PeWEC: preliminary design of a full-scale plant for the Mediterranean Sea

Nicola POZZI [a,1], Andrea BONETTO [a], Mauro BONFANTI [a], Giovanni BRACCO [a],
Panagiotis DAFNAKIS [a], Ermanno GIORCELLI [a], Biagio PASSIONE [a],
Sergej A. SIRIGU [a] and Giuliana MATTIAZZO [a]
[a] *Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy*

Abstract. Nowadays, atmospheric pollution and climate change have encouraged Governments to invest in renewable technologies for clean energy production. Wave Power constitutes an interesting option in the panorama of renewables and starting from the first results achieved in the '70s, in the last and present decade the major efforts have been concentrated to make Wave Energy Converters (WECs) more profitable and predictable. The research activities described in this work concern the development of a pendulum converter (PeWEC: Pendulum Wave Energy Converter), designed for the Mediterranean Sea scenario. In the first part of the paper, the mathematical model describing the floater and pendulum dynamics is presented. The equations previously described are then used to implement a model-based design and optimization methodology. The latter is constituted by three different tools connected in cascade and characterized by an increasing degree of complexity and fidelity. The combination of these tools, together with the evaluation of the plant Levelized Cost of Energy (LCOE), allow to determine an optimal device configuration for the installation site chosen. The methodology is here used to design a preliminary layout of the full-scale PeWEC device, considering the Pantelleria Island (Italy) wave climate as reference.

Keywords. Wave Energy, Mediterranean Sea, Wave Energy Converter, pendulum, design methodology, full-scale plant.

1. Introduction

Every historical period has some important challenges to deal with. Nowadays, the most important problems are related to climate change, pollution, limited energy resources (fossil fuels) and a continuous increase of energy demand.

Looking at the last decades, several efforts were performed in the CO_2 emission reduction, improving energy efficiency and increasing power generation from renewable energy sources (RES) [1]. In the renewables context, Ocean Energy offers a remarkable potential around the World, distributed on different sources, such as waves, tidal, ocean currents, ocean thermal energy and osmotic power [2]. Starting from the '70s, several studies have been carried out to make Wave Energy Converters (WECs) more profitable and predictable. However, the harsh and hostile marine conditions can cause problems in

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[1] Corresponding Author: Department of Mechanical and Aerospace Engineering, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy; E-mail: nicola.pozzi@polito.it

durability. For instance, during extreme weather conditions, structural loads can be one hundred times the rated ones.

Considering the Mediterrean Sea scenario, the calmer and semi-enclosed sea offers a lower amount of energy, but the milder extreme wave climate facilitates the technical issues related to these events. Clearly, because of the lower amount of energy available, an accurate design and engineering of the WEC is required, in order to make energy production still economically viable [3][4].

The research activities described in the present work are concerned with the development of a pendulum converter (PeWEC: Pendulum Wave Energy Converter), optimized for the Mediterranean Sea wave climate. The design of the preliminary layout is performed through a model-based methodology. The latter is constituted by three different tools, arranged in cascade and characterized by an increasing degree of fidelity and thus by an increasing computational cost. This means that the lighter models are used, at the begin of the design process, to perform a preliminary identification of the main system's physical parameters, while the final layout refinement and verification through the high-fidelity model can be performed on a small set of consistent device configurations. The design methodology is also combined with the evaluation of the project Levelized Cost iof Energy (LCOE). This step is fundamental to evaluate a cost effective ness of the solutions under investigation [5][6].

In the final part of this paper, the design and optimization algorithm is used to evaluate a preliminary full-scale PeWEC layout, suitable for the Pantelleria Island (Italy) wave climate.

2. The PeWEC device

2.1. Working principle

The PeWEC device is an offshore, floating, single body, pendulum-based Wave Energy Converter. It is mainly composed of a floating hull moored to the seabed and a pendulum connected to the shaft of an electrical generator, which is fixed on the hull structure. The generator shaft constitutes itself the pendulum's hinge. In Figure 1, a scheme of the device is reported.

