Wave Energy Exploitation in the North Aegean Sea: Spatial Planning of Potential Wave Power Stations

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Abstract During the last decades there has been an increasing interest in renewable energy sources applications especially for covering the electricity needs of non-interconnected islands. Among the emerging renewables, wave energy has the potential to make significant contribution towards a sustainable future.

Greece is located in the eastern Mediterranean region while hundred of Greek islands are located inside the Aegean Archipelago. Taking into consideration the vast energy potential available in sea as well as the fact that coastal areas can much benefit from the implementation of such energy solutions, the current study emphasizes on sea sites close to non-interconnected to the mainland grid islands, which are depended on fossil fuels and more precisely on oil imports.

This research describes a geo-spatial Multiple-Criteria Decision Analysis, based on the Geographic Information Systems technology, for the identification of the candidate locations to deploy a potential Wave Energy Farm in the North Aegean Sea, an area offshore the Greek mainland East coast. For this purpose, several factors are taken into account; restrictions such as protected areas, military exercise areas etc. and weighted factors such as distance to power grid, wave height etc.

Based on the results of this survey, future prospects of wave energy and the possible implementation of innovative marine technologies could be supported, providing the remote island communities of the Aegean Sea with clean electrical energy at a reasonable cost.

Keywords: *Significant wave height, Wave power, Wave energy potential, Marine technologies, Electrical Energy*

1. Introduction

The increasing energy demand around the world, mainly due to population increase, along with the high level of dependence on fossil fuels, in addition to their reserve issues, relevant price uncertainty, security and supply issues and their impacts on the environment, set the opportunity for a global, substantial shift to more environmentally friendly sources, that could offer the desired sustainability [1]. Scientific researches for climate change have indicated the necessity for reduction of global CO_2 emissions as they significantly affect the existing ecosystems and humanity [2]. In this context, RES applications are arising, contributing especially to the electricity production worldwide, being the main polluting sector [3].

Moving towards a more "green energy production" scheme, wind energy, hydropower and solar energy are considered mature technologies, while the interest is moving also towards other RES power plants' installations, such as the sea-based alternatives, concerning offshore wind parks or the promising and upcoming wave energy.

In general, a significant characteristic of sea waves is their high energy density, which is the highest if compared with the other renewables. Moreover, wave energy is an abundant energy source with a predictability of 1-2 days (in advance), which offers a more counterbalanced output if exploited, a clear advantage in the context of a more successful integration of the intermittent renewable energy supply into the electricity grids [4].

The main drawback of wave energy is the high installation cost, due to technology immaturity of the Wave Energy Converters (WECs). In this context, some strategies could be implemented in the scope of offsetting the capital expenditure of WECs, such as a combination with a desalination process or a co-located offshore wind park [5],[6].

Tested or operated marine energy technologies are classified according to their location, working principle and wave direction as shown in figure 1(Fig.1) [7].

In the special case of Greece, with the large coastline and numerous islands scattered in the Aegean Archipelagos, wave energy is a substantial option in order to restrict the dependence on fossil fuels and the

