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Dimensioning Methodology for Energy Storage Devices and Wave Energy Converters supplying isolated loads

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Abstract: One of the big issues ocean wave energy faces nowadays is the oscillation of the generated power. Among others, energy storage is a solution that has been widely proposed and validated for an adequate grid or isolated load integration. However, the unpredictability of ocean waves may pose a challenge when specifying the Energy Storage System (*ESS*) technology and specifications, especially in the case of stand-alone operation. This article presents a suitable methodology for the design of a certain Wave Energy Converter (WEC) and the calculation of a certain stochastic model of the latter necessary for the subsequent sizing of the *ESS*. As a result, the storage system is defined in terms of energy, power and type of technology for the specific *WEC* and chosen location. The problem is accomplished in the paper describing systematically the method and solving a particular example of the design of a wave converter in the Gulf of Mexico.

1. Introduction

One of the big issues for ocean wave energy to overtake the pre-commercial stage is the grid or load integration. As with wind power, wave power devices have the challenge of meeting the criteria of power quality [1–3] and frequency stability. When a *WEC* is connected to the electric grid, power quality problems and interruptions need to be avoided as a result of their important economic and security impacts [4]. Some of the typical disadvantages are: the oscillation of active power disturbs frequency control and causes voltage variations; the fact that some systems do not control reactive power and therefore do not contribute to voltage control; disconnection of the plant in case of grid fault would produce a loss of generation capacity. However, when a *WEC* connects with an isolated load some of the considerations are quite different, remaining others the same. The special requirements of the stand-alone operation will be explained through this article.

Due to the special characteristics of wave power extraction, especially some particular wave converters with direct-drives [5], there is an important impact of low frequency oscillation in the amplitude of the electric power, with periods of oscillation ranging from a few seconds to a few dozens of seconds [6]. There are several alternatives for the smoothing of power oscillations. Among these alternatives, it is already demonstrated that energy storage can increase the potential penetration of marine energies into the electric grid [7], while improving its performance [8].

Although energy storage can be also used to supply on-shore electrical substations or grids [9], this application is not analysed in this work. The present paper deals with the design of *ESS* to compensate the power oscillations produced by different types of *WEC* [10] and to ensure the power supply to on-board loads in *autonomous WECs*, named *AUTOWECs*. These *AUTOWECs* are suitable to supply meteorological stations, coastal security networks [11], aquaculture [12], mobile phone antennas, light signalling [13], desalinization [14], etc.

ESS operation principle is based on that the generated energy over certain value would be stored and the energy below it would be delivered when required by the control strategy [15–17]. In order to accomplish this procedure several technologies can be evaluated to check their suitability, depending on the power peak, the amount of energy compared to power, the number of operation cycles, the volume and mass restrictions, the accessibility for maintenance, environmental issues, cost limitations, etc.. Batteries, supercapacitors and flywheels are examples of devices that could accomplish this purpose [6, 15].

The paper presents a methodology to calculate the required power and energy values for an *ESS*, essential information to define the value of a continuous output power provided to the load (or to the grid), and to select the most appropriate storage technology depending on the particular *WEC*, payload and location. The problem of grid connection is significantly different to the problem of stand-alone operation [18] in terms of power and energy calculations, the control strategy consideration, and the power converters dimensioning and operation. The paper is focussed on the sizing of energy storage for isolated loads, which is more challenging than the case of grid connection as a result of the need for a long-term energy back-up.

According to the classification proposed in [15], the methodology proposed is focused on power reliability, in a similar way as [19, 20] (instead of cost reduction, a more suitable option for grid-connected systems [7, 21]). In addition, it is set as a probabilistic approach [7, 15] by means of an appropriate model of the resource and the *WEC*, instead of a sequential simulation approach [22]. In wave energy generation, the dimensioning methods are mainly focused on power quality for grid-connected systems [7, 21, 23]. Some stand-alone examples, such as [24], do exist; however the *ESS* is sized only in a short-time horizon (drawing away the problematic seasonal patterns of waves). In summary, the presented *ESS* dimensioning methodology faces the problem of assuring a continuous power supply to a stand-alone load through a *WEC* by means of a stochastic approach [25].

2. Description of the ESS Dimensioning Methodology

The methodology has been previously outlined in [25]. The analysis has to take into account that power oscillations are not defined along a timeline; rather they occur with a certain probability. Thus, it becomes necessary to develop a stochastic analysis for their study. The proposed methodology is divided in two stages:

- STAGE I: The calculation of the probability of every amplitude of the *WEC* generated power (P_g) oscillations.
- STAGE II: The study of these oscillations and their probability to obtain the storage necessities: in short-term (in each wave oscillation, E_{cycle}), medium-term (to level the power during a 24-hour period, E_{day}) and long-term horizon (considering longer periods, E_{year}).

For autonomous on-board loads, the *ESS* design should accomplish the three temporal scales (whereas for grid-connected systems only the short-term (and perhaps the medium-term) would be considered in order to face the power quality problems).

2.1. AUTOWEC Example Definition

The autonomous *WEC* (*AUTOWEC*) proposed is composed of a 2-body point absorber [26], a linear generator acting as a Power Take-Off (*PTO*) [27], an *ESS* and a particular load. The load (P_{load}) is defined as a constant electric load of 350W (P_{LOAD}).

The *ESS* dimensioning methodology is outlined to a specific *AUTOWEC*, located in the *Gulf of Mexico* (25.888 N 89.658 W). Namely, the data from the location are the annual wave energy spectrums profile and the annual sea-state occurrence table in terms of two wave spectral parameters: the significant height (H_s) and peak period (T_p) [28], obtained from the meteorological and oceanic data of the *NOAA-NBDC* Station 4200 [29] (Fig. 1.a). The needed data from the *AUTOWEC* are its expected electric power matrix ($[E(P_{elec}(H_s,T_p))]$), the relative velocity spectral moments ($[m_{n,vr}]$) and the energy extraction strategy ($[F_{PTO}(H_s,T_p)]$).