Pendulum, electrical generator and all other auxiliary equipment are enclosed inside the hull. Therefore, they are protected against the corrosive action of sea water and a greater level of durability is guaranteed.

The PeWEC working principle can be explained by using the bi-dimensional representation depicted in Figure 1. As the waves tilt the floater, it begins its motion along surge, heave and pitch directions. Since pendulum hinge is integral with the hull structure, it moves in the space with it and as consequence, pendulum oscillations are induced. The relative rotation of the pendulum with respect to the hull is used to drive the Power Take Off (PTO). The pendulum oscillations are damped by PTO, allowing the energy extraction from the device [7]. The PeWEC is also classified as passive device, since it does not need to be powered to produce inertial effects [8].

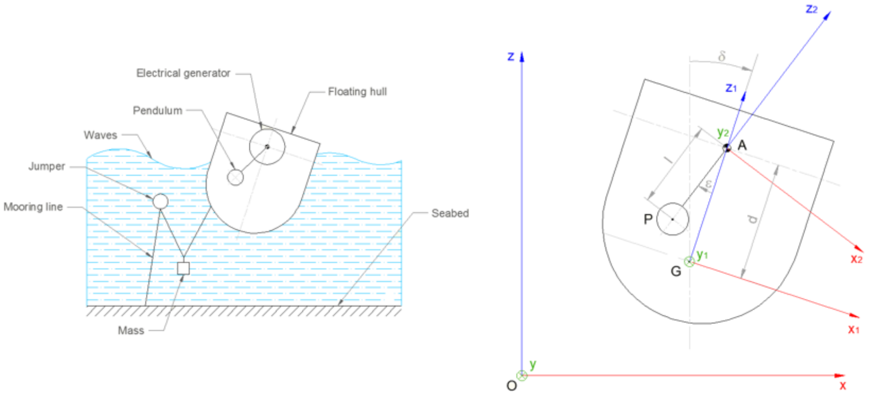

Figure 1. The PeWEC scheme (left) and reference frames (right) [7].

2.2. *Mathematical model*

The complex problem related to the computation of a Wave Energy Converter (WEC) dynamics, while undergoing to the action of the waves, can be often simplified and described through lumped parameters models. This branch of models is generally used for the implementation of model-based design strategies, since they constitutes a reasonable compromise between computational costs and accuracy [9].

The Cummins equation is widely used in ocean engineering for the evaluation of the dynamics and hydrodynamic loads of marine structures [10]. In general, linear assumptions are fulfilled however, in the case of WECs, it is known that the power extraction is optimal when the device is resonant with the frequency of the incoming wave [11]. In this operating condition, the motions amplitude can be very large and nonlinear viscous phenomena induced by vortexes and the intrinsic viscosity of the fluid can occur [9][12]. Therefore, Cummins equation needs to be improved introducing such nonlinearities.

The hydrodynamic model can be coupled with the inner pendulum dynamic equations expressed with respect to the fixed-Earth coordinate system $O-xyz$. Such equations can be derived starting from the set of reference frames reported in Figure 1 and considering the planar representation of the system (based on the assumption that pendulum does not exchange forces along y axis).

Eq. (1) summarizes the nonlinear time domain dynamic model of the PeWEC device, including both hydrodynamic and pendulum equations.

$$\begin{aligned}\left[\mathbf{M_s}+\mathbf{A}\left(\infty\right)\right]\ddot{\boldsymbol{X}}_{\boldsymbol{sys}}+\int_0^t \mathbf{h_r}\left(t-\tau\right)\dot{\boldsymbol{X}}_{\boldsymbol{sys}}d\tau+\mathbf{B_v}|\dot{\boldsymbol{X}}_{\boldsymbol{sys}}|\dot{\boldsymbol{X}}_{\boldsymbol{sys}}+\mathbf{K}\boldsymbol{X}_{\boldsymbol{sys}}= \\ \boldsymbol{F_w}\left(t\right)+\boldsymbol{F_d}\left(t\right)+\boldsymbol{F_m}\left(t\right)+\boldsymbol{F_{gr}}\left(t\right)+\boldsymbol{F_{cor}}\left(t\right)+\boldsymbol{F_{PTO}}\left(t\right)\end{aligned} \tag{1}$$

