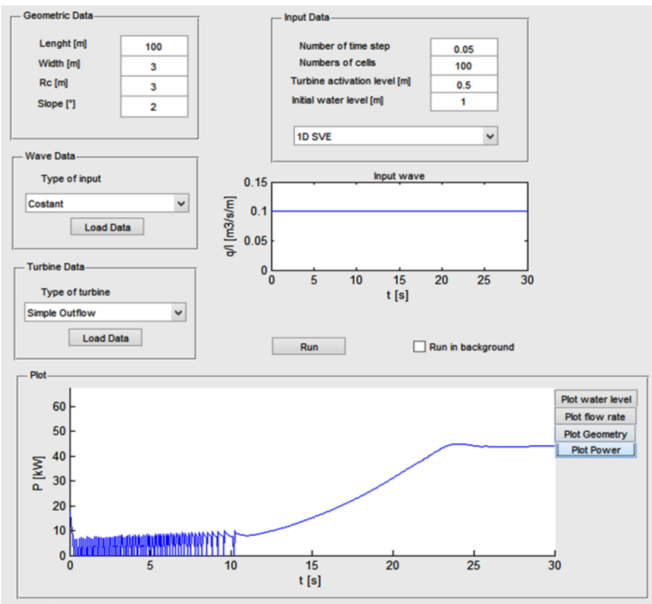

Fig. 3. Desktop environment of the OBRECsim code.

The code allows for modelling the structure's geometry and estimation of the incoming water flow into the reservoir. By schematizing the water volume balance process in the reservoir, considering both the flow-limiting device and the turbine operation, the model determines the produced energy and the overall system efficiency.

In summary, the input data for the model consist of:

- Sea states
- Overtopping ramp level
- Turbine characteristic curve
- Turbine control strategy

Figures 3 shows the images of the graphical interface of the OBRECsim code.

III. Results

A. *Strategy control of the OBREC operation*

he simulations were carried out for three different sizes (in terms of discharged flow rates) of an axial flow reaction turbine. This kind of turbine is not the only one that might works within the OBREC. For instance, Archimedeand or cross-flow turbines could be also considered. However, due to its extreme simple construction (which limits the maintenance) and the to its compcactness, the propeller turbine was choses as first option.

Figure 4 shows the performance curve (Q(H)) and efficiency curve (η(H)). Given a fixed hydraulic head H, as the turbine size Q (which varies based on the maximum flow rate Q handled by the machine) increases, the flow rate Q for which the turbine operates increases too. The efficiency η is constant within a wide range of H, instead. Normally, in hydraulic power plants the turbine speed is constant as the machine operates at a fixed head. For this application, a variable speed control strategy is necessary, contrarily. The efficiency characteristics in Figure 4 represent the envelope of the characteristics obtained at different turbine rotational speeds. The curve of the efficiency does not change with turbine size due to the assumption of similar flow conditions.

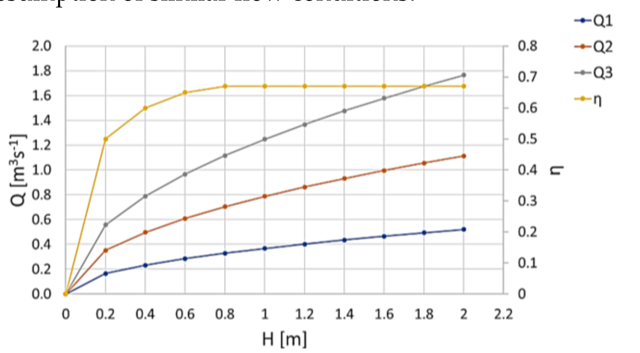

Fig. 4. Characteristic curves and efficiency curves of the reaction turbines.

Figure 7 shows the performance curves of the reaction turbines for different sizes and increasing crest levels of the overtopping ramp. The maximum average power is achieved by the turbine with an intermediate size (turbine no. 2) at a crest height of the ramp of approximately 1.40 m.

Once defining the "size" of the turbine, a detailed study of the various parts composing the system is required Particular attention was paid to the study of the runner. This study was first of all tackled by comparing different operating scenarios and different configurations (for example: number of blades, geometry and arrangement of the distributor, geometry of the single blade).

Figure 6 shows the final model of the chosen rotor.