The design of the *AUTOWEC* [30, 31] is faced in the paper by means of an optimization method. It defines a suitable *AUTOWEC* geometry and equally suitable *PTO* rated values (force, velocity and stroke), in order to apply the dimensioning methodology (sections 2.2, 2.3). The formulation of the optimization problem implies the selection of the design variables, constraints, objective functions and the definition of the *AUTOWEC* model. The *AUTOWEC* design problem is formulated as follows:

- The <u>design variables</u> define the search space of the problem, which defines a particular *AUTOWEC* solution. The variables to be optimized are five dimensions of the point absorber geometry and two *PTO* characteristics: maximum force and stroke (see **Table 1**). To specify the *WEC* geometry, it is necessary to define body-2 tube diameter (R_3, see Fig. 1.d)).

Considering the *PTO* is located inside the tube, R_3 is linked with the PTO size and then it is not a free design variable.

- The objective function is defined with the criteria of maximizing the energy extraction density (ρ_{Eelect}); maximizing the equivalent hours at rated power (h_{eq}) (defined as the annual generated electric energy divided by the *PTO* rated power); and minimizing the mean squared error between generated electric power and load power of each sea-state weighted by its occurrence ($\sum\_{}^{2}{}_{P\_LOAD}$) (see **Table 2**).
- The constraints are conditions to be satisfied for the *AUTOWEC* solutions to become feasible solutions. The aim of the technical constraints is to ensure the matching of the *AUTOWEC* behaviour with the *PTO* characteristics and the location sea-states. Moreover, the constraints ensure the load supply capacity and avoid *AUTOWEC* dynamic situations that can damage itself (see **Table 3**). The constraints are defined in similar way as in [32].
- The mathematical model allows the evaluation of the constraints and the objective functions using the design variables. The model used describes the dynamic of a 2-body point absorber and the behaviour of the *PTO*. The hydrodynamic coefficients [28] are evaluated by means of a *MEE* (Matching Eigen-function Expansion) method [33]. The stochastic model [34] allows to obtain statistical and probabilistic information about the mechanical variables; such as expectable values (as statistical property) or oscillation amplitude probability functions.

Table 1 Design Variables list

Design Variable	WEC part to be designed	Description
R_1	Point Absorber	Body 1 radius
d_1	Point Absorber	Body 1 draft
R_2	Point Absorber	Body 2 plate-radius
d_2	Point Absorber	Body 2 plate-height
d_3'	Point Absorber	Body 2 tube-length
F_{PTO}	PTO	Rated Force of the linear generator
s_{PTO}	PTO	Maximum Stroke of the linear generator
Definition of an *AUTOWEC* Solution		
X=[R_1, d_1, R_2, d_2, d_3', F_{PTO}, s_{PTO}]		

Table 2 Objective Functions list

nº	Objective Function	Aim
f_1	max (ρ_{Eelect}),	Maximize the use of the volume (~costs) of the *AUTOWEC* in order to extract energy
f_2	max(h_{eq})	Maximize the use of the nominal characteristics of the *PTO* (~costs)
f_3	min ($\sum\_^{2}{}_{P\_LOAD}$)	Maximize the suitability of the WEC and PTO to the LOAD power (minimizing the *ESS* requirements)

Table 3 Constraints list

nº	Description	Limit Variable	Aim	Description
g_1	Minimum Expected Extracted Power	P_{PTO} (: Rated electrical *PTO* power)	PTO suitability	Electric generated power values should be above a certain percentage of P_{PTO} in the sea-states with more occurrence
g_2	Maximum Expected PTO velocity	v_{PTO} (: Rated *PTO* velocity *PTO*)	PTO suitability	*PTO* velocity should be under v_{PTO} in the sea-states where the *PTO* is active
g_3	Probability of PTO over-stroke.	s_{PTO} (: *PTO* stroke)	PTO suitability	The probability of the *PTO* over-stroke (where the *PTO* displacement is over s_{PTO}) in the sea-states where the *PTO* is active should be under a certain value (in this example, 1.5^{-5}%).
g_4	Probability of slamming	d_1 (: Draft of the *WEC* body 1)	*AUTOWEC* integrity protection	The probability of the *PTO* over-stroke (where the body 1displacement is over d_1) in the sea-states where the *PTO* is active should be under a certain value (in this example, 1.5^{-5}%).
g_5	*AUTOWEC* resonance frequency	T_r (: period of the most probable sea-state)	Location Suitability	The *WEC* resonance period should be in a certain range (10% in this example) around T_r (in this example 8 s., see Fig. 1b)
g_6	Minimum annual Energy	E_{elect} (: Annual generated electric energy)	Payload Suitability	The value of E_{elect} should be over P_{LOAD} multiplied by an enlargement factor (in this example, 2)

The global formulation of the design *AUTOWEC* optimization problem can be expressed as in (1).

$$find\ X = [R_1, d_1, R_2, d_2, d_3', F_{PTO}, s_{PTO}]$$
$$that\ min\left(\begin{bmatrix} -f_1(X) \\ -f_2(X) \\ f_3(X) \end{bmatrix} = \begin{bmatrix} -\rho_{Eelect}(X) \\ -h_{eq}(X) \\ \Sigma^2{}_{P\_LOAD}(X) \end{bmatrix}\right) and\ subject\ to\ \begin{bmatrix} g_1(x) \\ \vdots \\ g_6(x) \end{bmatrix} \geq 0 \quad (1)$$

The optimization problem set out in (1) is solved by means of a Differential Evolutionary Algorithm (DE)[35], modified according to NGSA-II [36] in order to manage multi-objective functions and according to 'Deb's Rules' [37] in order to manage the constraints.