Where, $\mathbf{M_s}$ is the system mass matrix including both the floater tensor of inertia and the inertial pendulum actions discharged on the floater, $\mathbf{A}\left(\infty\right)$ the added mass matrix evaluated for a infinite frequency and $\mathbf{K}$ the floater restoring matrix. The convolution integral models the radiation forces induced by the body motions. Its numerical computation can be particularly time consuming and for this reason it is generally approximated through a state-space approximation, as suggested by Pérez and Fossen in 2009 [13]. $\mathbf{B_v}$

represents, instead, the matrix containing the nonlinear viscous force coefficients, that can be estimated through experimental free-decay tests or fully-viscous CFD simulations [9][12].

$\boldsymbol{F_w}(t)$ and $\boldsymbol{F_d}(t)$ are, respectively, the first-order and second-order wave forces, while $\boldsymbol{F_{gr}}(t)$ is the gravitational action due to the pendulum mass and $\boldsymbol{F_{cor}}(t)$ the Coriolis force due to the pendulum hinge motions in the vertical plane $O-xz$. For the sake of brevity, the full mathematical expression of such terms has not been reported here, but more details can be found in [7]. $\boldsymbol{F_{PTO}}(t)$ corresponds to the control force acting on the PTO, while $\boldsymbol{F_m}(t)$ includes the mooring line forces discharged on the floater. $\boldsymbol{X_{sys}}$ is a vector containing the system kinematic variables, that in this case are: surge (x), heave (z), pitch (δ) and pendulum angular displacement (ε).

It is also important to highlight that the nonlinear formulation here proposed is valid both for regular and irregular sea states and it can be linearized around the floater and pendulum equilibrium position [7].

3. Full scale PeWEC design and optimization methodology

The model-based design and optimization methodology is widely used in several engineering fields, including Wave Power, to aid in the development of cost effective solutions.

In this work, an algorithm for the development of the PeWEC full scale device layout is proposed. It is constituted by three different Wave-to Wire models arranged in cascade, that allow to design and optimize the device layout. In the following, the tools composing the design and optimization methodology are listed.

1. *PeWEC Linear Optimization Tool.*
2. *PeWEC Design Tool.*
3. *PeWEC Parametric Tool.*

Degree of fidelity and computational costs increase moving from the first to the third tool. This means that the lighter model is used, at the begin of the design process, to perform the identification of the main system physical variables while the layout refinement and verification through the high-fidelity model can be performed on a small set of consistent configurations.

The identification of the optimal solution, in the case of the energy production plants, is in general individuated through the Levelized Cost of Energy (LCOE), that takes into account both device performance and costs. For this reason, this parameter has been included in the methodology here proposed to determine the optimal device layout among the ones under investigation.

3.1. PeWEC Linear Optimization Tool

The *PeWEC Linear Optimization Tool* is based on the linearized PeWEC frequency-domain dynamic equations, that for the sake of brevity have not been here reported. As already mentioned, more details can be found in [7]. This tool has been designed to extrapolate a preliminary optimized device configuration, in term of pendulum mass, inertia, length and hinge position (free parameters), once the floater geometry, hydrodynamic database and device overall mass are defined. Regarding the hydrodynamic database, it has been computed through a potential flow code (Ansys AQWA, [15]).

More in detail, a parametric run tries all the possible combinations of the free parameters within a range defined by the user. Meanwhile, the program performs also a series of tests, in order to avoid the computation of unrealistic configuration where, for instance, the pendulum cannot be located inside the hull or the ballast quantity exceed the space available. In Figure 2, a sketch of the device cross-section computed by the optimization tool is reported.

