Deliverable 2: Environmental conditions report

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Abstract
Siting infrastructure works demands the consideration of multiple parameters for the optimum solution. Especially in the marine environment, the adequate location for offshore power plants presupposes a plethora of criteria to be followed and certain limitations to be covered. The current Deliverable provides a methodology for a preliminary selection of representative installation locations in the Aegean Sea for **ETHOS** OWC. Environmental data are utilized by the ERA5 reanalysis dataset while further information is discussed regarding marine protected areas through the Natura 2000 network, bathymetry, and marine traffic among others. For the selected locations, environmental design conditions are specified through an extreme value analysis and return levels calculation. The design values will enable the definition of the mooring characteristics in ultimate limit states, as well as the specifications for the optimum operation of the **ETHOS** OWC.

1. Introduction

Nowadays, marine renewable energy (MRE) has become the main focus of scientists and governments for producing green energy, aiming for net zero scenarios until 2030 [1]. Even though the majority of MRE production results from offshore wind farms, the integration of technologies to exploit ocean wave energy potential is also in the spotlight for more effective offshore power plants. With the advances of technology, wave energy converters are designed and tested in shallow and deeper waters, aiming to the optimization of the hydrodynamic characteristics of the structure, in order to increase the absorbed wave energy [2-5]. In this respect, the proper installation site is a key point, through the specification of the environmental conditions and the respective design values for operation and ultimate limit states. The particularized results can be utilized for the design of an optimum mooring system, the proper oscillating water column chamber shaping, as well as the definition of PTO mechanisms type at the top of the oscillating chambers, for better efficiency.

Seeking an appropriate marine location for installing power plants has been studied for years. Even from the 1970s, generating green energy offshore was in the spotlight through the implementation of floating nuclear concepts [6,7]. Lately however, rich literature has been written for siting infrastructure works that refer to marine renewables. When deciding on the best area for developing a project, a broad set of information should be considered. Analytical Hierarchy Process [8], multiple-criteria decision-making techniques, Geographic Information System (GIS) software, and statistical techniques are used to approach solutions to the problem and extract results for case studies [9,10]. Such example is a hybrid multi-criteria decision-making approach for locating offshore wind plants in Egypt [11]. The feasibility of installing offshore wind farms has been also addressed along the coast of India for depths between 20 m and 75 m [12]. Regarding offshore wave energy, a fuzzy multicriteria decision making (FMCDM) model has been introduced for analyzing a suitable site for wave energy production in Vietnam [13]. Similar approaches have been applied for hybrid offshore power plants following a combination of the aforementioned methods. Such studies referring to Greece can be found in [10,14] incorporating also environmental impact assessments [15]. Technical, economic, social, and environmental aspects of combined offshore wind and wave energy farm site selection are also jointly investigated [16] and can be found for a case study in China [17], while similar work is available for hybrid wind and solar power plants [18].

In the present Deliverable, three representative locations in the Aegean Sea were defined in order to install the **ETHOS** OWC. The areas were selected based on numerous criteria that will be further discussed herein. The necessary input parameters for the next stages of this research project are also provided, defining the design values of the environmental conditions.

2. Site Selection and Data

The optimum location for the **ETHOS** OWC operation depends on multiple factors, yet demanding specific principles. The main four criteria that were taken into consideration are the wave regime, bathymetry, marine protected areas and territorial waters. However, subsea grid, marine traffic, access to big ports and tourism development areas were also accounted for in the site selection process. The aforementioned standards will be discussed along with the respective utilized data.

2.1. Wave regime

As far as wave energy converters are concerned, due to their operation principles, an intense wave climate is of utmost importance for generating the highest possible energy. It is therefore fundamental to install such structures in areas with high wave energy potential. In this context, the wave regime will be evaluated based on the wave power density P in W/m (also known as wave energy flux per unit length of wave front) that is defined as follows:

$$P = \frac{\rho g}{64\pi} H_s^2 T_e \qquad (1)$$

where ρ is the density of seawater that is considered constant and equal to 1025 kg/m^3, g is the gravitational acceleration equal to 9.8066 m/s^2, H_s is the significant wave height in m, and T_e is the wave energy period in s.

The above metric requires a reliable dataset for the adequate extraction of inferences. Produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), the ERA5 reanalysis dataset was utilized, which combines vast amounts of historical observations into global estimates using advanced modeling and data assimilation systems [19]. Moreover, it provides hourly estimates of a large number of atmospheric, land and oceanic climate variables, covering the Earth on a ≈30 km grid and resolving the atmosphere using 137 levels from the surface up to a height of 80 km. The data can be freely accessed from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/, (accessed on 3 March 2021) see also https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, (accessed on 3 March 2021) [19,20]. In this work, 20 years (1 January 2000–31 December 2019) of available wave data were utilized for the Greek Seas (defined by a rectangle with the top left corner at 42◦ N, 19◦ E and bottom right corner at 33◦ N, 30◦ E). For the significant wave height and the wave energy period, the data are provided on a 0.50 × 0.50◦ spatial grid; see [20].