The result of the problem is a *Pareto* frontier of solutions. The three objective functions lead to the three-dimensional *Pareto* frontier depicted in Fig. 1.c); where ρ_{Eelect}, h_{eq} and $\sum^{2}_{P\_LOAD}$ are represented in the x, y and z axis, respectively. The *Pareto* frontier is composed by *AUTOWEC* solutions that are not surpassed in the three objective functions at the same time by any other solution and all of them are considered equally optimal according to the pre-set out criteria. Fig. 1.c) shows the AUTOWEC solutions belonging to the *Pareto* frontier (marked as magenta points) and their convex hull surface (depicted as a contour lines graph).

For the sake of example, a single *AUTOWEC* solution is selected from the set of *Pareto* frontier solutions as a compromise solution from the three objective functions, avoiding extreme solutions and weighting positively the variables ρ_{Eelect} and h_{eq}. The solution is marked with a blue cross in the Fig. 1.c) and the resulting *AUTOWEC* geometry is depicted in Fig. 1.d). The *ESS* design methodology uses as inputs the electric power generation matrix (calculated with a *WEC* stochastic model, Fig. 2.a) and the probability variance (σ_{vr}) of the *AUTOWEC* relative velocity displacement between the 2 bodies (Fig. 2.b)) and its spectral moments (first and second order: $m_{1,vr}$, $m_{2,vr}$, depicted in Fig. 2.c) and d) respectively). With these data and the following methodology, it is possible to evaluate the energy storage requirements.

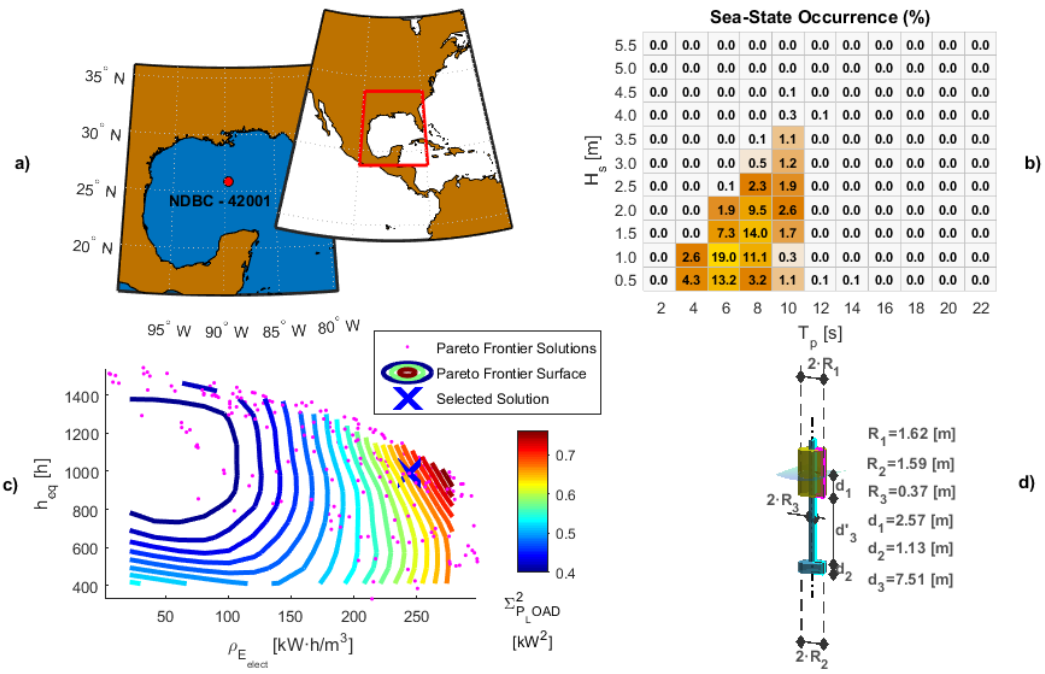


Fig. 1. AUTOWEC design methodology information
a) Geographical AUTOWEC example case Location
b) Sea-State Occurrence Scatter Diagram of the example case Location (from NDBC meteorological buoy 42001[29]*)*
c) Pareto frontier AUTOWEC solutions in terms of the objective functions
d) AUTOWEC solution geometry