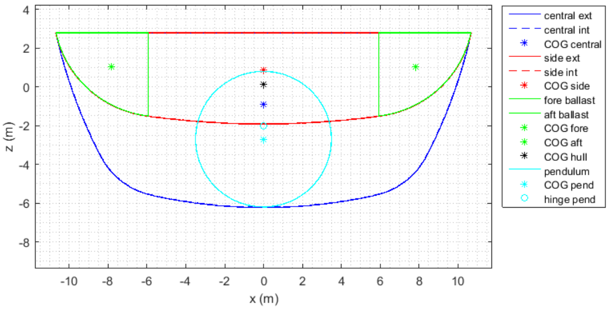

Figure 2. Scheme of the device cross-section computed by the *Linear Optimization Tool*.

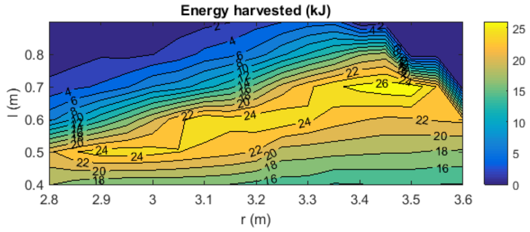

Figure 3. Harvested energy map, as a function of the pendulum radius r and length l.

The optimal configuration is then identified searching the combination of free parameters associated to the layout that maximizes the extracted energy. For instance, Figure 3 shows the harvested energy map as a function of the pendulum radius r and length l (here it is supposed to be to be an eccentric disk with radiur r and eccentricity l, as depicted in Figure 2).

A constraint related to the installation site occurrences distribution is also introduced in order to take into account the relationship between the device dynamic response and the site wave climate characteristics. In Figure 4, the Pantelleria Island occurrences scatter diagram is reported together with the frequency-domain average extracted power. It is possible to note that the maximum device performance occurs around 6 s wave period, where the maximum occurrences are located. Moreover, in the same figure, the comparison between the optimal and a generic sub-optimal configuration frequency-domain average extracted power function is reported.

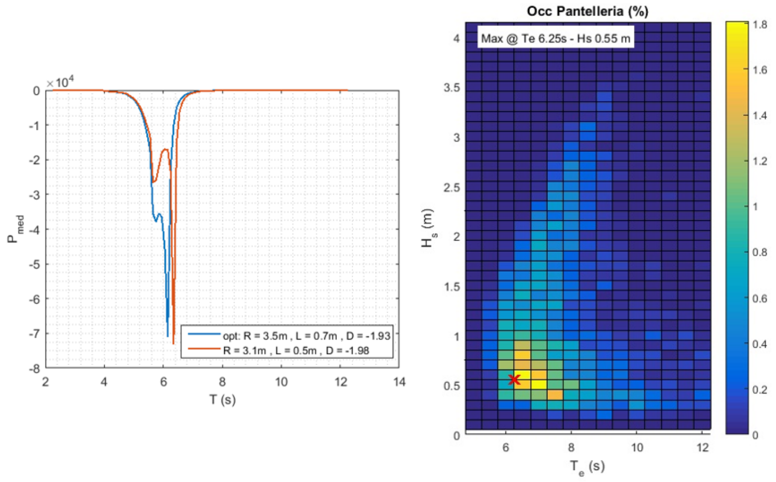

Figure 4. Comparison between the optimal and a generic sub-optimal configuration frequency-domain average extracted power function (left), Pantelleria Island occurrences scatter diagram (right).

3.2. *PeWEC Design Tool*

The *PeWEC Design Tool* is based on the linearized time-domain dynamic equations of the system. This tool has been developed starting from the *ISWEC Design Tool*, implemented at the Politecnico di Torino by Sirigu and Vissio [16]. The idea of this program was to obtain a sufficiently reliable and fast program able to optimize the net average extracted power over the entire scatter diagram, together with the possibility to carry out quickly and easily some preliminary information about the WEC dynamics.

