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GIS-based multi-criteria decision analysis for site selection of hybrid offshore wind and wave energy systems in Greece

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ABSTRACT

The deployment of Hybrid Offshore Wind and Wave Energy Systems (HOWiWaES) towards the simultaneous exploitation of the corresponding offshore renewable energy sources, may efficiently address the common challenge of the offshore wind and the wave energy sector to reduce their costs, with multiple additional benefits. A prerequisite at an early stage of the realization of a HOWiWaES project is the determination of marine areas suitable for the deployment of HOWiWaES. In the present paper, a methodological framework for identifying the most appropriate marine areas in Greece towards the deployment/siting of HOWiWaES is developed and presented. The framework is based on the combined use of multi-criteria decision making methods and Geographical Information Systems (GIS). At the first stage of the analysis, the unsuitable for the deployment of HOWiWaES marine areas are identified through the development of a GIS database that produces thematic maps representing exclusion criteria related to utilization restrictions as well as to economic, technical and social constraints. Then, at the second stage of the analysis, eligible marine areas not satisfying exclusion criteria are evaluated and ranked using the Analytical Hierarchy Process (AHP), based on evaluation criteria related to economic, technical and socio-political factors. The AHP's implementation is supported by the developed GIS database, eliminating significantly the subjectivity in judgments. The results of the paper illustrate the potential for deploying HOWiWaES in Greece, especially in the offshore areas of Crete and in a lengthwise zone extended from North-central to central Aegean.

1. Introduction

The efficient harnessing and exploitation of the indigenous offshore wind and wave energy potential is directly linked to the long-term strategies and energy policies of the European Union towards energy security enhancement, economic growth and reduction of CO_2 emissions [1–4] and [5]. As a result, in recent years the European offshore wind energy sector has been rapidly developed and this fact has lead to large-scale commercial deployment of offshore wind farms in Europe. By the end of 2015, offshore wind farms of 11,027 MW capacity have been installed and grid-connected, mainly in the nearshore areas of Northern Europe (average installation depth equal to 22.4 m) [3]. However, aesthetic considerations [6] and the scarcity of available shallow water sites [7] have initiated the need for deploying offshore wind turbines in deeper waters, where, additionally, stronger and more consistent winds exist [6]. This trend creates new technological and economical challenges that should be adequately addressed towards the sustainable and cost-efficient realization of offshore wind energy projects. On the other hand, wave energy technology represents nowadays one of the most advanced and rapidly developed ocean energy technologies, which is anticipated to be commercially available in the short-medium term [8]. The European wave energy sector is anticipated to reach 26 MW of installed capacity by the end of 2018 [8], while a target of 100 GW installed capacity for ocean (wave and tidal) energy in Europe by 2050 has been established [5]. However, there are still critical technological barriers [8] that should be overcome in order to achieve energy effectiveness, cost efficiency, safety, durability in harsh sea environmental conditions and, therefore, competitiveness with other renewable energy sources.

A common objective of both the offshore wind and the wave energy sector is the reduction of associated costs (e.g. [9] and [8]). The deployment of Hybrid Offshore Wind and Wave Energy Systems (HOWiWaES), that combine in one structure an offshore wind turbine with wave energy conversion systems, and enable the simultaneous exploitation of the corresponding energy potentials, may contribute to the satisfaction of the above objective, offering at the same time multiple additional benefits, such as increased energy yield, smooth and highly available power output, common grid infrastructure etc. [9]

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and [10]. Recently developed HOWiWaES have been investigated in [11,12] and [13].

An important prerequisite at an early stage of the realization of a HOWiWaES project is the determination of marine areas suitable for the deployment of the corresponding hybrid energy systems. The site selection for utilizing HOWiWaES corresponds to a complex, multi-dimensional decision making process. An effective spatial decision making requires explicit methodologies for managing jointly, conflicting criteria related to technical, economic, environmental and socio-political factors in order to evaluate and select among various siting alternatives. Multi-Criteria Decision Making (MCDM) analysis has made it possible to include in the assessment multiple, either quantifiable or non-quantifiable criteria. The application of multi-criteria assessment methods to support complex energy decision-making has gained great interest during the last decades and, so, they can support decision makers towards the systematic evaluation and prioritization of marine areas for HOWiWaES deployment.