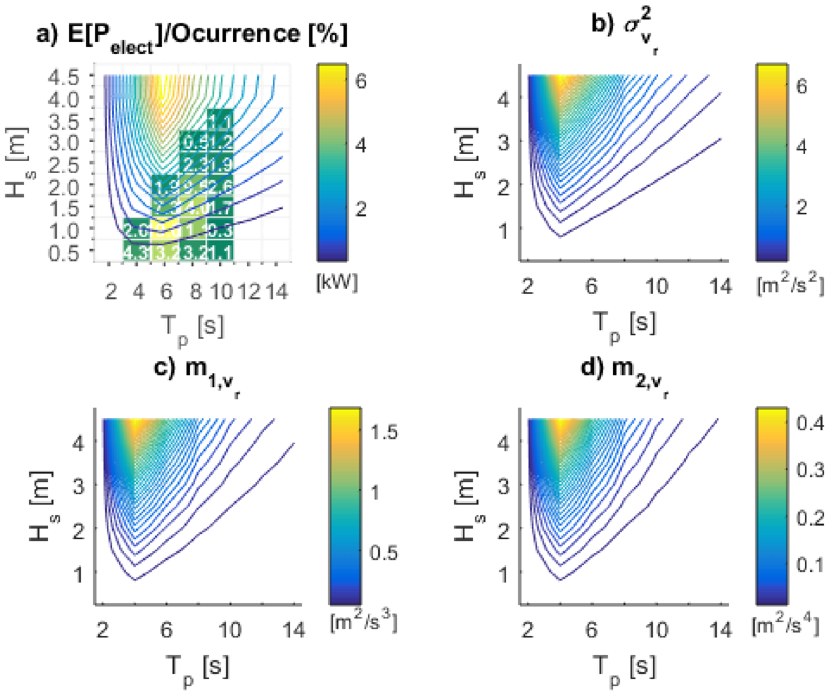


Fig. 2. AUTOWEC Dynamic Stochastic Variables
a) Electric Power Matrix generated by the WEC example case
b) Variance of the Velocity Displacement Power Matrix of the WEC example case
c) First order spectral momentum of the Velocity Displacement
d) Second order spectral momentum of the Velocity Displacement

2.2. Dimensioning Methodology Calculations – STAGE I: Stochastic Analysis

Firstly, the possible incident waves must be compiled in order to obtain all the possible generation profiles. However, due to the unpredictability of waves, it is not feasible to obtain the amplitude of waves in a deterministic way. Instead of that, it is possible to obtain the probability joint distribution (*PJD*) of the wave amplitudes and periods using the approximation presented by *Longuet-Higgins* [38]. This approximation is shown in its non-dimensional form by means of the equations (2), (3), (4), (5) and (6).

$$p(R,T) = \frac{2}{\pi^{1/2}\cdot\nu}\,\frac{R^2}{T^2}\,e^{-R^2\cdot\left(1+\frac{\left(1-\frac{1}{T}\right)^2}{V^2}\right)}L(\nu) \tag{2}$$

$$L(\nu) \approx 1+\frac{1}{4}\cdot\nu^2 \quad ; \quad \nu = \left(\frac{m_0\cdot m_2}{m_1^2}-1\right)^{\frac{1}{2}} \tag{3}$$

$$R = \frac{\rho}{(2\cdot m_0)^{\frac{1}{2}}} \tag{4}$$

$$T = \frac{\tau\cdot m_1}{2\cdot\pi\cdot m_0} \tag{5}$$

$$m_n(\omega) = \int_0^{\infty} \omega^n \cdot E(\omega) \cdot d\omega \tag{6}$$

where p is the probability joint distribution (*PJD*) of the wave amplitudes (ρ) and periods (τ) and m_n is the spectral momentum of order n.

Taking into account that the *WEC* dynamics could be considered as a linear model, the stochastic properties of the wave amplitude could be utilized with the *WEC* oscillatory motion. Therefore, the same *Longuet-Higgins PJD* expression may be applied to calculate the relative velocity (v_r) between the two bodies of the *WEC*. However, in order to use (2), the spectral momentums m_{0_vr}, m_{1_vr} and m_{2_vr} (Fig.2) need to be calculated first (as is explained at following).

The STAGE I of the methodology, which takes into account the stochastic characteristics of the ocean wave oscillations to evaluate the generated power oscillations, is summarized in Fig. 3. For each sea-state, the spectrum of the relative velocity (S_{vr}) is calculated from the *WEC* frequency-based model and the energy wave spectrum (S_w), as it is shown in equation (7). From S_{vr}, it is possible to evaluate the spectral moments (m_{vr0}, m_{vr1} y m_{vr2}, as in equation (6)). The frequency-based model is expressed as a transfer function (H_{vr}) between the relative velocity and the wave amplitude.

$$S_{v_r}(\omega) = H_{v_r}(\omega) \cdot S_w(\omega) = \frac{v_r(\omega)}{\rho} \cdot S_w(\omega) \tag{7}$$

After obtaining the v_r spectrum (defined as S_{vr}, [39]) and its spectral moments, its *PJD* function is easily calculated from (2).

Depending on the type of *WEC*, the relation between v_r and the amplitude of the maximum generated power (P_{gmax}) varies. Equation (8) shows this relationship for the case of a 2-body point absorber and the *damping energy extraction control* (7), as defined in [28]. In the case of having an isolated load, the damping control ensures a unidirectional power flow and, qualitatively, a minor *EES* power requirement [40]. It is worth mentioning that the selection of the control strategy has a great impact in the optimum AUTOWEC solution [32]. Hence, other control strategies could lead to different WEC geometries and PTO characteristics.

$$F_g = R_{PTO} \cdot v_r \tag{8}$$

$$P_{gmax} = P_{mec} - P_{losses} = F_g \cdot v_r - K_g \cdot F_g^2 = R_{PTO} \cdot v_r^2 - K_g \cdot R_{PTO}^2 \cdot v_r^2 \tag{9}$$

where P_{mec} is the *WEC* mechanical power, P_{losses} is the *PTO* power losses, F_g is the *PTO* force, K_g is the losses constant [41, 42] (mainly the copper losses) and R_{PTO} is the damping constant of the *PTO* imposed by the energy extraction control. This energy extraction control calculates the R_{PTO} value in order to maximize the electric energy extracted and taking into account the force, stroke and velocity *PTO* limits

(F_{PTO}, s_{PTO} and v_{PTO} respectively) in each sea-state [43]. For the sake of example, this control could be implemented by means of an adaptive control, taking into account the previously mentioned PTO limits by means of force and power levelling control [44, 45].