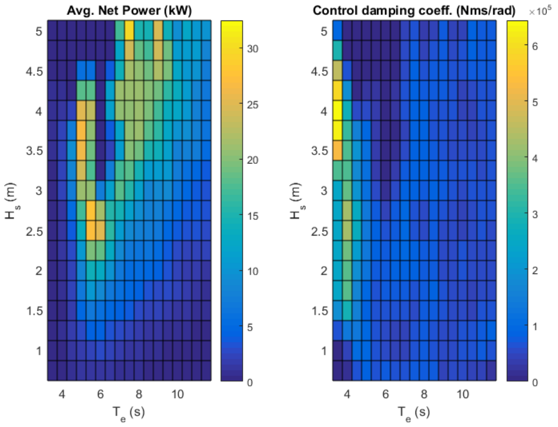

Figure 5. Net average power matrix (left) and optimal PTO damping coefficient matrix (right).

In this work, the *ISWEC Design Tool* has been improved expanding the hydrodynamic model from one DOF (pitch) to three DOFs (surge, heave, pitch), introducing the linear hydrodynamic viscous damping, the linearized mooring characteristic and substituting the ISWEC gyroscope linear dynamic equations with the pendulum linearized mechanical equations. Moreover, the *PeWEC Design Tool* has been connected in cascade with the *PeWEC Linear Optimization Tool*, allowing to simulate the time-domain behavior of the optimal configuration carried out through the *PeWEC Linear Optimization Tool*. The simulation is performed considering the irregular sea state and over the entire site scatter diagram. In Figure 5, an example of net power matrix and optimal PTO damping coefficient map are reported. Note that maps are a function of the significant wave height (H_s) and wave energy period (T_e).

3.3. PeWEC Parametric Tool

The *PeWEC Parameteric Tool* solves the PeWEC nonlinear dynamic equations, including nonlinearities due to mooring line, hydrodynamics phenomena and PTO saturations.

The idea of this tool is to perform and optimization of the device net productivity taking into account the pendulum bearings friction dissipation, bearings life and maximum stresses on the structure and PTO. Therefore, the *PeWEC Parameteric Tool* can be used to verify the optimal layout carried out through the previous tools. Moreover, it is particularly suitable to assess the correct PTO size and thus its influence on the device productivity. The latter is fundamental for the estimation of the Levelized Cost of Energy (LCOE).

4. Full scale PeWEC layout design

The design and optimization algorithms presented above have been used to determine a preliminary layout for the PeWEC full scale plant, assuming the Pantelleria Island site wave climate as reference. A specific floater geometry, here identified with the label *C19* and represented in Figure 6 has been tested. More in detail, four versions of such geometry are analyzed in term of dimensions and the respective features are summarized in Table 1.

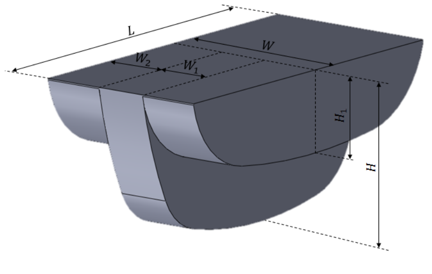

Figure 6. *C19* floater geometry.

Different pendulum mass values have been selected (60, 90, 135, 203 *tons*) in order to evaluate the optimal value. Figure 7 shows the productivity computed through the *PeWEC Design Tool*, as a function of the pendulum mass and of the flotater version. It is possible to highlight that the 135 *tons* pendulum mass is the optimal value for all the configurations investigated and that the *C19A* is the optimal configuration in terms of productivity.

Table 1. Floater family *C19* properties.

Code	L (m)	W (m)	W_1 (m)	W_2 (m)	H (m)	H_1 (m)	*Draft* (m)	Δ (*tons*)
C19A	21	10	3	3.5	9	4.7	6.2	518
C19B	19	10	3	3.5	8	4.8	4.9	402
C19C	16	10	3	3.5	8	4.8	5.4	323
C19D	16	8	2.5	2.75	8	4.8	5.4	302

