Identification of optimal sites for the deployment of wave energy converters: the importance of a technology-centred approach

Riccardo Novo, Giuseppe Giorgi, Giulia Cervelli, Nicolás Faedo, Giuliana Mattiazzo

***Abstract*—Driven by climate issues and geopolitical uncertainties, Europe faces the need to transform its energy supply dramatically and quickly. Various renewable technologies are proposed as a medium- to long-term solution for an environmentally and economically sustainable energy mix: among the available solutions, wave energy converters (WECs) are attracting growing interest due to the large untapped wave energy potential in European seas. In this context, the choice of optimal locations for the use of wave energy is fundamental to limit the technological gap with other fully developed conversion technologies, and to ensure competitive energy costs. In this paper, we compare different possible strategies to identify suitable sites for the installation of WECs, namely that based on pure analysis of the wave energy resource, and that considering the productivity of the device in different sea states, *i.e.*, its power matrix, the associated working hours, and the capture width ratio. Using the performance matrices of a notional WEC, an oscillating surge wave energy converter (OSWEC), we estimate optimal locations on the Italian coast, highlighting the advantages and disadvantages of each different approach. The analysis, which can be extended to other WECs, demonstrates the importance of a technology-based approach for the spatial planning of future wave power plants. We use the obtained results to introduce some advancements in the MORE-EST platform, a recently released web-based tool for straightforward estimation of wave resources and WEC productivity in European seas. The proposed platform is able to integrate information on wave resource assessment, bathymetry, marine space use, and technological features, representing a tool aimed at researchers, WEC developers, and policy makers.**

***Index Terms*—Optimisation, Wave energy, Site identification, Capture width ratio, Correlation coefficient**

I. Introduction

WAVE energy development is gaining increasing attention from decision-makers, investors and lending institutions, given the fundamental role it is expected to cover in the transition towards a clean and secure energy supply [1]. As such, wave energy converters (WECs) are expected to contribute to the power mix of continental areas [2], as well as to play a key role for off-grid islands and remote coastal areas [3]. Their importance is expected to progressively increase as energy systems go towards a 100% renewable penetration, to complement the characteristic timeseries of most-diffused non-dispatchable sources, namely wind and solar energy [4], [5].

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To support the deployment of new WECs and wave farms, it is fundamental to identify the most suitable areas for installation, so as to contribute in reducing the cost of energy [6], and ensuring an effective technology development [7]. DLarge effort has been invested by the scientific community in the analysis of both global and local wave energy resource [8]–[10]. Also, increasing attention is being devoted to the mapping of WEC productivity across large sea areas [11]–[13]. Motivated by this issue, the MOREnergy Lab recently published the so-called MORE-EST Platform[1] [14], aimed at a straightforward analysis of the wave energy resource and estimation of WEC productivity. Nevertheless, current literature is still missing a comprehensive analysis of indicators for the evaluation of the suitability of sites for the installation of WECs, and the corresponding identification of prioritised locations.

In this paper, we study optimal spatial positioning of WECs, comparing the mere analysis of the wave energy resource with the results obtained using different yardsticks for the evaluation of device performances: Annual Energy Production (AEP), working hours and capture width ratio (CWR). In particular, we seek for the statistical correlation between these indexes and the wave energy resource, highlighting the importance of a technology-centered approach when planning the installation of new WECs. This paper presents, to the best of our knowledge, the first analysis of this kind developed at a broad spatial scale.

II. Materials and methods

This section presents the methodology and input data used for the performed analysis, and is structured as follows: Subsection II-A discloses the concept and overall procedure; Subsection II-B describes the wave data used as input for the study; Subsection II-C recalls the fundamentals of numerical modelling for WECs; Subsection II-D details the characteristics of the notional WEC used in this paper; while, finally, Subsection II-E illustrates the employed evaluation metrics.

A. Procedure

The procedure used in this paper is as follows:

[1]The MORE-EST platform was developed by researchers from the MOREnergy Lab and the EST Lab at Politecnico di Torino. The platform is available at the following link: https://energyplat.est.polito.it/

1) Wave energy data are obtained and processed for part of the Mediterranean Sea, namely the areas off the coast of Italy. A resource map is produced to highlight regions with higher potential in terms of mean available wave power.
2) An archetypal WEC is modelled and its power matrix is computed, taking into consideration of the resource directionality. Four different configurations are adopted, based on possible considerations in terms of cut-in and cut-off significant wave height, affecting the WEC productivity.
3) The WEC yearly productivity is calculated over the different spatial cells for which wave data has been extracted. Post-processing of the raw results enables the calculation of two additional metrics, namely the working hours and the CWR.
4) The location with the highest wave energy resource is compared with the optimal WEC locations obtained when considering the device productivity, the working hours and the CWR.
5) For the four WEC configurations, the statistical correlation between each of the three technology-related indexes and the wave energy resource is estimated.