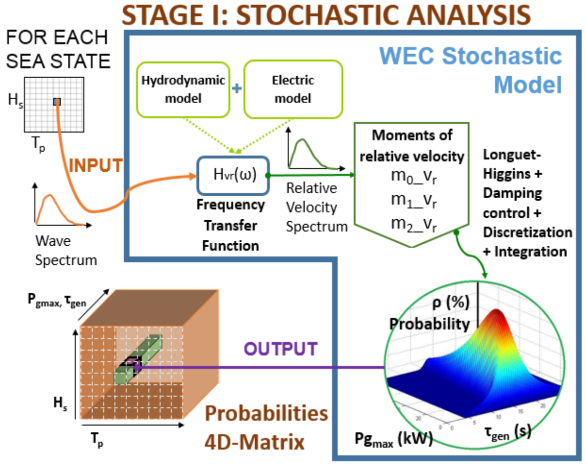


Fig. 3. Graphic Diagram of the STAGE I calculations of the Dimensioning Method.

Thus, a wave oscillation will cause a certain v_r profile that can be related to the oscillation of the P_g through equations (8) and (9), allowing the calculation of the *PJD* of the P_g amplitudes (P_{gmax}) and periods (τ_{gen}). P_{gmax} and τ_{gen} are defined with a constant length (100 elements) and with a range that encompasses the 99.99% of the *PJD* cumulative probability of each sea-state. These two variables define all the possible power oscillations for each sea-state. Consequently, if this process is applied to each sea-state (H_s-T_p), a four-dimensional (4D) probability matrix may be found with axis H_s, T_p, P_{gmax} and τ_{gen} as axes. This matrix will be used to provide the power information used in the energy store dimensioning of the following section.

2.3. Dimensioning Methodology – STAGE II: Power Oscillation Analysis

The analysis of the power oscillation is carried out in three time horizons, short-term (wave period), medium-term (day) and long-term (one year). Time domain is now considered.

2.3.1 Short-Term Analysis: In the short-term analysis, the power generation profiles $P_g(t)$ are analysed. Depending on the control strategy of the *WEC*, they have different shapes. In the case of *damping energy extraction control* (7) $P_g(t)$ can be, approximated to a regular oscillation, and it has a sine squared shape with a mean value of $P_{gmax}/2$, as in equation (9):

$$P_g(t) = P_{gmax} \cdot \left(\sin\left(\frac{2\pi t}{2 \cdot \tau_{gen}}\right)\right)^2 = \frac{P_{gmax}}{2}\left(1 - \cos\left(\frac{2\pi \cdot t}{\tau_{gen}}\right)\right) \tag{10}$$

The value of the power consumption of a stand-alone load or the power injected into the grid is denoted as P_{load} and the rated power of the *ESS* is denoted as P_{ESS}. It is possible to determine the requirements of the

ESS (Fig. 4.a and Fig. 4.b) from these two variables and it is possible to do a parametric analysis of the variation of these two variables (P_{load}, P_{ESS}) for the *ESS*.

Analysing each possible cycle of power generation profile from the sea-state scatter diagram, the *ESS* must storage an amount of energy E_1 during the time when $P_g(t)>P_{load}$ and must deliver a total amount of energy E_2 when $P_g(t)<P_{load}$ (see Fig. 4.a)). Therefore, there is an amount of energy that is self-compensated in every cycle, $E_{cycle}= min(E_1, E_2)$, which is first stored and later delivered during the cycle. Additionally, there is another amount of energy that the *ESS* must store/deliver in each cycle, depending on how is the cycle, defined as E_{backup}. Fig. 4 presents an example of cycle where E_{backup} is positive, which means that there is an extra amount of energy to be stored that will be used in following cycles. The sum of E_{backup} and E_{cycle} defines the storage requirements of the system (P_{ESS}).

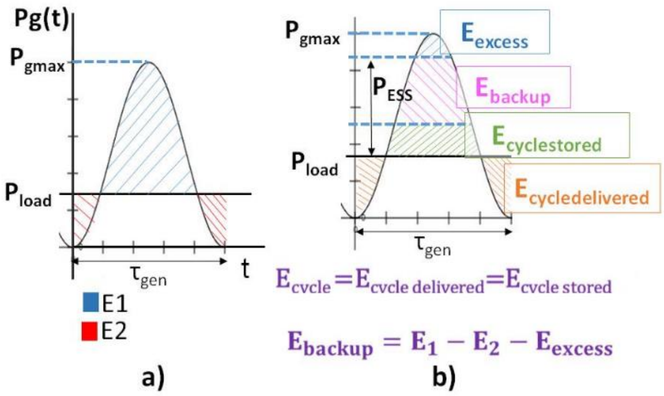
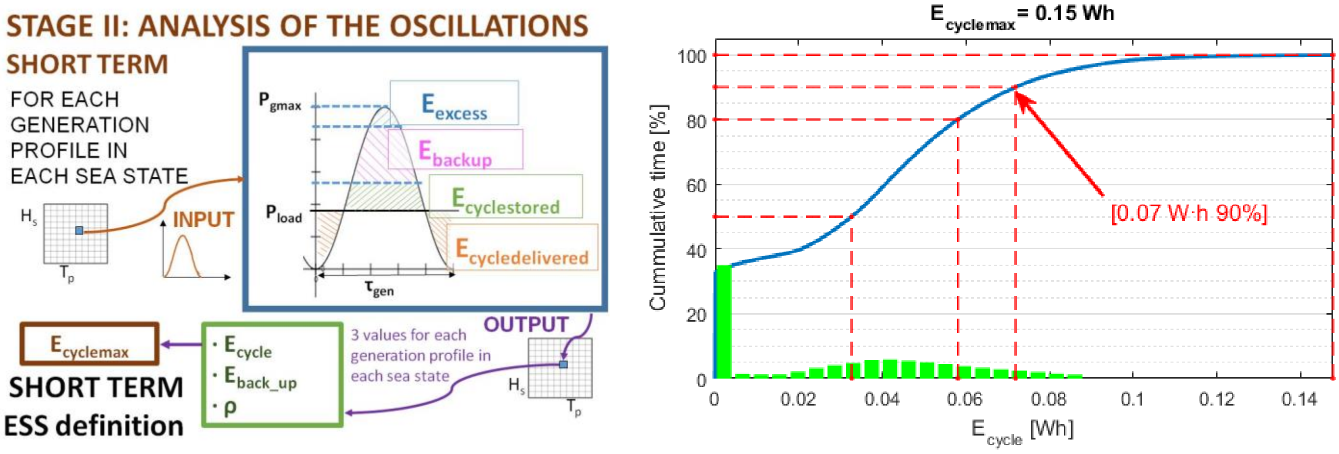