The spatial distributions of the mean annual wave power potential of the Greek seas are presented in Fig. 1. Wave energy flux appears higher in areas characterized by large fetch lengths that lead to larger wind waves and swells. Although the Aegean Sea is an area characterized by strong winds, the presence of many islands limits the wind fetch blocking swells from being developed [21]. Consequently, wave power density values are relatively low (3-5 kW/m), while in northeast of Skyros Isl. and west and northeast areas of Crete Isl., it ranges between 5-7 kW/m.

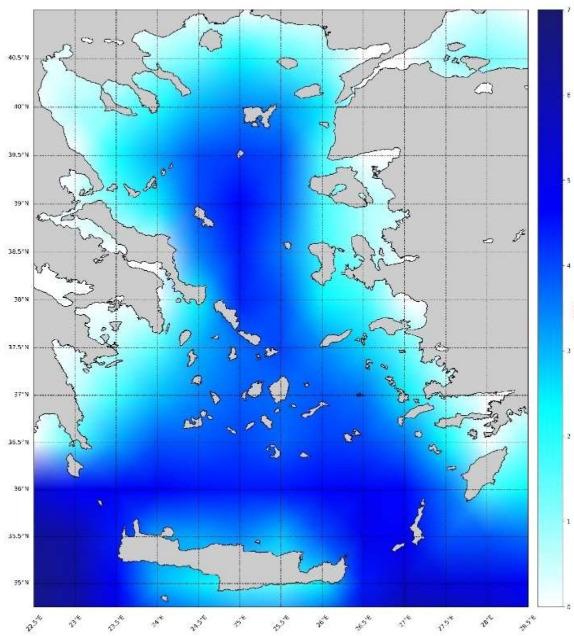

Figure 1: Wave power density of the Aegean Sea.

2.2. Bathymetry

The Aegean Sea is known for its deep waters and steep seabed slopes. Considering the fact that floating structures, such as **ETHOS** OWC, demand depth limitations for financial feasibility due to increased costs and complexity of their mooring systems, the representative installation locations should be advantageous both in terms of wave power production and bathymetric conditions. The bathymetry data of the examined region were derived from the European Marine Observation and Data Network [22]. The investigated marine territories were limited offshore to water depths between 50 m and 200 m, as presented in Fig. 2 (brown areas).

At this stage, three possible locations for installing **ETHOS** OWC are presented (Fig. 2) considering the two main discussed criteria. To fulfill both, all sites are located in the range of 100 m to 200 m water depth with a significant wave energy potential. Furthermore, requirements that are further elaborated herein, were accounted for during the selection process. Locations 1 (L1) and 2 (L2) are in the northern part of the Aegean Sea and more specifically south of Ag. Efstratios Isl. [39.40° N, 24.95° E] (at ≈130 m water depth) and north of Skyros Isl. [39.10° N, 24.51° E] (at ≈200 m water depth), respectively. Location 3 (L3) is located in the southern part of the Aegean Sea, northwest of Kasos Isl. and Karpathos Isl. [35.90° N, 26.51° E] (at ≈150 m water depth).