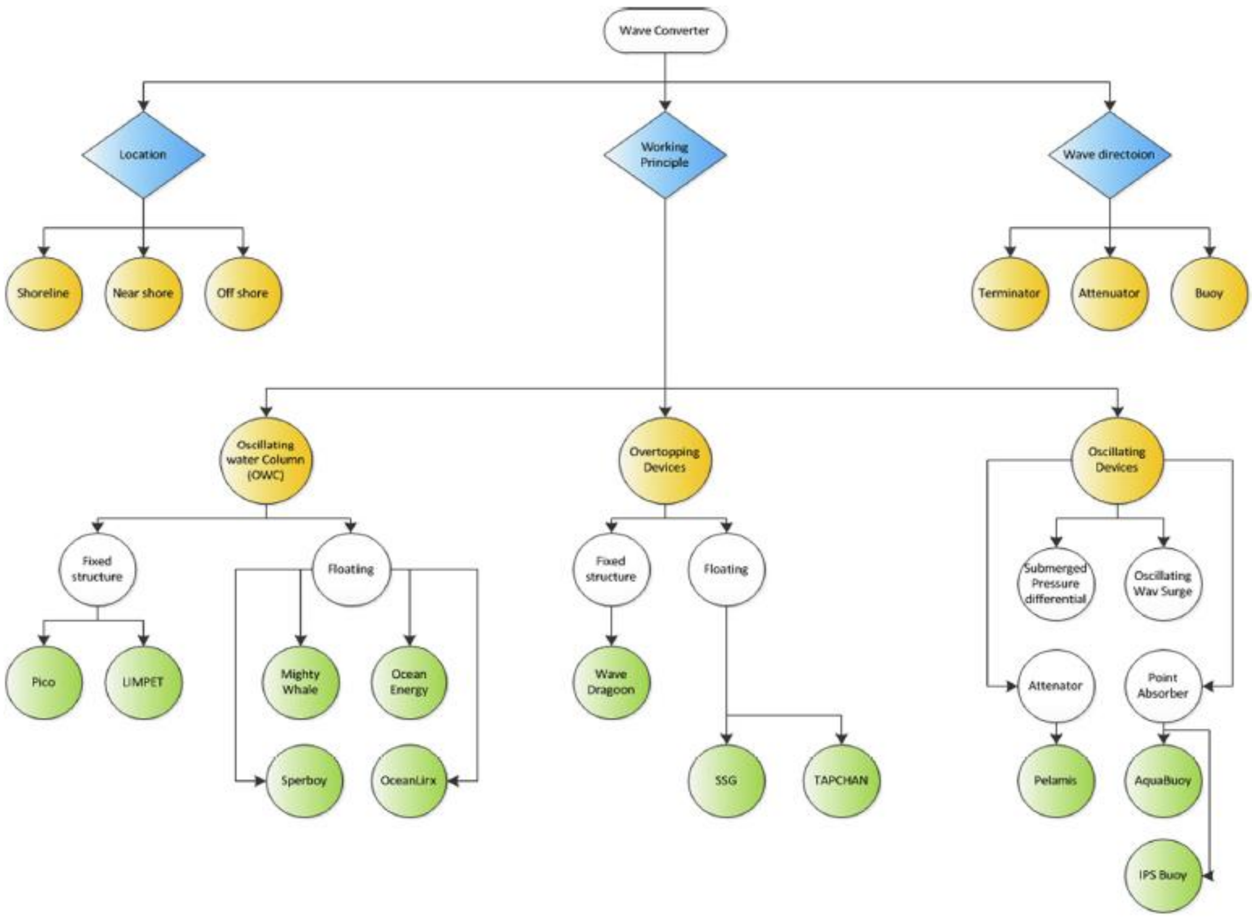

Figure 1: WECs' classification (Fadaeenejad et al., 2014).

corresponding costly imports as well as to prevent further air pollution in the future resulting from the high energy demand. Specific WECs in the Aegean Archipelagos have been already proposed in a recent research study [8].

In terms of the available wave energy potential in the Greek seas, it is estimated at 4-11kW/m of wave crest length, with N-S direction, while the complexes of the several islands cause several "hot spots" [9],[10],[11].

Hence, the proper selection for the implementation of a possible wave farm is a process of high significance for the projects feasibility thus GIS applications can be used at this stage. Useful conclusions can be derived from the geographic l analysis of the data, such as conflicts of use in the view of the best implementation choice.

The present research regards a geo-spatial Multiple-Criteria Decision Analysis (MCDA), based on GIS technology, for the determination of the best location to imply a possible Wave Energy Farm (WEF) in the North Aegean Archipelagos. This area possesses remarkable wave potential which if exploited may contribute to cover the islands' electricity consumption. Note that the electricity production cost in the entire area is quite high, hence the introduction of WEFs may be quite competitive. Finally, the potential wave energy exploitation eliminates any issue of land use and/or visual and noise impact. The adopted methodology and the results along with the main conclusions are described in the following sections.

2. Methodology

As aforementioned, data concerning the criteria for selecting the best area for a wave farm implementation are gathered in Table 1. These data are elaborated using a GIS tool, an integrated information system which enables collection, management, analysis and visualization of geographical information.