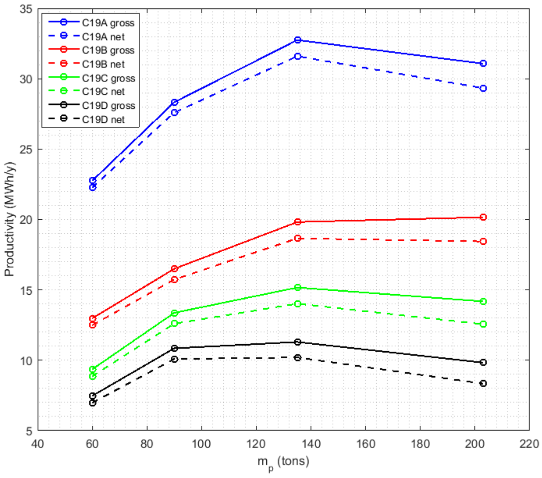

Figure 7. Productivity computed through the *PeWEC Design Tool*, as a function of the pendulum mass and of the four floater configurations proposed.

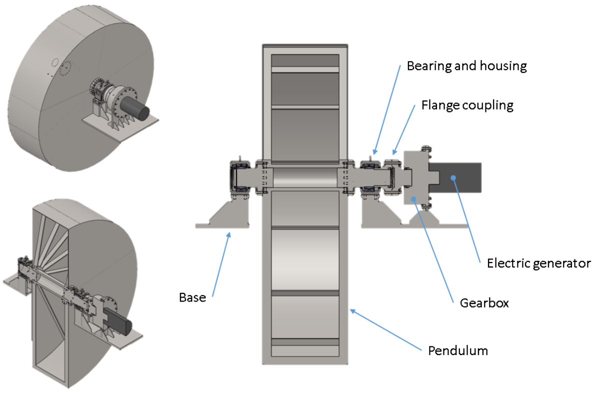

Figure 8. 3D CAD model of the pendulum and PTO subsystem.

The optimal pendulum mass and dimensions, estimated through the *Linear Optimization Tool* and validated through the *PeWEC Design Tool*, were used as input for a mechanical design of the swinging mass. A 3D CAD representation of the layout is depicted in Figure 8. The pendulum is constituted by an external reinforced steel structure filled with concrete (not represented in Figure 8). This solution allows to achieve the desired pendulum mass and a suitable strenght of the structure, maximizing the quantity of the cheaper material (concrete) and minimizing the quantity of the more expensive material (steel).

Lastly, the optimal layout determined per each floater version has been simulated through the *PeWEC Parametric Tool*, considering three different PTO solutions (in term of torque) available on the market. In particular, permanent magnet torque-motors have been here considered. Table 2 summarizes the characteristic of the motors taken into account.

Table 2. Electric PTOs features.

Description	Symbol	PTO 1	PTO 2	PTO 3	U.M.
Rated torque	T_{rated}	4950	6900	3450	*Nm*
Max. torque	T_{max}	8150	11400	5700	*Nm*
Rated speed	n_{rms}	250	250	250	*rpm*
Max. speed	n_{max}	440	460	460	*rpm*
Rated power	P_{rated}	130	181	90	*kW*
Max. power	P_{max}	137	209	105	*kW*

The last part of the design process has been dedicated to the evaluation the economic aspect of the project. The parameter considered in this work is the LCOE (Levelized Cost Of Electricity), through which is possible to compare different technologies (e.g. wind, solar, natural gas, etc.) of unequal life spans, project size, capital cost, risk, return and capacities on a consistent basis [6][7]. Eq. (2) shows the LCOE analytical expression.

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX}{\left(1+r\right)^{t}}}{\sum_{t=1}^{n} \frac{E_t}{\left(1+r\right)^{t}}} \tag{2}$$

Where, CAPEX is the initial investment, OPEX is the operating and mainternace expenditure and E_t the device productivity. CAPEX has been calculated splitting the entire system in its main subsystems, as reported in Figure 9.