B. Wave resource data

Wave data are retrieved for the decade 2010-2019 from the ECMWF-ERA5 database [15], which is deemed to be appropriate for preliminary analysis [16]. The database provides hourly time-series of significant wave height (H_s), wave energy period (T_e), and mean wave direction (Dir_m). The available spatial resolution is 0.5° x 0.5° , corresponding - in the analysed area - to ∼55 km in latitude and ∼45 km in longitude. To limit the computational burden related to wave data processing and WEC productivity estimation, the analysis is limited to cells located within 50 km from the coasts of the Italian peninsula and islands (i.e., primarily a single cell along the coast is considered).

The coarse spatial granularity of the employed wave data facilitates an analysis at a large (national) spatial scale, thus making the approach appropriate for a high level planning phase. We note that the same methodology is also applicable to smaller areas with refined meteorological data resolution. Nevertheless, the statistical correlation, which is envisaged at the last step, may benefit from a rather large range of site properties in terms of wave energy availability.

C. Numerical modelling of WECs

The aim of this subsection is to briefly describe the method employed to model a WEC, and obtain its corresponding power matrix, *i.e.*, the look-up table associating output power with each combination of H_s and T_e.

Highest accuracy in WEC modelling can be achieved through the inclusion of nonlinearities [17], primarily viscosity [18] and non-linear Froude-Krylov forces [19] in weakly nonlinear models, or fully-nonlinear models, based on Navier-Stokes equations [20]. However, such models are computationally prohibiting for relatively fast operations, thus posing limitations to a straightforward replicability of the methodology presented in this study. For this reason, in this study we make use of a linear potential flow model [21] for computing the power matrix of the WEC under analysis. The hydrodynamic characteristics of the WEC are computed via the open-source Boundary Element Method (BEM) code Nemoh [22]. The general equation of motion of the WEC is the following:

$$(M + A)\ddot{\xi} + B\dot{\xi} + K_h\xi = F_{ex} + F_{PTO}, \tag{1}$$

where $n \in \mathbb{N}$ is the number of degrees of freedom (DoFs), $\xi(t) \in \mathbb{R}^{n\times 1}$ is the generic vector of displacements, $M \in \mathbb{R}^{n\times n}$ is the inertial matrix, $A \in \mathbb{R}^{n\times n}$ is the added mass at infinite frequency, $B \in \mathbb{R}^{n\times n}$ is the total damping (radiation and linearised viscous drag), $K_h \in \mathbb{R}^{n\times n}$ is the hydrostatic stiffness, $F_{ex}(t) \in \mathbb{R}^{n\times 1}$ is the incoming wave excitation force, and $F_{PTO} \in \mathbb{R}^{n\times 1}$ is the power take-off (PTO) force. For the sake of simplicity, the mooring force is here neglected [23].

The excitation force F_{ex} depends on the incoming wave elevation and, for non-axisymmetric WECs, on the relative angle between the device orientation and the wave propagation direction. A JONSWAP spectrum [24] is employed to describe (stochastically) incoming waves. The considered sea states are all those with T_e between 3 s and 15 s, and H_s between 0.5 m and 8 m,, in line with the characteristics of the Mediterranean Sea [25].

A control strategy is implemented in order to synthesise the PTO force, maximise power absorption, and, thus, power production, being also compliant with physical constraints related to the WEC structure. Including physical constraints is indeed essential to avoid an unrealistic estimation of productivity that may arise from the combination of an unconstrained control with a linear model [26]. Being the control strategy related to the WEC typology and characteristics, further details are provided in Section II-D.

D. The Oscillating Surge Wave Energy Converter

To highlight the importance of a technology-based approach for optimal WEC site selection, we adopt a non-axisymmetric device. In particular, we select an oscillating surge wave energy converter (OSWEC), inspired by the Oyster device [27]. However, the procedure is replicable with any other notional WEC, provided that an adequate control strategy is chosen.

Fig. 1 shows a schematic representation of the WEC, whereas Tab. I presents its main technical characteristics. Note that all the presented quantities are calculated under the assumption of uniform mass distribution. Also, being the focus of this work on the variability of evaluation metrics, we neglect bathymetric constraints; the device is then assumed to be hypothetically installed in any of the sites described in Section II-B.