In the chart below (Fig. 2), the main stages of this research are presented.

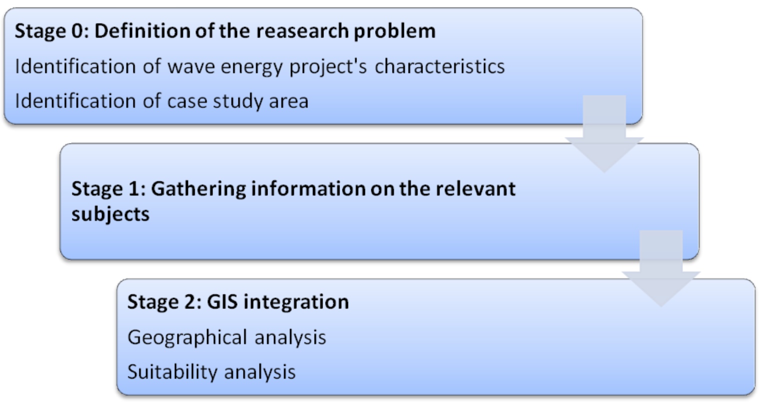

Figure 2: Methodology stages

Table 1 Main factors affecting the selection of the area for wave energy installations

1)	level of power resource
2)	seabed morphology and bathymetry
3)	proximity ports
4)	interaction with other land uses
5)	connection to the grid

In general, the activity of sea exploitation for energy production in Greece is not subjected to any legislative scheme as no relevant projects exist. In this context, for the purposes of the current study, the existing national legislation regarding offshore wind parks has been used. In the scope of planning and implementing a wave energy farm, there are several factors that affect the choice of the most suitable area. For the purposes of this research the most important factors are presented below:

2.1. Conflicts with other uses

The sea area around the site of interest must not be included in any kind of protected areas (like NATURA 2000), anchoring zones, vessels routes, subsea cabling areas.

2.2. Seabed morphology and bathymetry

The installation of a WEC includes the phase of anchoring, so the potential installation site must also be determined after the examination of the seabed's morphology along with the depth in order to have the less possible anchoring equipment as well as cabling.

2.3. Grid Connection

The electricity produced from the WECs will be subsequently supplied to the grid, so the implementation site must be selected after considering the distance from the shore and by extension to the existing grid. The distance of the WEF to the grid connection shall be as short as possible in order to reduce the cabling cost which contributes significantly to the overall CapEx (installation cost).

2.4. Proximity to Ports

Another factor that should be taken into account for the implementation site is the relative distance and proximity to nearby ports, as a variety of services will be running during installation, during M&O periods, as well as during the decommissioning phase [12].

2.5. Wave Energy Potential

The basic parameter when choosing the proper site for a WEF is the wave energy potential of the area. The assessment of the wave energy resource is a procedure of high significance [11[,[12] concerning the feasibility of the project.

In the present work, data concerning the wave energy potential have been derived from satellite based measurements (AVISO) as well as in situ measurements of POSEIDON scattered in the Greek seas buoys of the Hellenic Center of Marine Research (HCMR).

AVISO is a reliable data service that provides different kinds of reference information concerning the state of the oceans and regional seas. The data extraction tool allows users to select several kind of information, e.g.:

- Sea Surface Elevation data
- Wind and Wave data (Wind speed value, Significant Wave Height)
- Auxiliary data derived from altimetry or used in altimetry data process
- Indicators, i.e. "calculated quantities" or "elements showing the characteristics of the ocean". Mean Sea Level is one of them.

In the context of in-situ measurements, the HCMR through the POSEIDON system offers forecasting, monitoring and information data of the Greek Seas (Fig. 3), via the available active (or previously active) observational buoys [13].