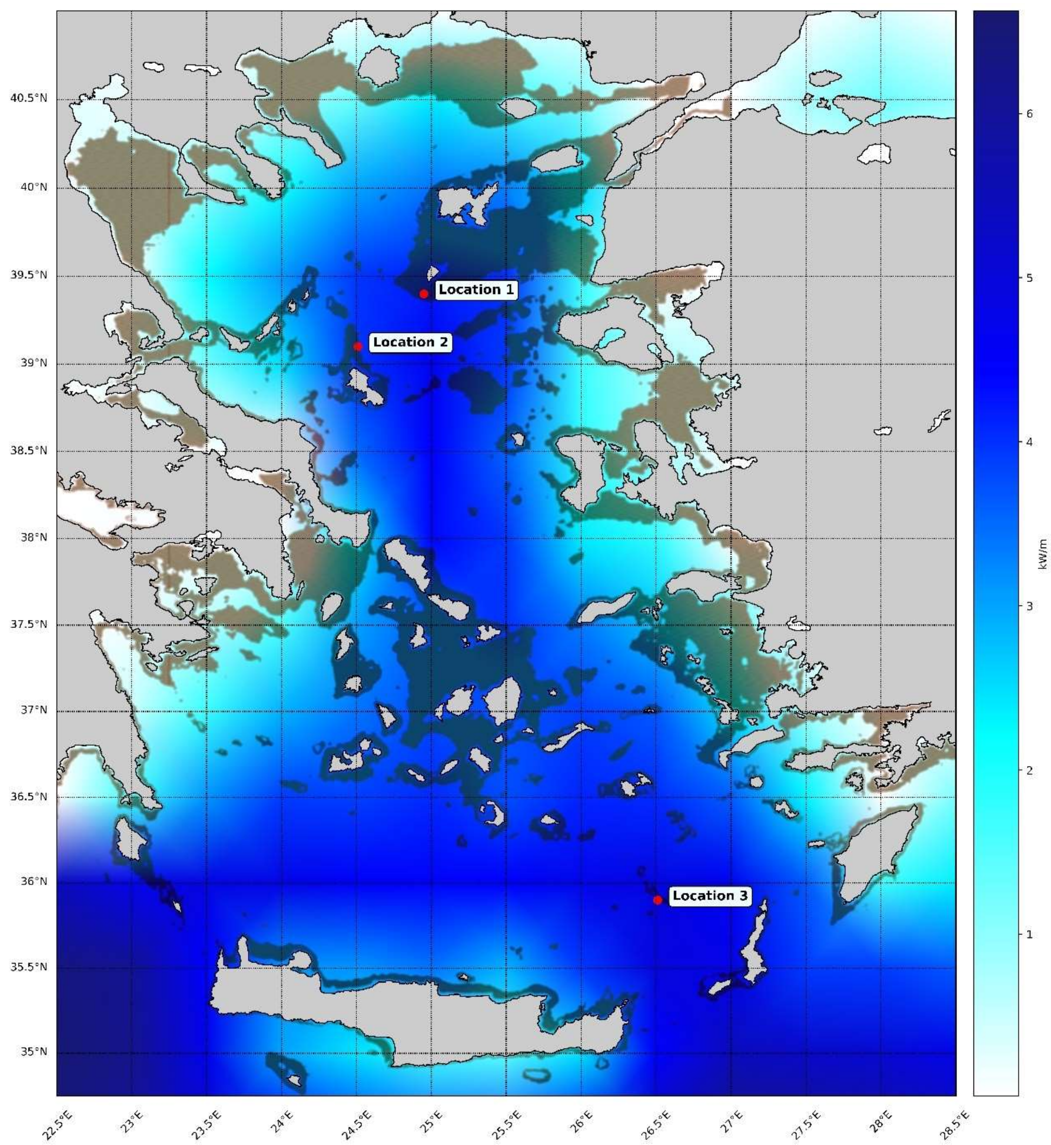

Figure 2: Aegean Sea map of wave power density along with territories with up to 200 m water depth (brown areas) and the three selected locations.

2.3. Marine protected areas

Environmental goals globally, focus on expanding the protected area network for biodiversity loss interception. The European Union's Natura 2000 network covers a high percentage of the terrestrial area of Greece (27.3%), one of the highest in Europe [23]. When siting infrastructure works, a major factor for decision making is to comply with the framework of protected areas. Although such environmental studies are formed in great detail as an independent part of a project, it is vital to locate the unavailable territories in the preliminary design. In this context, selected sites are outside of marine protected areas (shown with green hatch in Fig. 3) described by the Natura 2000 network [24].

2.4. Territorial waters

The concept of an exclusive economic zone (EEZ) was adopted through the 1982 United Nations

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Convention on the Law of the Sea [25]. Under international law, within its defined EEZ, a coastal nation has:

(a) Sovereign rights for the purpose of exploring, exploiting, conserving, and managing natural resources of the seabed, subsoil, and waters above it.
(b) Jurisdiction as provided for in international law with regard to the establishment and use of artificial islands, installations, and structures; marine scientific research; and the protection and preservation of the marine environment.
(c) Other rights and duties provided for under international law.

However, to tackle bureaucracy obstacles, the installation of ETHOS OWC is chosen not to exceed the territorial waters over which Greece has full sovereignty and have been established to the breadth of a 6 nautical mile zone [25]. In this respect, although potential installation areas were limited significantly, Fig. 3 shows that the three selected locations cover these requirements. It is noted that the purple line indicates the 6 nautical mile zone limit.