The productivity of the OSWEC device, which is not axisymmetric, is largely affected by the incoming wave direction. Therefore, the BEM code is run 24 times around the 360° angle, thus with a resolution of

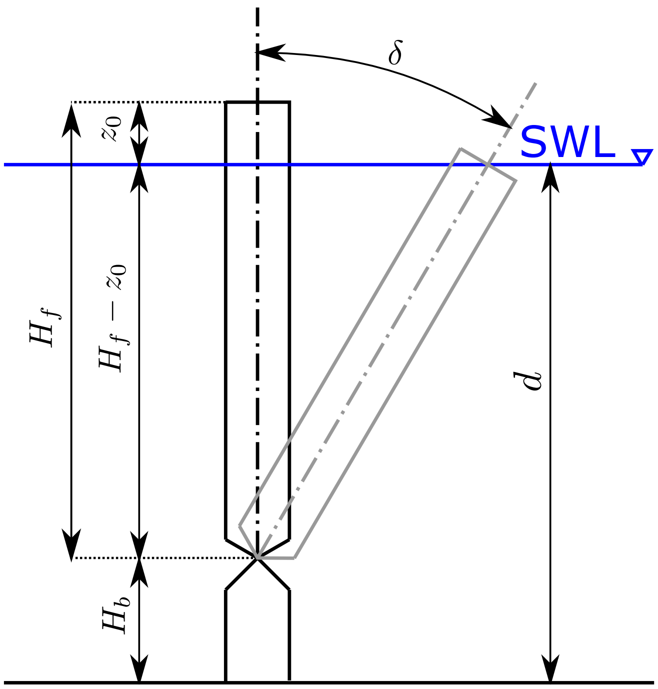

Fig. 1. Sketch of the OSWEC device.

TABLE I
CHARACTERISTICS OF THE OSWEC DEVICE

Quantity	Symbol	Unit	Value
Flap height	H_f	m	15
Flap freeboard	z_0	m	3
Flap base	H_b	m	3
Flap width	W_f	m	2
Flap length	L_f	m	22.5
Center of gravity	L_f	m	-4.5
Flap equivalent density	ρ_f	kg/m^3	250
Inertia	I_f	kgm^2	$1.86x10^7$

For a graphical representation of the geometrical quantities, please refer to Fig. 1.

15°; the procedure generates 24 hydrodynamic curves, corresponding to 24 power matrices. Being the device symmetrical along its median plane, no difference was observed between 0-180° and 180-360°.

Because of the OSWEC working principle, a single DoF model is implemented: the dynamic equation (Eq. (1)) can thus be rewritten with respect to the pitching angle (δ) of the flap about the hinge. Concerning the control strategy, a constant-coefficient reactive controller (*i.e.*, a proportional-integral strategy) is used to estimate the power capture for each condition (sea-state and direction). The optimisation of the associated PTO stiffness and damping is performed in the frequency domain, for an equivalent regular wave. Although this is sub-optimal with respect to a time-varying damping [28] or real-time control [29], constant-coefficient reactive control provides a simple preliminary estimation of the productivity potential. However, to achieve realistic results with linear models, the maximum displacement of the pitching angle is constrained in such a way that the flap is never fully submerged:

$$|\delta| \leq \arccos\left(1 - \frac{z_0}{H_f}\right). \tag{2}$$

For the OSWEC under analysis, the maximum angle corresponds to 37°. Once the pair of control parameters is defined, the actual productivity for an irregular sea state is computed via a spectral approach [30], thus inherently including the stochastic nature of the waves [31].

The power matrices as a function of the incoming direction (Θ_w), for a quarter of the 360° angle, are presented in Fig. 2. The angle $\Theta_w = 0°$ represents a wave propagating perpendicularly to the flap surface, which is the best condition in terms of productivity. In order to highlight the loss in power due to waves directionality, all power matrices are normalised with respect to the maximum power (P^0_{max}) achieved in a certain sea state, with $\Theta_w = 0°$.

Additionally to what discussed above, it should be mentioned that most WECs operate within a restricted set of sea states (especially, in a well defined range of H_s), mainly due to two main reasons. First, a cut-in H_s may be implemented to ensure that the device enters into functioning when enough energy is available in waves, to cover the power consumption of its related systems. Such a minimum threshold may be lower for passive devices (*e.g.*, PeWEC [32]), whereas higher in case of active devices (*e.g.*, SWINGO [33]). Second, a cut-off H_s is often considered at the WEC design stage in which the device enters to safety mode, when sea states become over energetic.