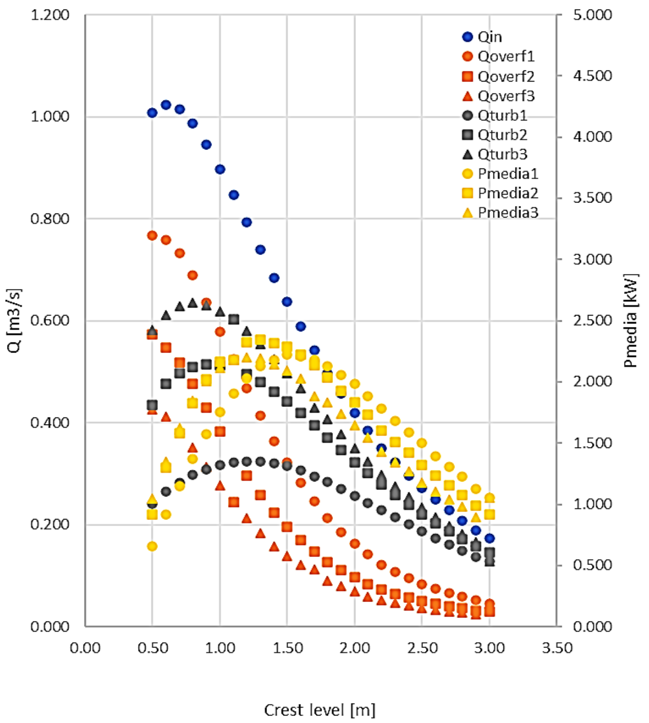

Fig. 5. Flow rates and average power as a function of the crest level of the overtopping ramp for the axial flow turbines.

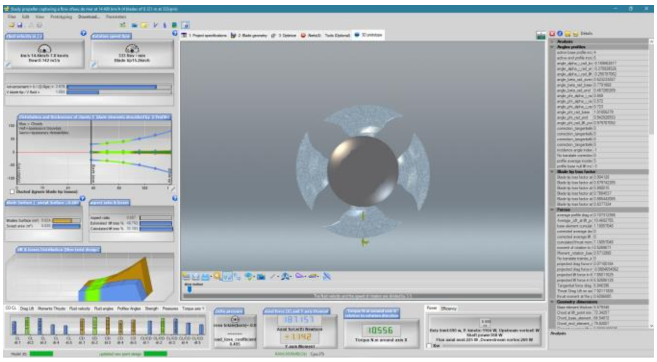

Fig. 6. Simulations on the final model of the propeller.

The optimization of the rotor was carried out by means of a numerical code (Mecaflux PRO 3d®). The simulations concerned the number of the blades and the profiles characteristics. The rotor have the following characteristics:

- Runner outer diameter: 400 mm
- Number of blades: 4
- Blade stagger angle at mid-radius: 58°.

The material chosen for the runner is polyamide fiber with 30% glass fiber content. In fact, AISI 304 stainless steel is not a suitable steel in the marine environment. Even AISI 316 steel could suffer material failures due to cavitation processes. The appropriate material is the chromium-molybdenum AISI 317 but, consequently, the production costs would be very high and not in line with the standardization and relative mass production.

Simulation results allowed to obtain the non-dimensional turbine power as function of the non-dimensional flow rate, figure 11, and the efficiency characteristic as a function of the head, figure 12.

The maximum efficiency is 68%, corresponding to a water head of about 1.5 m and a flow rate of about 0.18 m3/s. The maximum power is about 1.8 kW. Is interesting to note as this value is similar to the wave energy flux content in the study site. However, is important to take into account as the turbine serves about 3 m of reservoir width (i.e. 3 m of wave crest width).

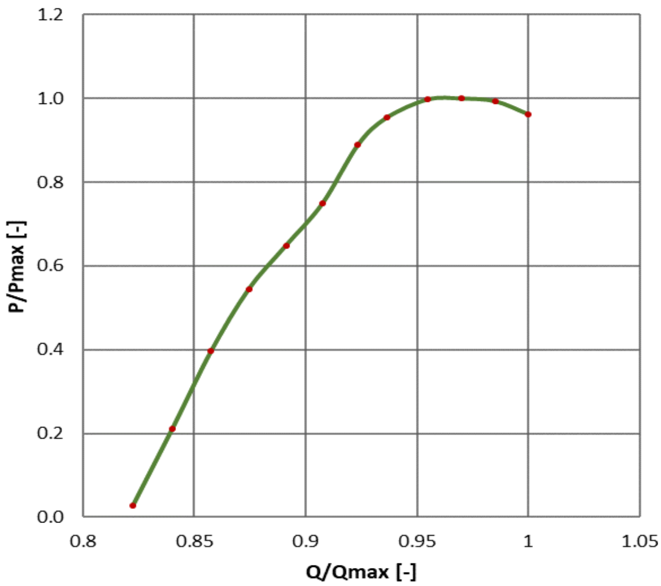

Fig. 7. Non-dimensional curves of Power and Flow referred to the maxima.