Fig. 4. AUTOWEC power cycle analysis.
a) Electric Generation profile.
b) Cycle Energy representation.

Moreover, when the generated power is higher than the sum of P_{load} and P_{ESS}, a certain amount of energy cannot be used and it must be dissipated in every cycle (E_{excess}). That will be accomplished by means of a DC/DC converter and a dissipative resistor. During this analysis, the power losses of the *ESS* have not been considered. They are not a key factor in the decision of the type of storage but a refined calculation can be done afterwards to consider them.

E_{cycle} is the energy that the *ESS* is able to manage (store and deliver) to smooth the generated power in each cycle (short-term). E_{backup} is the energy that the *ESS* must store along the cycles. When the mean generated power ($P_{gmax}/2$) exceeds P_{load}, $E_{backup}>0$ and when $P_{gmax}/2< P_{load}$ $E_{backup}<0$. In fact, E_{backup} is an energy that must be stored or delivered to guarantee medium-term operation. This process of calculating E_{cycle} and E_{backup} is taken for every possible generation profile in each sea-state of the scatter diagram. The Fig. 5.a shows the general block diagram of the short-term analysis.



a) **b)**

Fig. 5. Short-term analysis of the Dimensioning Method
a) Graphic Diagram of the short-term analysis of the Dimensioning Method. $E_{backup}>0$ *case.*
b) Short-term energy storage necessities vs. cumulative time for a certain P_{load} *and* P_{ESS}

The previous considerations correspond to the *autonomous WEC* case. In the case of grid connection, the mean generated power can be always evacuated into the grid. Thus, E_{backup} is considered null and only E_{cycle} is taken into account for the *ESS* dimensioning. The procedure is simplified and it is just needed to calculate E_{cycle} for every possible generation profile and select the worst case, named $E_{cyclemax}$, to define the storage requirements.

The results of the short-term analysis to dimension an *ESS* (applied to a real wave scenario) show that if 100% of oscillations are aimed to be perfectly smoothed, the requirements of energy storage are relatively high. Therefore, the *ESS* could be designed just to compensate a certain percentage of power oscillations in terms of time. The Fig. 5.b) shows the E_{cycle} needed to guarantee that the *ESS* has enough capacity to completely compensate power oscillations in the short-term during a certain % of the period of time considered in the study (one year in this case). For instante, a cummulative time of 90% means that the *ESS* lacks capacity to completelly compensate power oscillations during 10% of the time but the energy storage requirments are reduced to the half part.

This issue presents some problems when supplying an isolated load since it is quite sure it will not be supplied with energy at any time and will remain non-operative for a short period. That should be taken into account when defining the application, maybe adding and additional back-up power supply if required a 100% of reliability, such as diesel generator or additional renewable energy resource. For instance, the use of photovoltaic – PV panels would be positive in the sense that generation hours during the day are complementary to the wave generation hours [46]). Stand-alone systems only based on wave energy have been proposed by certain companies and researches [11, 12, 14, 47] due to advantages such as its higher power density or its more reliable forecasting [46] (compared with PV).

Although in the case of grid connection the following stages of the method would only be useful to estimate the energy supplied into the grid, they allow the calculation of energy storage devices when isolated loads are faced.

2.3.2 Medium-Term Analysis: Regarding the medium-term time horizon, waves are a random phenomenon where the amplitude and period are not conditioned by the preceding wave, considered as independent events [39]. They will set up a concatenation of waves, with different heights and periods, and therefore a concatenation of wave oscillations. The probability of occurrence of a certain concatenation of wave oscillations (each oscillation defined by its height and period) can be obtained by multiplying the individual probability of each oscillation. This approach implies to solve a complex combinatory problem, simplified with some approximations to reduce the computational load. If a particular wave has a certain probability of occurrence, it is assumed that this wave will occur that percentage of the time. For each day of the year, there is an occurrence sea-state diagram (analogue to the annual diagram of Fig. 1.b)). The value of the occurrence hours (*Hours*) of each sea-state is multiplied by the probability (ρ_i) of occurrence of each generation profile and divided by its period (τ_{gen}), obtaining as a result the number of cycles ($cycles_i$) that every generation profile will occur in that specific day of the year (equations (11) and (12)).