Within this paper, to consider the impact of different metrics for optimal WEC site selection, the device power matrices are further modified according to the following hypotheses:

I. No cut-in, no cut-off.
II. Cut-in = 1 m, no cut-off.
III. No cut-in, cut-off = 3 m.
IV. Cut-in = 1 m, cut-off = 3 m.

Therefore, we consider in our analysis four different records, to discuss the possible necessity of proper assumptions on WEC working conditions at an early planning phase.

E. Evaluation metrics

Beside the analysis of the wave energy content, we make use of three indexes to evaluate WEC performance across the studied area:

- First, we study the *AEP* $[MWh/y]$, which - once the device under analysis is effectively chosen - is a major criteria for the minimisation of the cost of energy. The OSWEC power matrices and the hourly time-series of H_s, T_e, and Dir_m, are used to calculate the hourly energy production in each spatial cell. For each site, the best orientation of the OSWEC is calculated with an exhaustive-search approach. The final quantity is computed - for every cell - as an average over the yearly production in the 10 years for which wave data is retrieved. The AEP is obtained from a set of power matrices in which optimal control of the device has

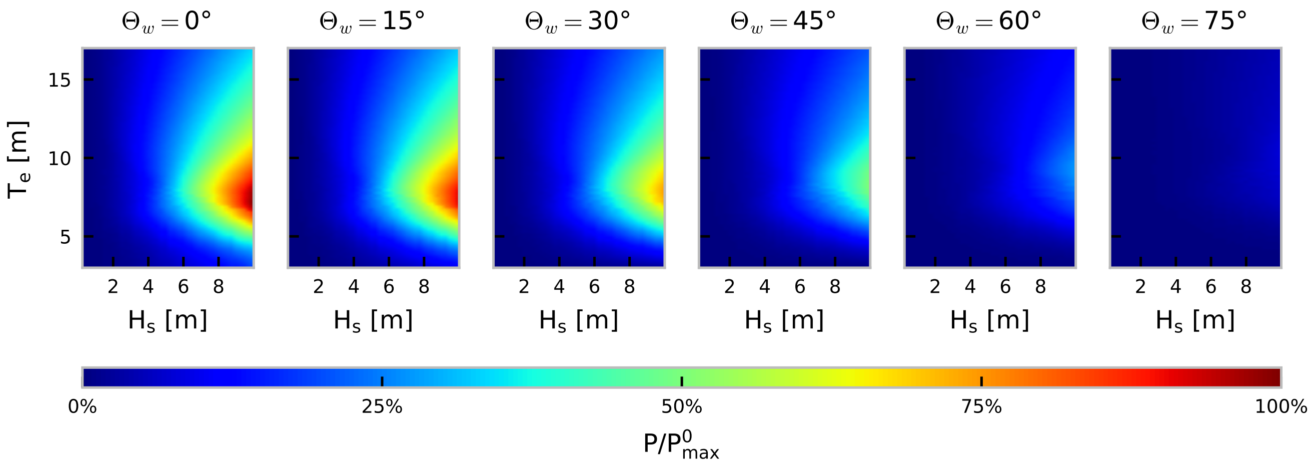

Fig. 2. Normalised (%) power matrix of the OSWEC device for different incoming wave directions Θ_w, computed as P/P^0_{max}.

been applied in each sea state and for each incident wave direction (see Section II-D.

- Second, we make use of the WEC *working hours* $[h]$, corresponding to the average number of hours per year in which the device is expected to produce electricity. Such metric becomes particularly important when the WEC supplies a microgrid or a remote grid. Furthermore, it is a significant yardstick also when dealing with renewable power plants connected to national power grids, because of the increasing importance of baseload production and the costs associated to the management of non-dispatchable peak production. It is worth mentioning that this metric, likely more than others, is influenced by cut-in/cut-out assumptions.
- Lastly, the *capture width ratio* $[\%]$ is used to estimate the performance of WECs in different sea areas. A capture width (CW) was first introduced by Budar and Falnes [34], and is defined as the ratio of the absorbed wave power P_{abs} to the available power per unit wave crest length $p_{wave/length}[kW/m]$:

$$CW = \frac{P_{abs}}{p_{wave/length}}. \tag{3}$$

The CW is therefore expressed in $[m]$, and represents the width of wave crest which is effectively absorbed by the WEC. Recently, researchers employ hydrodynamic efficiency for evaluating the hydrodynamic performances of WECs. The most largely used quantity is the CWR, which is obtained dividing the CW by the characteristic width D of the WEC [35]:

$$CWR = \frac{CW}{D} = \frac{P_{abs}}{p_{wave/length}D} \tag{4}$$

In the case of the OSWEC, D corresponds to the flap width W_f. As for the previous two metrics, the CWR is also computed in each site as an average over the 10 years of analysed resource.