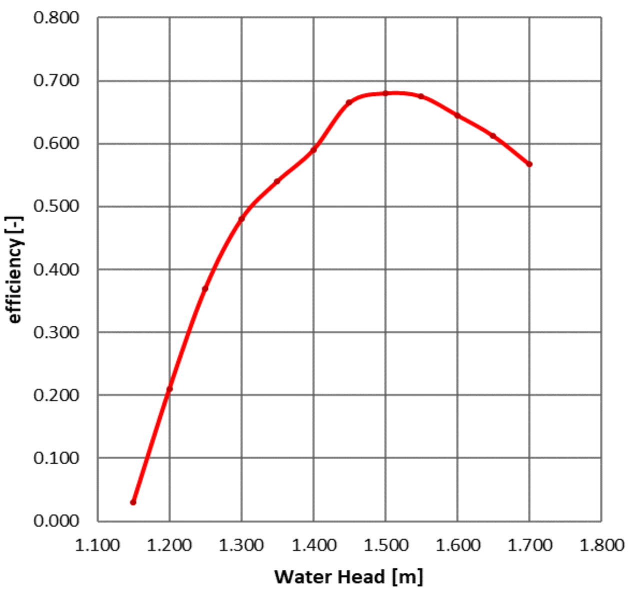

Fig. 8. Efficiency curve as a function of the hydraulic head

B. *Deployment of the new PTO system*

The new turbine was installed in the OBREC prototype at the port of Naples (Figure 13). The machine has a diameter of 400 mm and a height from the top of the bulb to the lowest part of the runner equal to 550 mm.

The turbine was installed under the vertical axis configuration. The draft tube, which connects the turbine outlet cross-section to the sea water receipt, has a conical shape, with a diverging cross-section, with a minimum diameter of 400 mm and a maximum diameter of 540 mm. Turbine and draft tube were built by Turbiwatt [14]. The turbine is connected to an intake basin consisting of a tank with dimensions of 2.00 m (width) x 0.80 cm (length) x 1.00 m (height). The tank was shaped in a way to supply water through a properly fitted hole at the bottom (Fig. 9).

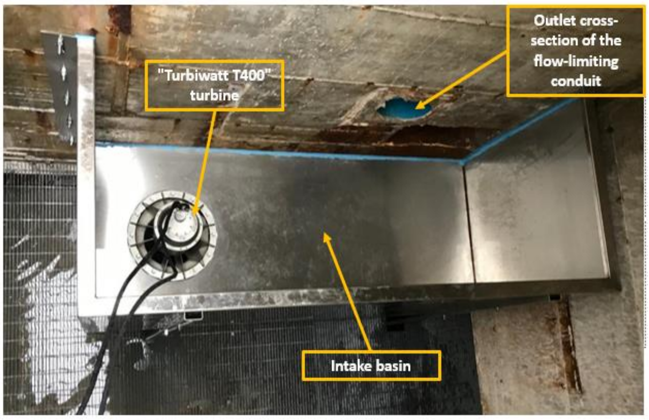

Fig. 9. Upview of the intake basin and the turbine placed inside the reservoir of the OBREC prototype at the port of Naples.

1) *hydraulic circuit reductions losses*

The characterization of the energy losses in the hydraulic system conducted during the first year of research through field measurements allowed for the identification of interventions to be made on the structure in order to improve the water outflow to the sea receipt and to reduce the water level inside the engine room. At this purpose, the discharge outlet openings were enlarged to reduce the head required for water to flow through them. The expansion of the outlet openings was carried out as part of civil engineering works conducted on the structure in 2021. An 800 mm wide and 400 mm high outlet opening was created on the wall opposite the sea, enabling the discharge towards the harbour, which is protected from wave motion, thereby preventing water from flowing back into the engine room caused by waves. This adjustment sensibly improved the hydraulic performance of the device.