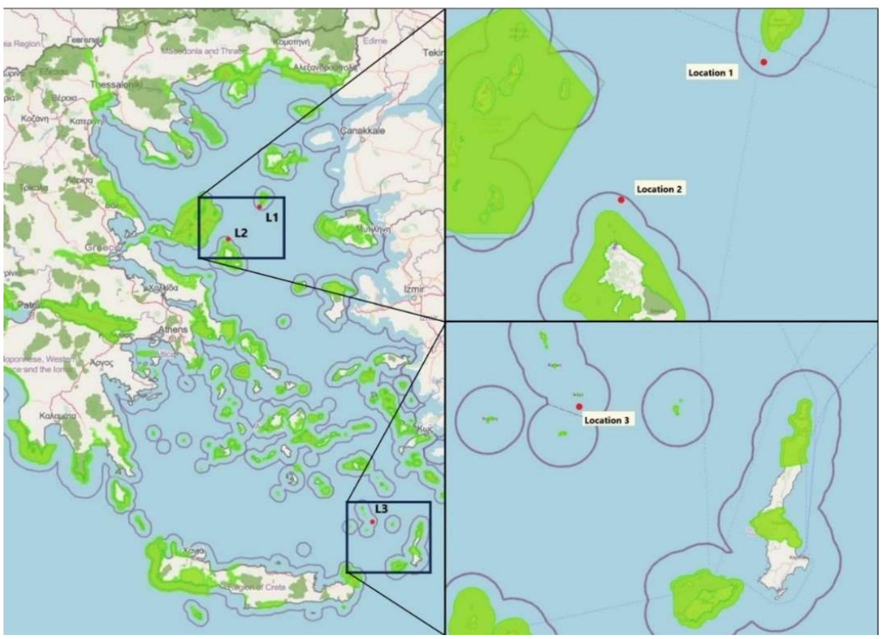


Figure 3: Aegean Sea map of marine protected areas (green – Natura 2000 network), territorial waters (purple line) and selected locations (red dots). Adapted from: [24].

2.5 Subsea grid

In order for anchoring problems to not arise, selected sites are not located above submarine cable routes. However, it is beneficial for the respective areas to facilitate subsea grid in a relevant close distance not only for easier connection and power transfer, but also for a potential installation of an offshore substation. Fig. 4a depicts the aforementioned locations with the present subsea cables of the Aegean Sea, confirming the capability of a direct connection to the nearest available shore.

2.6 Access to big ports

The installation of an offshore facility demands access to big ports with a proper industrial zone where onshore works can be completed efficiently. Regarding the selected sites, the nearest ports for supporting installation and maintenance operations are:

i) Port of Thessaloniki: ≈265 km from L1 and ≈250 km from L2

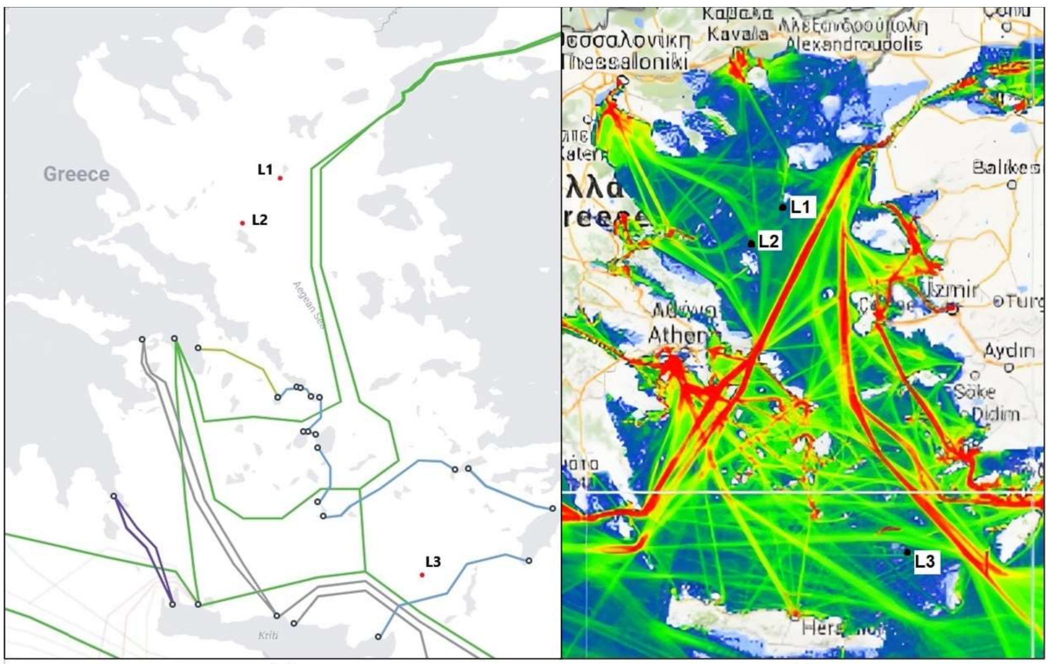
ii) Port of Volos: ≈220 km from L1 and ≈165 km from L2

iii) Port of Heraklion: ≈140 km from L3

More detailed analysis on transportation costs as well as adequate port facilities, skilled labor force and crane capacity will determine the optimum location.

2.7 Marine traffic

An offshore power plant should operate in territories where no marine traffic occurs or ship traffic density is relatively low. Navigational safety as well as vessel traffic risk analysis have to be taken into account otherwise. In the discussed process, major ship routes were avoided and minor ones were accounted for during the site selection process (Fig. 4b).



(a) (b)

Figure 4: (a) Subsea cables of the Aegean Sea [26]. (b) Ship traffic density in the Aegean Sea [27]. Locations are depicted with red and black dots, respectively.

2.8 Tourism

Tourism development areas were also considered in the current methodology (Fig. 5). The presence of such offshore energy systems may downgrade the areas aesthetically and visual disturbance may rise to visitors; thus, the respective territories were avoided.