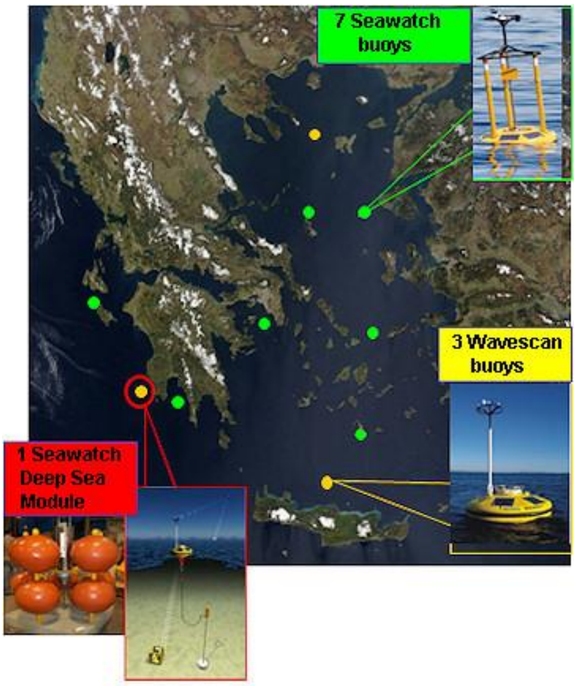

Figure 3: Poseidon Systems buoys

As the research is focused in the North Aegean Archipelagos, data are acquired from the POSEIDON data base and the existing buoys within the area being investigated, as it is shown in the following map (Fig. 4)

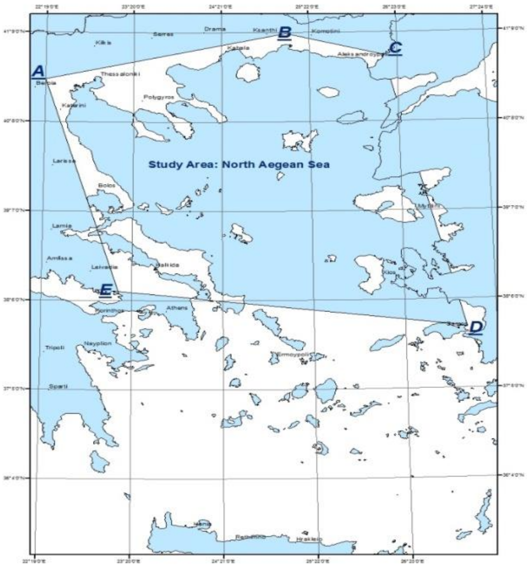

Figure 4: Polygon of North Aegean Sea Area

Having evaluated all the aforementioned factors, the next stage is the GIS integration, in which the factors and parameters are gathered for a geographical analysis and representation. The global positioning system WGS84 was used as a common referencing map. Data from military exercise areas and data concerning the power grid have been obtained from the Hellenic Navy and HTSO (DESMIE) respectively, in a non-digital format and digitization has been carried out.

Concluding, the research is subjected to a MCDA which is based on the existing restrictions (marine routes, areas used for military purposes, protected areas, fisheries, etc.) while the proposed solution processes a group of major factors (distances to ports and shore, distance for grid connection, wave energy potential), Fig. 5.

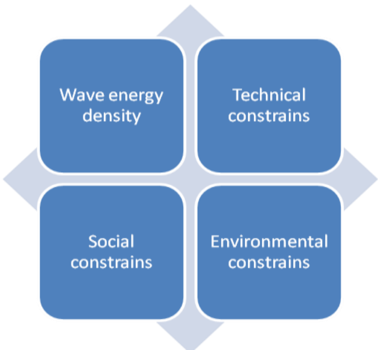

Figure 5: Criteria (layers) for the design of site selection

Aiming at the final site selection for the WEF implementation, the phase of GIS integration is implemented in three sub-phases (Fig. 6); a) excluded areas map presentation, b) identification of technically available areas and c) the geographical representation of the wave energy potential in order to take the proper decision when accounting the restrictions.