2) *Regulation and Control of Electrical Production*

The control strategy of the alternator is crucial to ensure that the converter operates at maximum efficiency. While hydraulic power plant performance is typically based on a fixed head value, in the case of OBREC the head is variable. To ensure high system efficiency at all conditions, a variable-speed control strategy for the alternator was adopted, allowing the turbine to operate close to its maximum efficiency.

From an electrical perspective, the system consists of a primary driving machine (hydraulic turbine) and a permanent magnet synchronous generator (AC brushless) directly connected to the turbine, as shown in Figure 8. The generator is made of neodymium, a rare earth metal or lanthanide, present in the alloy called mischmetal up to 18%. The control system has access to current/voltage measurements of the generator and liquid level in the tanks. The table below shows the manufacturer's catalog of generators, with the selected option highlighted in bold. The choice was made based on the generator with the fewest pole pairs, as the turbomachine becomes more compact with increasing rotational speed for the same processed flow rate.

Extracting power from low short-circuit power three-phase generators, as in this case, presents several limitations if not properly implemented. It is known from scientific literature that low short-circuit power is associated with high series impedance in the circuit. When the generator operates at full power, the current in each line cannot be discontinuous. Therefore, with a conventional three-phase rectifier, all phases conduct for a fraction of the fundamental period. If we consider a rectifier with only 3 diodes for simplicity, when the voltage of one phase exceeds that of the adjacent phases, two phases conduct at the same time. Experimentally, voltage drops are observed across the load. This phenomenon is called overlap and results in a reduction of the extracted power. The problem can be solved by using active rectifiers called "three-phase power factor correction front end".

The following topologies were considered for the application, each with different advantages/disadvantages:

- PFC buck/boost derived,
- Vienna Rectifier,
- Bi-directional active front end.

The first group of conversion systems is the simplest in terms of implementation, cost, and control. Its disadvantages include unidirectionality in power flow and lower efficiency. The Vienna rectifier can achieve higher efficiencies compared to the previous option, higher switching frequencies, and improved electrical quality, but it has the disadvantage of increased control complexity and unidirectionality of power flow. The third group, active front end (AFE), is bi-directional in power flow, allowing the hydraulic system to be used even in calm sea conditions, providing ancillary services to the grid. Furthermore, AFEs can achieve higher efficiencies. The disadvantage is the increased complexity of control. For future system expandability, it is considered appropriate to use this family of converters.

From a control standpoint, focusing on a single phase for maximum power extraction and reduced machine heating, it is necessary to impose zero reactive power and active power equal to the maximum that can be provided. Based on the theory presented above, it is evident that with the proposed approach, the series inductance in the generator, which previously caused the overlap problem, is now necessary for the converter's operation. The final behavior is that of a voltage booster, so the DC bus will be controlled to operate at a voltage higher than 700V.

The design specifications used for sizing the converter are summarized below. It was deemed appropriate to use a commercial drive for this conversion, such as the Bonfiglioli Agile® series.

To limit hardware stress conditions, a 2.2 kW, 400 Veff three-phase drive was selected, such as the AGL402-13 1 F A. The choice is based not only on the system's extensive configurability but also on the internal availability of a basic PLC, which allows the supervision code to be delegated to the drive itself.

IV. CONCLUSIONS

The results of a turbine selection process and optimization for the OBREC prototype installed at the port of Naples were described in the present paper. The design studies aimed to select the optimal turbine by means of numerical simulations conducted through the utilization of the software OBRECsim. The model allowed for the comparison of the hydraulic performance of turbines with a variable machine size. Due to technical, logistic and economic reasons, the study was carried out considering a propeller turbine. Additionally, the code Mecaflux PRO 3d® was used for the design of the runner.

Construction works on the OBREC prototype allowed to improve the hydraulic system serving the turbine. All modifications were based on previous field measurements, which allowed to identify the main sources of head losses in the circuit. The modifications were outlined in the paper, with particular attention to the description of the turbine arrangement inside the intake basin.

Finally, a detailed resume of the main characteristics of the electrical devices and of their control strategy was provided.

Future investigations will be necessary to monitor the new arrangement of the OBREC prototypal plant at the port of Naples and derive the direct measurements of the power generation by the new turbine.

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