To study the relation between the wave energy resource and the above metrics, we make use of the Pearson correlation coefficient, that is, a measure of the linear dependence between two sets of data. The coefficient is defined as the ratio between the covariance of the two variables and the product of their standard deviation. Given two random variables x and y with m semples, the Pearson correlation coefficient r is thus expressed as [36]:

$$r = \frac{\sum_{i=1}^{m}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{m}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{m}(y_i - \bar{y})^2}}, \tag{5}$$

where $\bar{x}$ and $\bar{y}$ are, respectively, the mean values of the two variables. The coefficient is, in synthesis, a normalised measurement of the covariance, and it always has a value within the range [-1,1]. A rule of thumb for the interpretation of the coefficient in evaluating the relation between the two analysed variables, is presented in Tab. II [37].

TABLE II
RULE OF THUMB FOR THE INTERPRETATION OF THE PEARSON CORRELATION COEFFICIENT (r) [37]

r	Interpretation
$\pm$ 0.9 *to* $\pm$ 1	Very high correlation
$\pm$ 0.7 *to* $\pm$ 0.9	High correlation
$\pm$ 0.5 *to* $\pm$ 0.7	Moderate correlation
$\pm$ 0.3 *to* $\pm$ 0.5	Low correlation
$\pm$ 0.0 *to* $\pm$ 0.3	Negligible correlation

Positive values of the correlation coefficient indicate a positive correlation, whereas negative values indicate a negative correlation.

III. RESULTS AND DISCUSSION

Results are structured as follows: Subsection III-A presents outputs in terms of optimal WEC site identification. Subsection III-B presents a characterisation of the correlation between the wave resource and the three metrics. Subsection IV-B introduces some future advances in the web-based MORE-EST platform, arising from the results of this paper.

A. Optimal location

The analysis of the wave energy resource, and the estimation of the evaluation metrics described in Subsection II-E, is presented in Fig. 3. The charts illustrate results achieved under the different hypotheses (I. to IV.) of cut-in and cut-off H_s, highlighting, in each case, the optimal location identified by means of the different evaluation metrics (A. to C. - see Section II-E). The heatmap of each plot depicts the wave energy resource intensity in terms of available power per unit wave crest length, highlighting in yellow the areas with the highest resource, and in dark blue those with the lowest one.

It can be observed that, in case I. and II., *i.e.*, when no cut-off H_s is considered, the optimal location in terms of production (A.) corresponds to the site with the highest resource, off the north-western coast of Sardinia. This area is well-known for receiving large swell from the Lion Gulf, under the effect of the Mistral wind. Nevertheless, such resource is clearly not fully exploitable when considering a cut-off H_s (cases III. and IV.): a large part of these source is associated to significant wave heights over 3 m. This brings other sites, namely towards the southern part of the west coast of Sardinia, to be preferable.

In terms of working hours (B.), the inclusion of a cut-in H_s seems to be a key factor for the identification of a truly optimal site. When no cut-in H_s is used (cases I. and III.), the optimal identified area is a near-coast site with relatively low wave energy resource, in the order of 4 kW/m. However, the inclusion of cut-in H_s cancels the contribution of very low-energetic sea states, thus identifying sites with higher resource as optimal. All the sites are nonetheless in the surrounding of the north-west coast of Sardinia.

Finally, taking into consideration an appropriate cut-off H_s seems to be a key driver for a correct estimation of the capture width ratio (C.). Results depict very large differences between the site identified when cut-off is considered or not. Under the former hypothesis (cases III. and IV.), the optimal area is a low energetic site on the Tirrenian coast of Calabria; under the latter hypotheses (cases I. and II.) it is, again, a cell in the north-western coast of Sardinia. This result, alongside the importance of using accurate technology models already at a planning phase, remarks the unsuitability of the CWR when dealing with optimal site identification.

As a final remark, for fixed cut-in and cut-off H_s, the use of the three metrics always leads to different optimal sites. Such outcome stresses the need for an accurate choice of evaluation metrics for the optimal siting of WECs, based on the project needs and priorities.

B. Correlation between evaluation metrics and wave resource

Notwithstanding the significant outcomes arising from Fig. 3, the analysis is so far focused only on the optimal sites, thus posing some limits to the generalisation of the results. To extend the analysis, in Fig. 4, we show - for each of the four cases (I. to IV.) - the correlation existing between the wave energy resource (expressed in power per unit wave crest length, $[kW/m]$) and the evaluation metrics (A. to C.), across the complete set of sites considered in this study. The interpretation of the results is supported by the rule of the thumb presented in Tab. II.