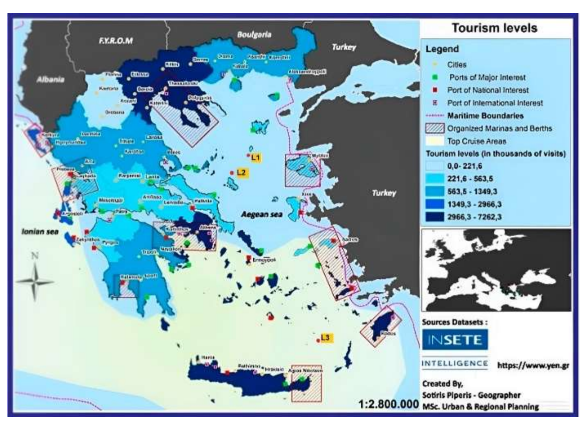


Figure 5: Main touristic areas of the Aegean Sea [28].

For a holistic approach of the ETHOS OWC installation phase, further details on marine spatial planning [28] should be investigated along with a comprehensive environmental impact study. At the current stage, the data from the three selected locations will be further analyzed to extract the design values that refer to critical environmental conditions determining the robustness of the floating structure and its mooring system.

3. Design values

In this section, an extreme value analysis (EVA) will be performed on wave parameters. The results along with the sea-state frequency tables, will enable the definition of the mooring characteristics in ultimate limit states and the energy output estimation of the installed system.

3.1 Peaks-Over-Threshold (POT) method and model diagnostics

As far as EVA methods are concerned, the most widely used are the Block Maxima (BM) and the Peaks-Over Threshold (POT). The latter is chosen amongst the two, since the available sample size of annual maxima is rather poor (20 years) [29,30]. More applications regarding the estimation of metocean extremes can be found in [31-39]. For the current data analysis of the extremes, the Peaks-Over-Threshold (POT) method is utilized. A detailed description of the method can be found in "An Introduction to Statistical Modeling of Extreme Values" by S. Coles [40].

Using the POT method presupposes the selection of a threshold above which all values are considered extreme. The main challenge, however, is to choose a threshold u that balances bias and variance. Too low a threshold is likely to violate the asymptotic basis of the model, leading to bias, whereas too high a threshold will generate few excesses with which the model can be estimated, leading to high variance. In this context, two approaches are available for threshold selection. One is an exploratory technique carried out prior to model estimation; the other is an assessment of the stability of parameter estimates, based on the fitting of models across a range of different thresholds [41]. Regarding the first approach, above a threshold u_0 at which the generalized Pareto distribution provides a valid approximation to the excess distribution, the mean residual life (MRL) plot should be approximately linear in u. The MRL plot consists of the pairs:

$$\left\{\left(u, \frac{1}{n_u}\sum_{i=1}^{n_u}\left(x_{(i)}-u\right)\right): u < x_{max}\right\}, \tag{2}$$

where $x_{(1)}, \ldots, x_{(n_u)}$ consist of the n_u observations that exceed u, and x_{max} is the largest of the $x_{(i)}$. In the second approach, the aim is to estimate the model at a range of thresholds and to look for stability of parameter estimates. This argument suggests plotting both $\sigma^* = \sigma_u - \xi u$ (modified scale) and ξ (shape) estimates of the generalized Pareto distribution against u, together with confidence intervals for each of these quantities, and selecting u_0 as the lowest value of u for which the estimates remain near-constant. The parameters of the generalized Pareto distribution can be estimated by the Maximum Likelihood (ML) method.

The quality of the fitted generalized Pareto model can be assessed by probability (PP) and quantile (QQ) plots. For a threshold u, threshold excesses $y_{(1)} \leq \ldots \leq y_{(n)}$ and an estimated model $\widehat{H}$, the probability plot consists of the pairs

$$\left\{\left(\frac{i}{k+1}, \widehat{H}\left(y_{(i)}\right)\right); i = 1, \ldots, k\right\}, \tag{3}$$

where

$$\widehat{H}(y) = 1 - \left(1 + \frac{\hat{\xi} y}{\hat{\sigma}}\right)^{-1/\hat{\xi}}, \tag{4}$$

while the quantile plot constitutes the locus of points

$$\left\{\left(\hat{H}^{-1}\left(\frac{i}{k+1}\right), y_{(i)}\right); i = 1, \dots, k\right\}, \quad (5)$$

where

$$\hat{H}^{-1}(y) = u + \frac{\hat{\sigma}}{\hat{\xi}}\left[y^{-\hat{\xi}} - 1\right], \quad (6)$$

provided that $\hat{\xi} \neq 0$. If $\hat{\xi} = 0$ the equations (4) and (6) are modified, accordingly, as follows:

$$\hat{H}(y) = 1 - exp\left(-\frac{y}{\hat{\sigma}}\right), \quad y > 0, \quad (7)$$

$$\hat{H}^{-1}(y) = u - \hat{\sigma}\log(y), \quad y > 0 \quad (8)$$

Provided that both plots depict a very close relation between theoretical and sample quantities, the model diagnostics are completed, and the model is adequately identified.