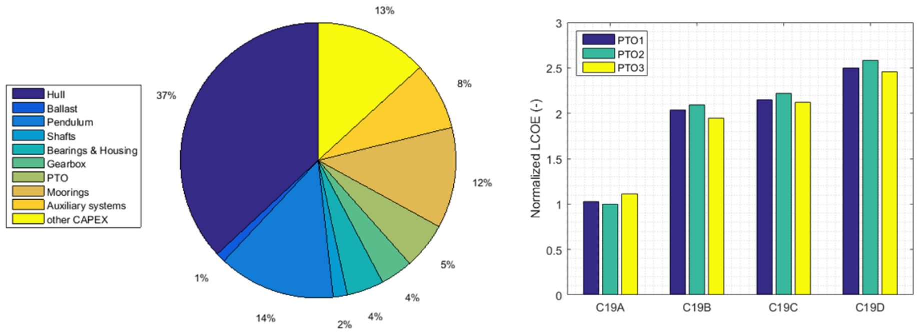

Figure 9. PeWEC CAPEX percentage composition (left) and normalized LCOE, as a function of the floater version and of the PTO size (right)

Floater, pendulum, pendulum shafts and ballasts costs have been calculated considering unit prices $\left(\frac{€}{kg}\right)$, that include both material and manifacturing costs. On the other hand, bearings, gearbox, PTO, moorings and auxiliary systems costs have been estimated considering detailed quotations of solutions available on the market. Lastly, *other CAPEX* includes engineering and installation costs.

OPEX has been estimated as the 2.5% of the overall CAPEX. This assumption is commonly used in literature, especially when specific information are not available (e.g. in the initial stage of the project).

In the right graph of Figure 9, the LCOE normalized with respect to the optimal solution (C19A, PTO 2) is reported, as a function of the floater configuration and of the PTO version. The configurations C19B, C19C and C19D show a LCOE 2 – 2.5 times higher that the optimal configuration. This is due to a weak productivity of such layouts. Regarding configuration C19A, it is possible to point out that PTO 2 allows to mimimize the LCOE value, while a smaller PTO (PTO 3) induces a sensible reduction of productivity that, as consequence, produce an increment of the LCOE. From this analysis it is possible to conclude that the floater equipped with a 135 *tons* concrete filled pendulum (external diameter equal to 3.5 *m* and 0.7 *m* eccentricity) and equipped with PTO 2 is the optimal solution. In Figure 10, a 3D CAD view of the optimal layout is reported.

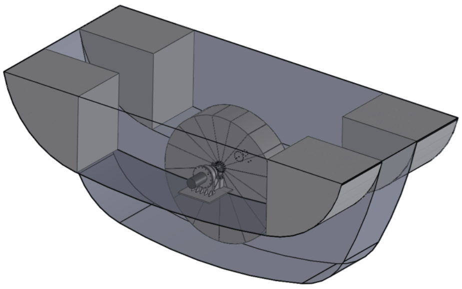

Figure 10. 3D CAD model of the optimal full scale PeWEC layout.

5. Conclusions

This paper deals with the development of a model-based design and optimization methodology for the identification of the optimal layout of a full scale pendulum wave energy converter. It is constituted by three different models arranged in cascade and characterized by an increasing degree of complexity, fidelity and thus computational cost. This arrangement favours a fast identification of the main device features at the begin of the design process, while the final refinement can be performed on a consistent and feasible device configuration. The design methodology is also combined with the evaluation of the project Levelized Cost iof Energy (LCOE). This step is fundamental to evaluate a cost effectiveness of the solutions investigated.

The context of the Mediterranean Sea is considered and the design algorithm proposed in this work is used to identify an optimal full scale PeWEC layout for the Pantelleria Island (Italy) wave climate. The design process allowed to optimize the most important system variable, such as the pendulum mass and inertia, pendulum hinge vertical position and PTO size, once the floater geometry was defined. In particular, four different floater geometries were investigated and a cost effective configuration was identified on the base of the LCOE.

Further work will regard the investigation of new floater and pendulum geometries, different installation sites and the integration of the Nemoh potential flow code into the *PeWEC Linear Optimization Tool*. The aim is to avoid the necessity to use and external code (Ansys AQWA) not programmed in the Matlab ® environment.

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