Primarily, it can be observed that the yearly WEC production (A.) shows a *very high* correlation with the wave energy resource. Despite when considering production we also consider the resource directionality and the characteristics of the WEC power matrix, the two metrics are strongly linearly dependent across the available dataset. Nevertheless, it can be observed that the trend line significantly decreases its slope when including a cut-off H_s (cases III. and IV.). All the points characterised by high expected production undergo a significant decrease, up to around 50%. It can be therefore stated that, for the analysed case study (Mediterranean Sea), the analysis of the wave resource in a planning phase can be a good proxy for WEC productivity if an appropriate cut-off significant wave height is considered.

Shifting the focus to working hours (B.), we can observe a much broader distribution of the data points in the charts, indicating a lower correlation level of the metric with the wave resource. *Low to moderate* correlation can be observed when no cut-in H_s is considered (cases I. and III.), whereas *high* correlation is achieved when including the cut-in (cases II. and IV.). Also, in line with the results of Fig. 3, neglecting a cut-in H_s also leads to a large general overestimation of the working hours.

Finally, looking at the CWR (C.), we can observe a *moderate* correlation when disregarding the cut-off H_s, but a negligible correlation when the cut-off height is considered. This suggests that the CWR is strongly technology-dependent, and that the mere analysis of the resource cannot be considered as a proxy for the CWR calculation, not even at a planning phase. In light of the large differences in the behaviour of the CWR metric with respect to the expected production, it is one more time suggested to deepen the knowledge on the capture width ratio, so as to evaluate the appropriateness of its use for planning purposes, as well as for the comparison of the performance of different WECs.

IV. Conclusions and future work

In this paper, the suitability of different metrics for the evaluation of WEC performances is studied, so as to support the identification of optimal sites for WEC deployment. A specific procedure is developed to numerically model an OSWEC and analyse three metrics related to its functioning (device productivity, working hours and capture width ratio) across the sea areas off the coasts of Italy. Furthermore, the linear relation between the evaluation metrics and the wave resource is studied by mean of the Pearson correlation coefficient. Specifically, four possible WEC configurations are analysed, in consideration of different approaches in handling the cut-in and cut-off significant wave heights.