In offshore engineering applications, the concept of return period and design value is applied to adequately cover the ultimate limit state scenarios. The formal definition of the return period implies that the n–year design value is expected to be exceeded on average once during the next n years. The period of n years is called the return period, associated with the design value [40]. Denoting ζ_u as the exceedance probability or the proportion of data above a threshold u, and n_y the exceedance observations per year, the N-year return level z_N is estimated as follows:

$$z_N = \begin{cases} u + \frac{\sigma}{\xi}\left[\left(Nn_y\zeta_u\right)^{\xi} - 1\right] & if \quad \hat{\xi} \neq 0 \\ u + \sigma\log\left(Nn_y\zeta_u\right) & if \quad \hat{\xi} = 0 \end{cases} \quad (9)$$

3.2 Results

Having concluded to the three representative locations in the Aegean Sea for installing the **ETHOS** OWC, both timeseries of significant wave height and wave energy period are analyzed using the peaks-over-threshold (POT) method, modelling the extremes and resulting in 100-year return levels.

More specifically, the ERA5 reanalysis dataset was spatially co-located with the selected locations via the nearby grid point values by using a simple form of inverse squared distance weighting interpolation function based on the values of the four nearest grid points (Fig. 6). Denoting by x_1, x_2, x_3 and x_4 the respective variables at the four grid points surrounding the selected location, and r_1, r_2, r_3 and r_4 the corresponding distances from that location, the requested data for each variable at the installation sites can be estimated as follows:

$$x = \frac{\sum_{i=1}^{4}\frac{x_i}{r_i^2}}{\sum_{i=1}^{4}\frac{1}{r_i^2}} \quad (10)$$

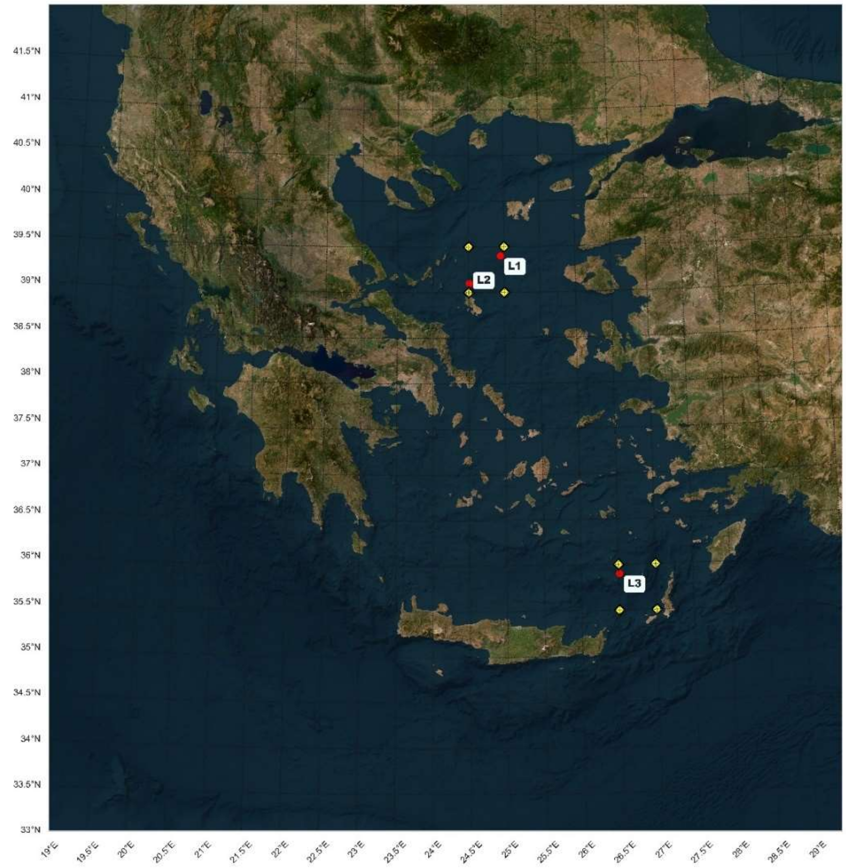


Figure 6: Proposed installation locations (in red) with their neighboring grid points (in yellow).

The proper threshold selection for each parameter is based on the aforementioned methodology. Nevertheless, higher thresholds than the ones obtained from the two previous approaches are accepted, if enough excesses are considered and proper diagnostic plots are attained. Besides, such approach is in favor of safety when designing a project, since EVA results are utilized for robustness in extreme scenarios. Table 1 presents the thresholds for both examined variables of the three selected installation sites along with the amount of each analyzed dataset. Indicatively for the significant wave height of the third location and noting that enough excesses were considered, diagnostic plots show a fair agreement of fit (Fig. 8), although MRL and stability plots may suggest lower values of u (Fig. 7). None of the plots gives any real cause for concern about the quality of the fitted model, which supports the bias-variance trade-off, suggesting that extremes can be adequately modelled.