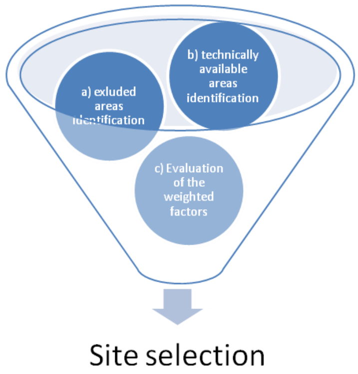

Figure 6: GIS integration phase

3. Analysis and Results

a. Exclusion zones

Taking into account national and EU legislation for marine energy projects, it is possible to create the map of the North Aegean Archipelagos areas with the corresponding excluded zones, being subjected to other uses as aforementioned (protected areas, military exercising areas, ferry routes etc.). In Figures 7-8, all these restricted areas are gathered in the corresponding maps.

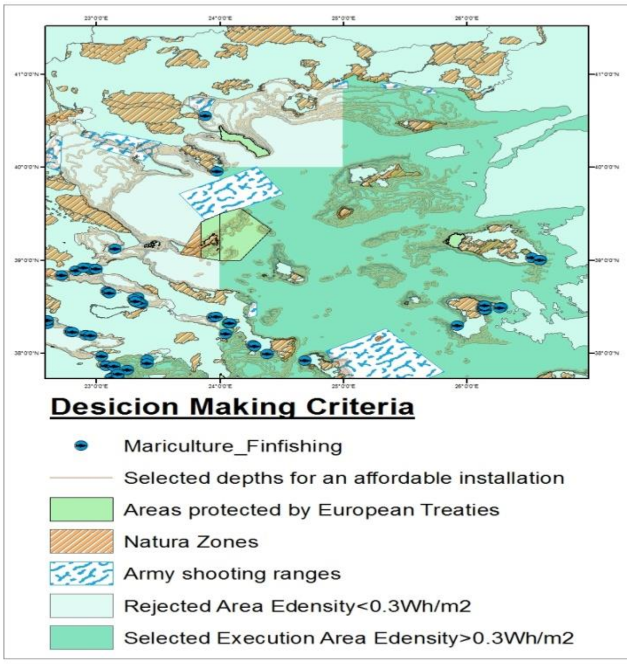

Figure 7: Restricted zones

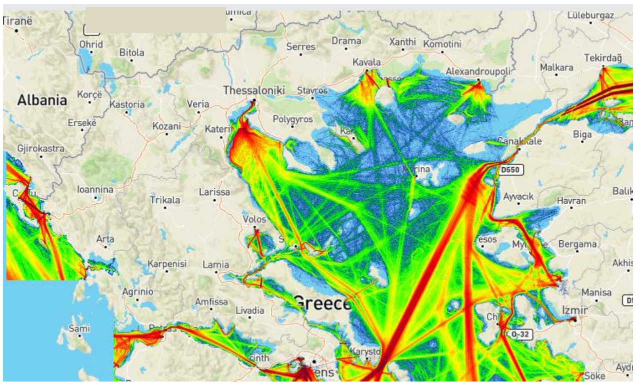

Figure 8: Maritime traffic density map

b. Technically available areas

Continuing to the second step, after the identification of the excluded areas, those technically available for the project implementation are also identified. With the term "technically available areas" one may determine the areas with depth permitting to anchor the WECs, while the distance from the existing grid is considered acceptable. Concerning the bathymetry integration (Fig.9), the candidate areas are those where the depth ranges between 50m and 200m, since for depth values less than 50m visual impact may be a deterrent fact, while for values greater than 200m the necessary anchoring of the WECs is much more difficult and costly.