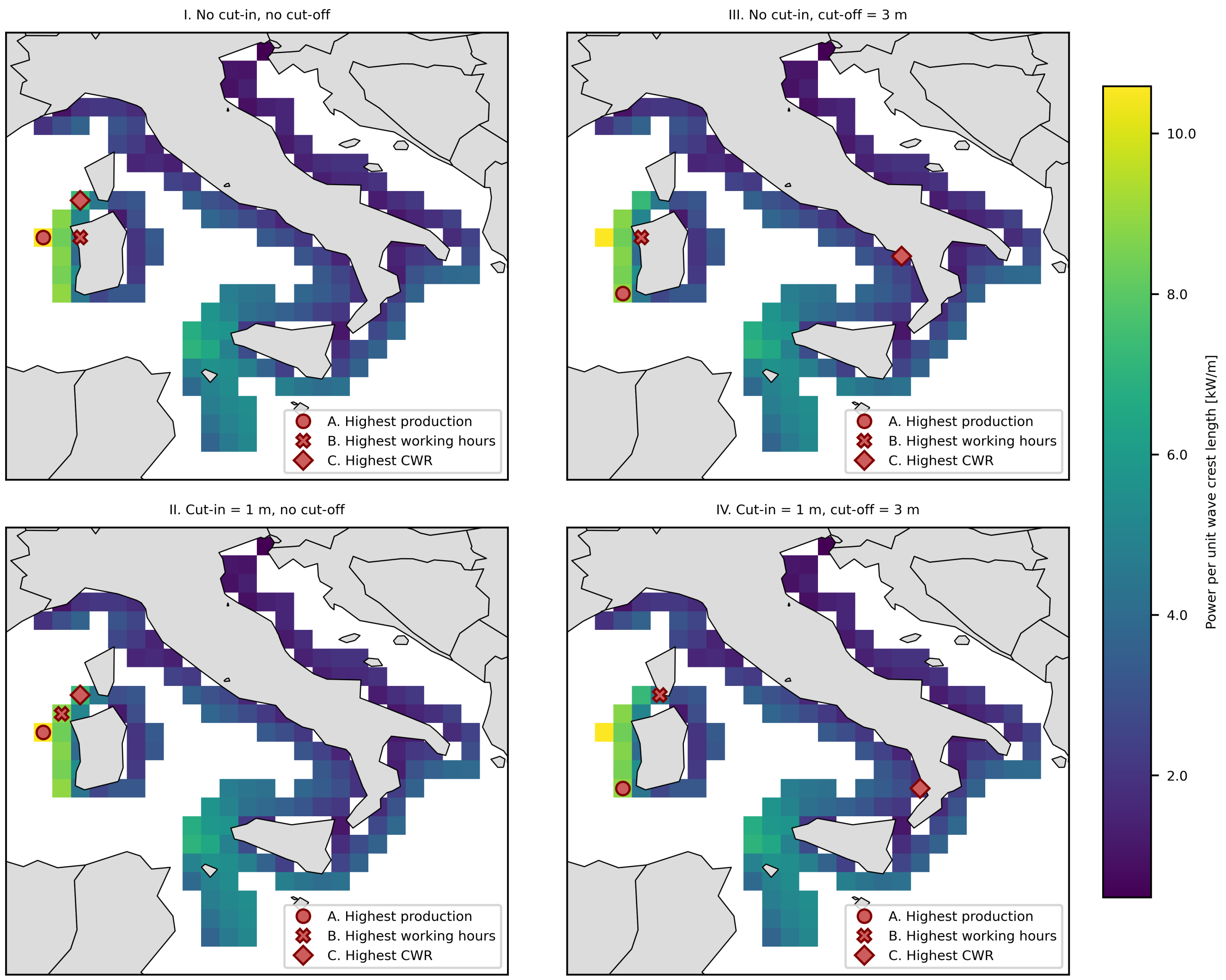

Fig. 3. Wave energy resource and optimal location of WECs. The heatmap represents the wave energy resource. Each of the plots (I. to IV.) present results under different hypotheses in terms of cut-in and cut-off of the H_s. In every plot, different symbols (A. to C.) identify the optimal location in consideration of different evaluation metrics.

A. Key outcomes

The key achieved results are summarised as follows:

- The identification of optimal sites as a function of WECs productivity is especially affected by the consideration of a cut-off H_s, that may help in discarding over-energetic sites. A very high correlation between the device productivity and the wave energy resource (power per unit wave crest length) is observed, thus enabling the use of the latter as a proxy for the former at a planning phase, as long as a suitable cut-off H_s is implemented.
- The use of WEC working hours as an evaluation metric is not suitable under the assumption of no cut-in H_s, because of a low to moderate correlation between the WEC working hours and the wave resource. High correlation is achieved when cut-in H_s is included.
- The CWR demonstrates negligible correlation with the wave energy resource in the most realistic case, i.e., when considering both cut-in and cut-off H_s. Therefore, the resource analysis can't be considered a proxy of the CWR, which is strictly technology-related. The large differences observed in the behaviours of the CWR and the expected production, however, suggest further analysis to evaluate the suitability of the CWR in comparing different sites for WECs installation.

B. Future works: advances in the MORE-EST Platform

The MORE-EST platform is a recently introduced community-open web-based tool for the analysis of the wave resource and the estimation of WEC productivity in the European seas [14]. It aims to support different stakeholders operating in the field of wave energy and, in particular:

- **WECs developers**, supporting the preliminary identification of the characteristics of future installation sites.
- **Energy planners**, by providing a tool for the straightforward inclusion of WECs in energy plans and strategies
- **Decision-makers, investors, and lending institutions**, encouraging a transparent and independent