Table 1: Thresholds and excesses dataset length for every examined parameter and location.

Location	H_s *(excesses No.)*	T_e *(excesses No.)*
L1	4.7 m (541)	7.2 s (1402)
L2	4.3 m (952)	7.7 s (886)
L3	4.0 m (482)	7.0 s (1809)

As far as design values are concerned, Fig. 9 depicts the return levels, where the well fitted model is also justified by the narrow confidence bands. Respective inferences as the aforementioned ones can result for the rest examined variables. In some cases, the 50-year return level is applied for covering the structural integrity criteria in the design process. However, the 100-year return level is mostly used in such projects to determine the final specifications of a robust structure. Table 2 presents the design values with a return period of 100 years, which will be considered as the main input for further analyses of **ETHOS** OWC and its mooring system.

Table 2: 100-year return values and 95% confidence intervals of H_s (m) referring to the three presented locations.

Variable	*Location 1*		*Location 2*		*Location 3*	
	Ret. Level	95% Conf. Int.	Ret. Level	95% Conf. Int.	Ret. Level	95% Conf. Int.
$\boldsymbol{H_s}$	7.07	[6.90, 7.24]	7.16	[7.04, 7.28]	5.45	[5.35, 5.55]
$\boldsymbol{T_e}$	9.07	[8.93, 9.21]	9.28	[9.21, 9.35]	8.66	[8.53, 8.79]

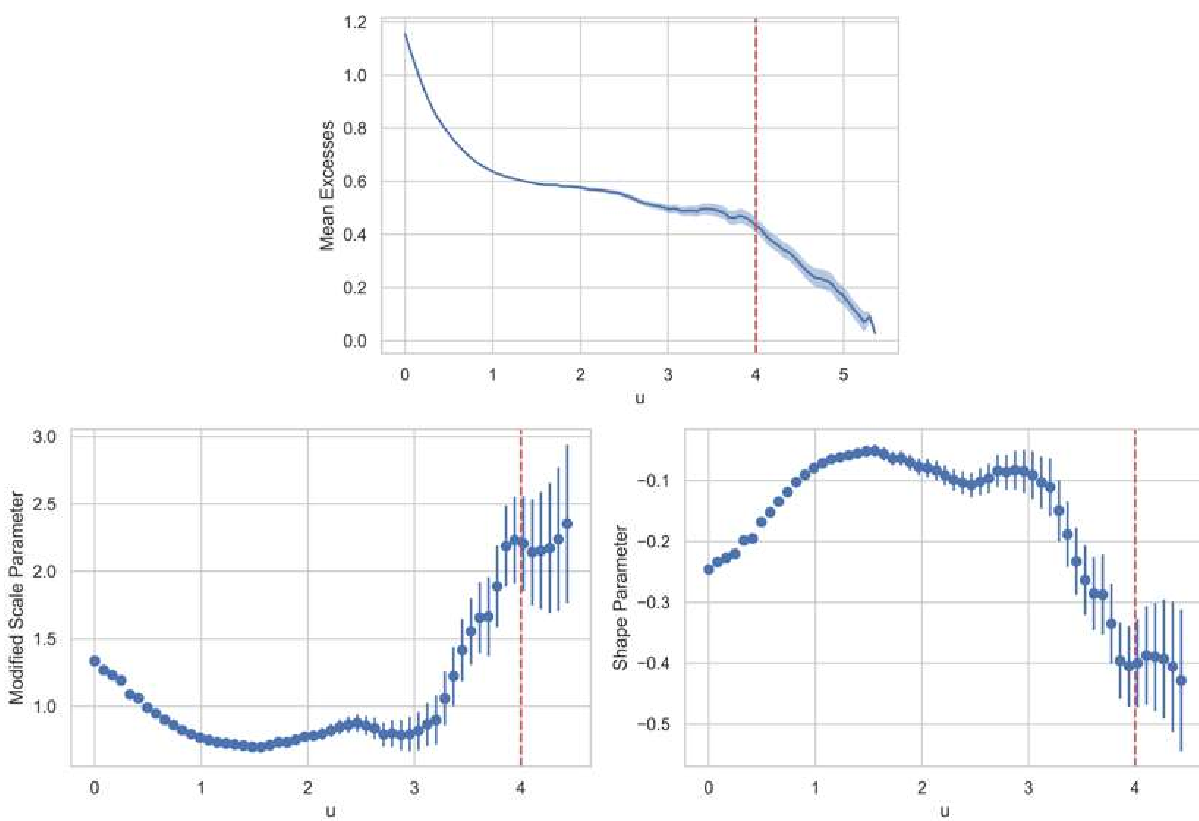


Figure 7: MRL (top), shape stability (right) and modified scale stability (left) plots of H_s for L3.