$$cycles_i = \frac{Hours \cdot 3600 \cdot \frac{\rho_i}{100}}{\tau_{gen_i}} \tag{11}$$

$$E_i = E_{backup_i} \cdot cycles_i \tag{12}$$

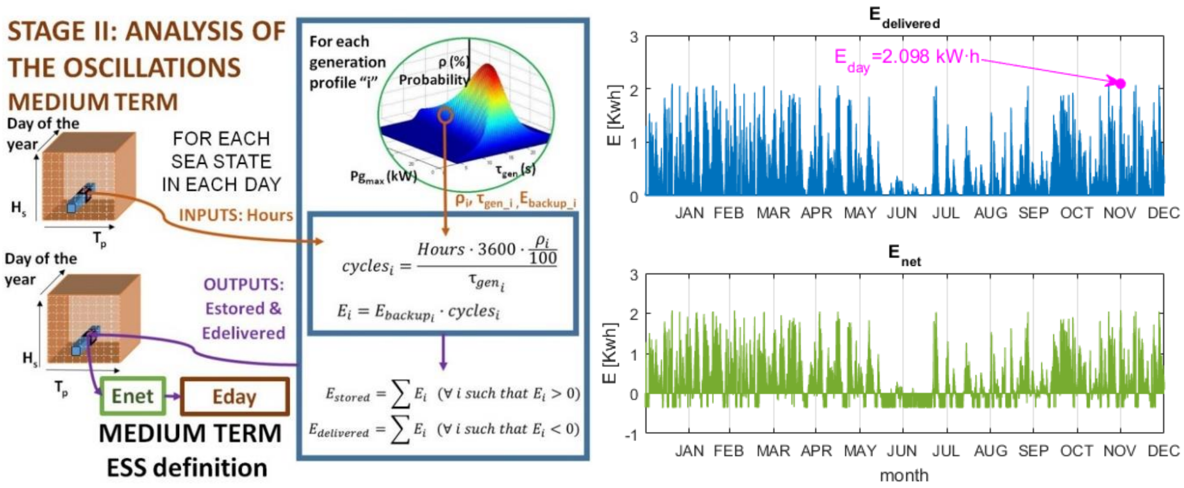
The most restrictive case for each day is defined as follows: all the storage moments ($E_{backkup}>0$) occur consecutively, and all the delivering moments ($E_{backup}<0$) occur in the same way. Two values are obtained: E_{stored} (summation of all positive values of E_{backup} weighted by the number of cycles of each generation curve, equation (13)) and $E_{delivered}$ (summation of all negative values of $E_{backup}<0$ weighted by the number of cycles that this E_{backup} occurs, equation (14)), as presented in Fig. 6.a). Consequently, the final net energy needed to be stored during one day is expressed in (15). It is worth remarking that these most restrictive cases have an occurrence probability of 100% in low energy sea-states, where E_{backup} is negative in each instant (the generated power values are below the value P_{load}). In the AUTOWEC example, these low energy sea-states encompass ~9% of the year. The most restrictive cases definition emphasizes the objective of ensure the load energy supply.

$$E_{stored} = \sum_{i,E_i>0} E_i \tag{13}$$

$$E_{delivered} = \sum_{i,E_i<0} E_i \tag{14}$$

$$E_{net} = E_{stored} - E_{delivered} \tag{15}$$

The Fig. 6.b) shows an example of E_{net} annual profile for the particular case of a 350W load. Although the energy provided along the days seems to be quite high, it can be observed in Fig. 6.b) that some days it is not possible a continuous power supply (power generation is under 350W) to the load and therefore the designed *ESS* should supply energy to the load. Therefore, once defined the load power, $E_{delivered}$ determines the amount of energy to be provided from the *ESS* to the load. Thus, the medium-term energy storage requirement can be found by taking the worst day of the considered days (E_{day}), being 2,098 kWh for the example.



a) b)

Fig. 6. Medium-term analysis of the Dimensioning Method
a) Graphic Diagram of the medium-term time horizon calculations of the Dimensioning Method.
b) E_{net} and $E_{delivered}$ profile of one year for a certain P_{load} and P_{ESS}.

2.3.1 Long-Term Analysis: Concerning the long-term operation, the occurrence of some sea-states is more probable than others so it would be necessary to study the probability of concatenation of certain sea-states in a location. More specifically, the proposed method uses the E_{net} annual profile. It calculates the *ESS* long-term energy stored from the cumulative net energies (E_{net}), taking into account: initial value of the cumulative net energy is the initial state of charge (*SoC*); and the cumulative net energy has a superior bound at the rated *ESS* long-term energy (E_{year}). Thus, it is necessary to define a maximum limit to the energy stored (E_{year}) to impose that the *SoC* is the same at the beginning and at the end of the considered time period (one year in the case of the example) in order to have a zero balance in the charge and discharge of the energy. The Fig. 7 shows the results of these considerations. If the *ESS* supplies 350W to an isolated load and at the end of the year there is no excess of charge or discharge, the design energy value (E_{year}) is 33,78 kWh. This value allows the continuous load power supply during the whole year since the cumulative E_{net} never reaches zero value.

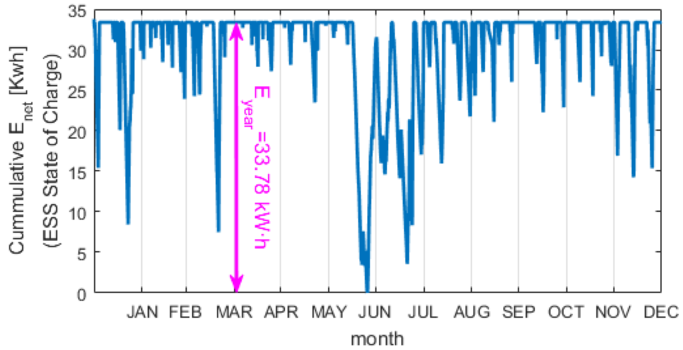


Fig. 7. Cumulative Net Energy (E_{net}) profile of one year with energy storage restriction for a certain P_{load}

3. Results Analysis, Energy Storage selection and conclusions.

Considering the wave profiles and occurrence during a complete year, it is clearly difficult to supply power to an isolated load during the 100% of the time, due to some days of flat-calm seas, to energy-saving reasons and to the seasonal pattern of waves, among others.