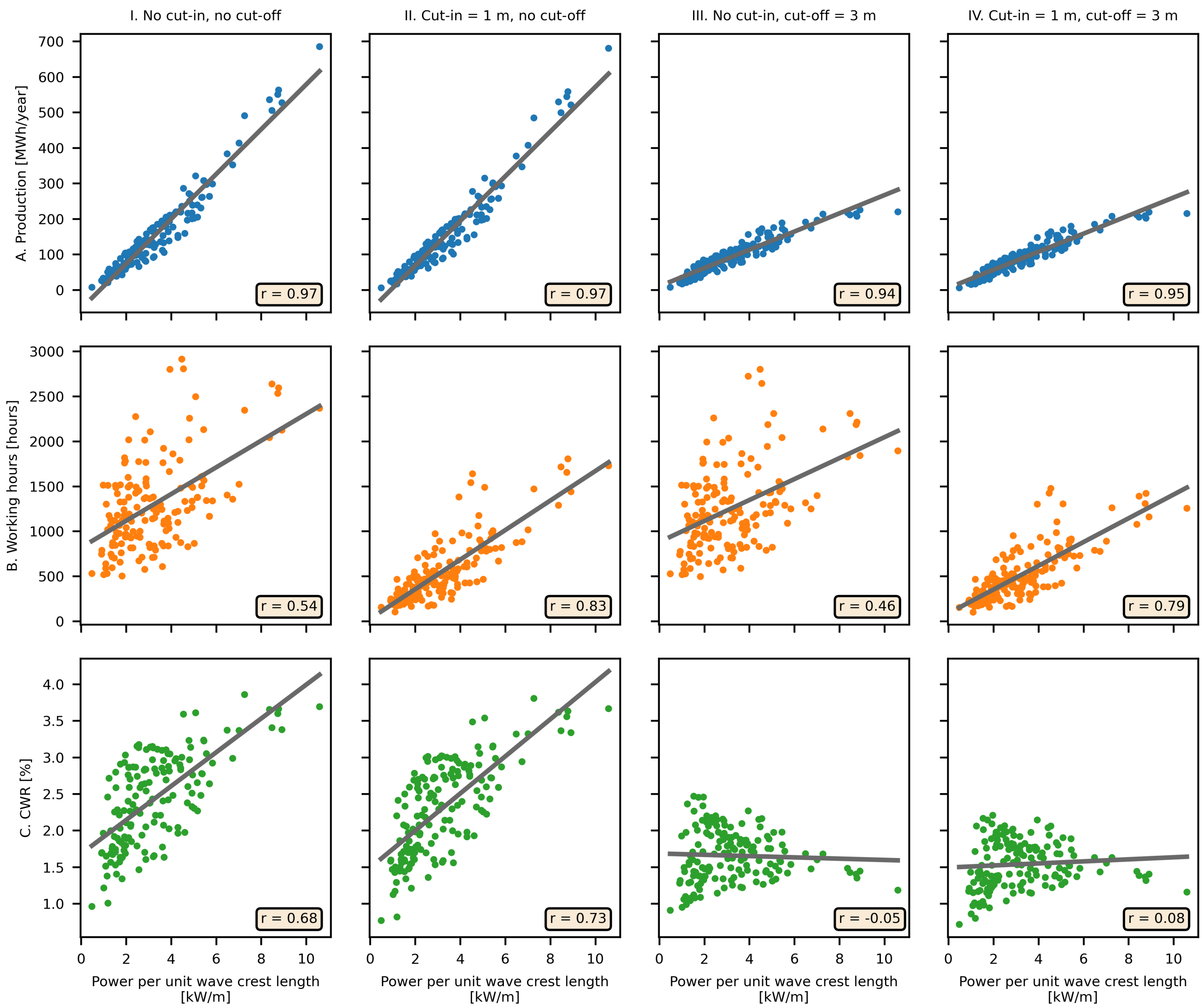

Fig. 4. Correlation between the wave energy resource (power per unit wave crest length) and the quantification of the implemented evaluation metrics (A. to C.) across the different combination in terms of cut-in/cut-off H_s. Boxes show the evaluation of the Pearson Correlation Coefficient (r) for each case and evaluation metric. Highly dispersed plots are characterised by lower absolute values of r, whereas plots in which points are more compact present higher absolute values of r. Grey lines indicate the linear trend lines for each combination of variables.

audit of WECs productivity, as well as the identification of the best performing WECs in different sea areas.

The platform underlying database consists of four layers: bathymetry (retrieved, as in this study, through the EMODNet website [38]); wave energy resource (obtained from the ECMWF-ERA5 database [15]); maritime spatial planning layers (downloaded from EMODNet); and WECs characteristics (technological database developed at the MOREnergy Lab with a similar methodology to the one depicted in Subsection II-C).

The current version of the tool enables the user to select a certain site in the European seas, also in view of the bathymetry and maritime spatial planning layers, to analyse the related resource and to estimate the productivity of different WECs. The results of this paper suggest the implementation of additional evaluation metrics, as well as of a tool for a visualisation of such metrics over broad sea areas. Especially, the MORE-EST Platform enables to analyse the resource availability and the WEC productivity with a flexible temporal resolution. Inter- and intra-annual variations of WEC performances in terms of the discussed evaluation metrics will therefore be made available, because of their possible relevance at the planning phase [39].

In addition, O&M aspects, which have not been taken into account in this research paper nor in the MORE-EST Platform, should also be considered in future, because of their significant impact on the overall costs related to wave farms [40], [41]. It is realistic to think that O&M projected costs could also have a significant impact on the choice of optimal sites for wave farms deployment.

The update work is expected to be started in the next months (fall 2023), and the authors are delighted to have a discussion with the scientific community on the appropriateness of the above mentioned and other evaluation metrics for wave energy converters.

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