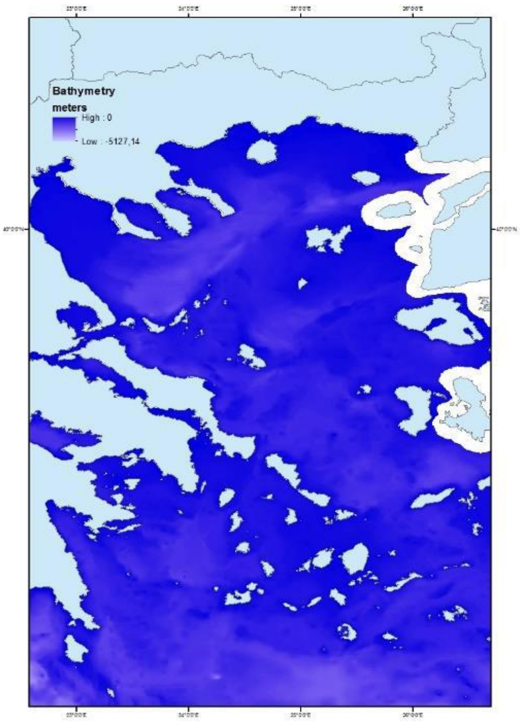

Figure 9: Bathymetric data

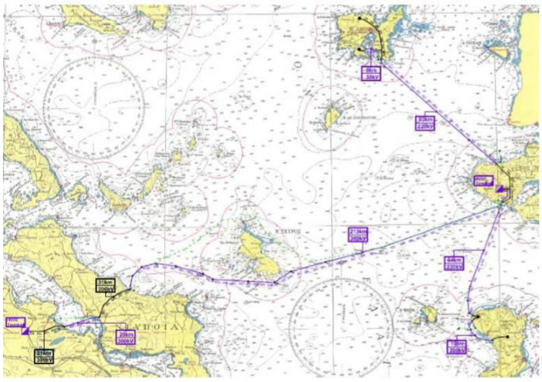

Figure 10: Submarine power transmission plans (source: ROKAS Renewables)

As it can be seen from Figure 10 a projected plan for a submarine cable crossing the North Aegean Sea already exists, which -if implemented- will provide a major opportunity for wave energy power plants in the area.

c. Wave Energy Potential and selection of the implementing area

The last but probably the most important parameter is the wave potential of the area under investigation. The evaluation of the wave energy resource is at the moment limited to measurements of the wave height for one year, comparing the satellite based data from AVISO with the corresponding in-situ measurements of POSEIDON. For more detailed evaluation long-term data should be included, concerning also the energy period of the waves [11],[12]. In this context, the wave energy potential is integrated along with the previously mentioned factors/restrictions in the GIS forming the following map (Fig.11).

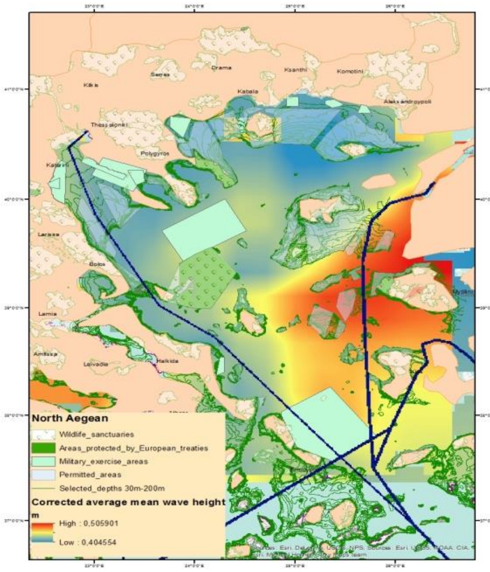

Figure 11: Mean Wave Height and restricted/permitted areas in N. Aegean

Taking into account both the mean wave height and the technical and administrative factors and restrictions, as already presented geo-spatially, three possible areas for a WEF implementation are evaluated [10],[11] in order to select the most adequate one.

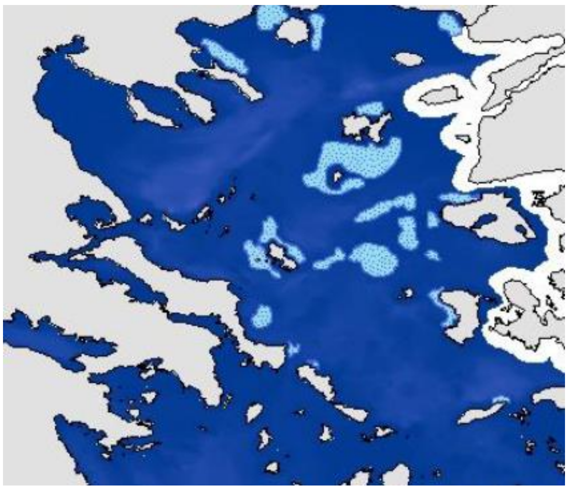

Figure 12: Proposed Wave Energy Application Areas (light blue) in N. Aegean

According to the data of Fig. 12-13, Skyros island measurements present the greatest wave potential (annual mean significant wave height equal to 1m or wave potential in the order of 10kW/m) of the three candidate areas examined. On top of these the corresponding wave height does not exceed 5m protecting thus the possible application from excessive loads and supporting the long-term reliable operation of such installations. Actually, the detailed analysis of the available data indicates that for all three regions investigated the wave potential values range in the same level, but significant wave height values are higher in Skyros (Fig. 13) for a longer period.