Thus, in order to solve the *ESS* dimensioning problem and to select the autonomous load to be supplied by the *WEC* example, a family of curves with different power (P_{load}) has been obtained from the dimensioning method, as shown in Fig. 8.a). From his information, a design decision to select the power to install at the application has to be taken. For a given load power and percentage of stand-by time of the load during the whole year, the energy required for a certain *ESS* (E_{year}) can be obtained. As expected, the more availability required for a certain power load the more energy is required in the *ESS*.

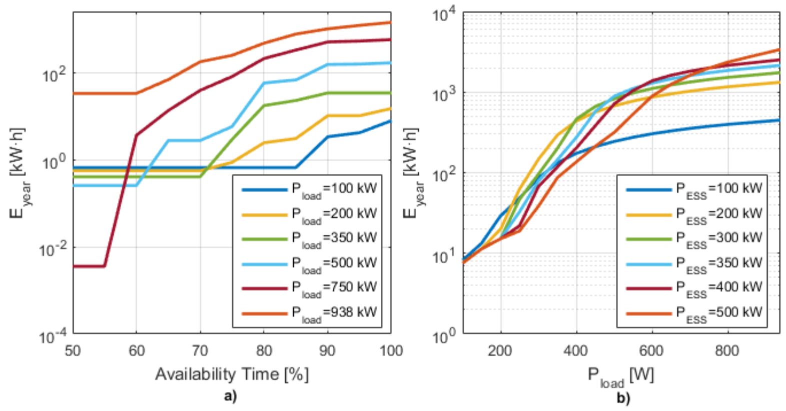


Fig. 8. Parametric analysis of ESS characteristics.
a) Relationship between the energy of an ESS (E_{year}), percentage of available time and P_{load}.
b) Relationship between E_{year} ,P_{ESS} and P_{load}

In order to dimensioning the *ESS* in terms of power (P_{ESS}), the method described in section 2.2 and 2.3 has been applied. The results are shown in Fig. 8.b) for different P_{load} values. Ultimately, the *ESS* rated power P_{ESS} is the variable that defines the excess energy (E_{excess}) dissipated at the resistor (see Fig. 5.a)).

In the case of the example, it is possible to calculate the annual average generated power from the electric power generation matrix (Fig. 2.a)) and the sea-state scatter-diagram (Fig. 1.a)). Specifically, 0,938 kW of annual average power are generated, setting this value the upper limit for a constant P_{load}. The closer gets P_{load} this upper limit, the higher are the energy storage requirements. In this regard, analysing the results from Fig. 8 with P_{load} values over 0,5 kW (included), the necessities of energy storage could be considered excessively high when taking into account the price of the *ESS* and the resulting volume and weight (considering energy storage technologies such as batteries and super-capacitors). A compromise solution could be to select 0,35 kW as P_{load}, not considering any stand-by time annual rate. In that case, the value of E_{year} would be 33,78 kWh. This value could correspond to a battery-based *ESS* because the number of charge/discharge cycles is quite low (see Fig. 7.a)). The battery technology selection would be carried out according to technical and economic considerations, such as cycle life, volume, environment, temperature, etc.

Once the long-term requirements are accomplished, the medium-term and short-term requirements are studied. The values of E_{day} and $E_{cyclemax}$ obtained are 2,098 kWh and 0,07 Wh, respectively. Those energy storage needs are lower when compared to the long-term requirements, while the number of cycles increases considerably. In consequence, although the energy storage value is determined by long-term operation, the short-term and medium-term operations define the appropriate technology to be taken into account. Specifically, a supercapacitor-based *ESS* is considered suitable for this particular application, both because their higher cycle life (in terms of number of cycles) and because their higher efficiency (when compared to batteries). As a consequence, a *hybrid-ESS* could be considered, fulfilling the long-term requirements with an *ESS* battery based and the short- and medium-term with an *ESS* supercapacitors based.

As the dimension methodology presented does not use beforehand a specific management energy strategy definition, once defined the type of *ESS* to be installed in combination with the *WEC* and the amount of energy and power required, the operation in time domain should be studied and tested [48, 49]. A proper control and power man agent should be implemented in order to take advantage of the energy storage capacity of the *ESS*. For instance, a constant power supply control (including a *SOC* regulation) in the common DC link (where *PTO*, *ESS* and the payload are interconnected) could be implemented [16], being capable of facing a constant or pulse load. In addition, an energy management strategy of hybrid ESS should be implemented [15, 17] (identifying the short-, medium- and long-term storage necessities by means of filtering the generated power).

Future works could extrapolate the methodology to design *ESS* suitable for grid-connected *WEC* farms. In this case, the stochastic model should be improved to take into account the interactions between *WECs* and the *WEC* design method, considering the number of *WECs* and its relative position as design variables (to take advantage of the aggregation effect to reduce the power oscillation [50]). Other control strategies could be considered in the case of *WEC* farms, and a comparative study of the control-strategy selection impacts on the *ESS* design could be carried out in order to co-optimize the *AUTOWEC* and its control. In order to reduce *ESS* requirements, hybrid systems are proposed, such as solar PV or diesel generators in combination with *WECs*. In addition, the time-domain implementation of the control strategy could be modified to consider the payload profile and the *SoC,* reducing the rating of the dissipative resistor.

4. Conclusions

The article analyses the integration of an energy storage system in a *WEC* in order to operate as a power supply for isolated loads in the marine environment. The reason to include an *ESS* in such application is to compensate the power oscillations related to the ocean-wave energy generation. A stochastic methodology is defined and it is based on the scatter diagram of a certain location and the analysis of the sea-states. Several mathematical developments determine the short-, medium- and long-term energy storage requirements, which are useful to define the power and energy needs for a certain application, as well as the most suitable storage technology and the power of the load that can be afforded with a certain wave energy converter.

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