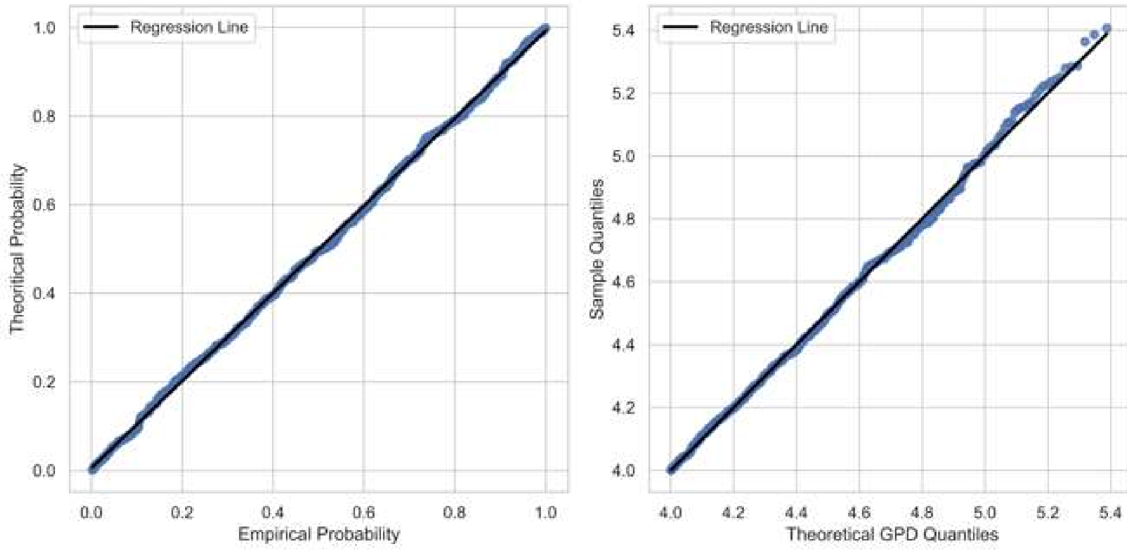


Figure 8: Probability-Probability (left) and Quantile-Quantile (right) plots of H_s for L3.

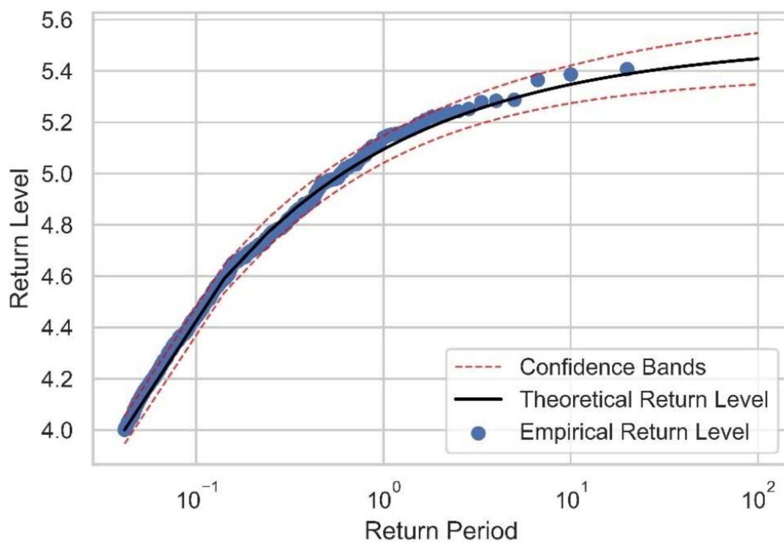


Figure 9: Return level plot with confidence bands of H_s for L3.

4. Conclusion

Siting offshore power plants demands the consideration of a number of principles for an optimum location. In the methodology discussed herein, the three representative selected installations sites cover not only fundamental, but also operational criteria for the **ETHOS** OWC. Advantageous locations regarding wave power potential and bathymetry are preferred, while marine protected areas, territorial waters, ship traffic density and subsea grid were accounted for among others. The areas of study were limited in depths between 100 m and 200 m to justify offshore zones without ultra deep significance for a financially feasible mooring system.

As far as the POT method is concerned, higher threshold selection than the one suggested from theory gave improved results based on the relevant diagnostic plots. All selections did not negate variance prerequisites and supported the bias-variance trade-off. Moreover, regarding return levels, the lowest wave design values correspond to Location 3. The maximum 100-year return values of the examined variables appear around 7.3 m for significant wave height and 9.4 s for wave energy period and thus, an extreme sea-state of $[H_s–T_e]$ = [7.3–9.4] is defined.

After the preliminary study, the selection of the final installation areas requires a set of reports, i.e. environmental, financial etc., for a comprehensive and holistic investigation of such specific and complex topic. Offshore power plants generating wave energy are the next step for the exploitation of marine renewables aligning with the global decarbonization targets and thus, detailed analyses referring to both structural aspects and financial feasibility (construction, O&M costs) are essential for the implementation of infrastructure works such as the **ETHOS** OWC.

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