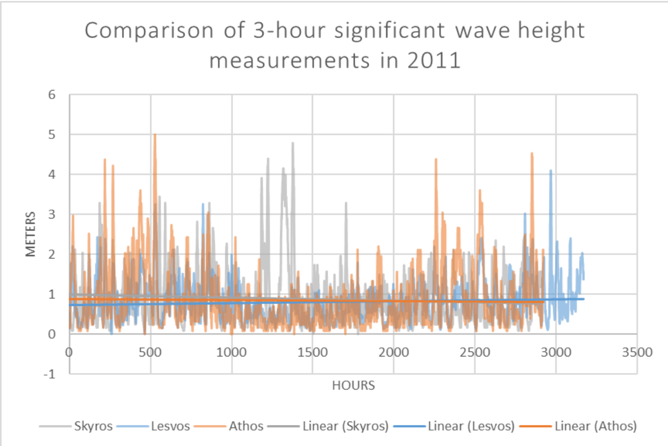

Figure 13: Significant Wave Height for three selected areas in N. Aegean

The next step following this preliminary analysis is the detailed evaluation of the above mentioned parameters (wave potential included) in a micro-scale in order to locate the most attractive regions of Skyros island and execute the necessary micro-siting study, Fig, 14.

Figure 14: Skyros Island characteristics

Moreover, the possibility of developing a combined off-shore/near shore wind and wave installation [14],[15] sharing the same infrastructure, (see for example the experimental/pilot device of Fig. 15 developed by SEALAB postgraduate students [16]) may further support similar renewable energy solutions. Finally, an extensive cost-benefit analysis is also required in order to check the viability opportunities of similar investments under the current techno-economic environment [17].

Figure 15: Wind and Wave Application Experimental (pilot) Device developed by the SEALAB [16]

4. Conclusions

The Greek Electricity Generation System is characterized by its high dependence on fossil fuels and the corresponding CO_2 emissions, while more RES penetration is required in order to achieve the national and EU targets for more environmental friendly and sustainable electricity production. In this context, the upcoming wave energy exploitation can contribute significantly to the RES penetration in the local grids, as the corresponding wave energy potential in Greece seems to be adequate for wave energy farms across its extensive coastline or near its scattered islands. In the current study, a MCDA has been carried out evaluating the wave energy potential of the North Aegean Archipelagos, along with the several factors that must be considered when choosing an appropriate site for the implementation of a wave power station. In this context, the spatial planning analysis takes into account the excluded zones (environmental protected areas, military activity areas, fisheries or ferry routes) along with other parameters as the bathymetry of the area, the grid accessibility and port proximity in order to make the project as feasible as possible. The integration of all the considered parameters for a possible wave farm has been achieved using a GIS tool in order to create a map which includes all the available data supporting a preliminary decision. During the overall process, the factor which has the higher significance is the evaluation of the available wave energy potential.

Considering the analysis of the North Aegean Archipelagos and its possible areas for a WEF, it could be proved that there are some indicative areas where wave conditions are remarkable. Among three final proposed areas, Athos area, Lemnos and Skyros, it was found that the significant wave height values are slightly higher in Skyros for a longer period.

Concluding one may state that although the significant wave height in the area examined is not as high as in open seas, nonetheless the existing wave energy potential is quite interesting and may support future investments, especially in combination with analogous near-shore wind parks. Furthermore, opportunities for effective wave energy applications exist around the North Aegean

Archipelagos, while WEF is a candidate solution to provide clean and stable electrical energy to the islands of N. Aegean with a rational life cycle energy production cost.

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