While a variety of MCDM methods exist [14,15] and [16], in [14] it is noted that the Analytical Hierarchy Process (AHP), initiated by [17], represents one of the most popular MCDM technique on sustainable energy planning. It is a flexible and simple optimization method that has been widely explored in the literature for locating facilities. Although AHP has been used for solving numerous problems related to onshore wind farms site selection (e.g. [18–24] and [25]), its applications on site selection of offshore renewable energy technologies are really handful and are mainly restricted to offshore wind farms (e.g. [26] and [27]).

The efficient application of a MCDM method for the site selection of offshore renewable energy technologies requires collection, storage, processing, analysis and accurate representation of geo-spatial data related to site selection criteria. The above can be easily implemented through the use of Geographic Information Systems (GIS), which provide a comprehensive framework with multiple spatial analysis capabilities, necessary for the efficient management and visualization of digital geo-spatial data. Consequently, the use of a MCDM method combined with GIS could lead to an effective spatial planning of offshore renewable energy technologies, including HOWiWaES, enabling the evaluation of various siting alternatives in a spatially accurate, systematic, robust and integrated manner, eliminating in a great extend subjectivity in judgments.

Up to now, GIS techniques combined with various different MCDM methods have been mostly applied for onshore wind farms site selection (e.g. [18,21–25,28–30]), while a GIS-based site selection methodology, including a fuzzy decision making process, has been developed in [31] for deploying hybrid onshore wind and solar energy systems in Turkey. Considering the spatial planning of offshore wind farms, GIS combined with AHP has been applied in [26] for evaluating offshore wind farms' siting in Greece, while a web-based participatory GIS including AHP as the MCDM method has been developed by [27] for assessing offshore wind farms' suitability. Moreover, there are other investigations focusing on the identification of suitable areas for offshore wind farms by utilizing only GIS (e.g. [32]). As far as the site selection for deploying wave energy conversion systems, a geo-spatial multi-criteria analysis, where the applied MCDM method is based on the multiple-attribute value theory, has been developed and applied by [33], while a new method, combing AHP with artificial neural networks, for determining the feasibility of wave energy projects has been proposed by [34].

With regard to the determination of suitable marine areas for deploying HOWiWaES, a site selection methodology addressing this objective has been developed in the framework of the EU FP7 project "Off-shore Renewable Energy Conversion platforms – Coordination Action" (ORECCA). More specifically ([35,36]), by taking into account a variety of siting criteria, such as available resource, water depth etc., a web-based GIS platform was developed; this platform in combination with the multiple-attribute value theory for multi-criteria analysis was applied for the site selection of combined offshore wind and ocean (wave and/or tidal currents) technologies in three large geographic regions (North and Baltic Seas, Atlantic Coast and the Mediterranean and the Black Seas). The project made the first attempt for collecting data and promoting knowledge towards the spatial planning of combined offshore renewable technologies, including HOWiWaES, in an integrated manner at a high regional (European) level with a satisfactory degree of accuracy considering the large extent of the investigated marine areas. Recently, a GIS database including data from high resolution co-located, cotemporal wind and wave models, along with additional environmental and physical parameters at European level has been developed in [37], along with a decision support tool facilitating users to input criteria limits and weightings for a multi-criteria analysis (based on a weighted sum method) for the site selection of combined offshore wind and wave energy technologies. Application of all the above has been made for identifying marine areas suitable for the siting of specific HOWiWaES concepts in Northern Europe. A spatial analysis towards the optimal siting of co-located offshore wind and wave energy technologies in the Danish North Sea has been implemented in [38], taking into account wind and wave characteristics, along with human pressure indicators related to ship traffic and fishery productivity.

Finally, it is worth to note that in the case of Greece, as far as the spatial planning of offshore wind and wave energy technologies is concerned, all existing studies so far focus on the site selection of either only offshore wind farms [26] or only wave energy converters [39,40]. Especially, regarding wave energy conversion systems, guidelines and a general methodology for determining relevant suitable marine areas are proposed in [39] in the framework of the EU project WAVEPLAM, while in [40] the above methodology is used at a preliminary stage for the site selection of wave energy farms at a specific marine area in Greece. Suitable marine areas in the Greek seas for potential deployment of HOWiWaES have been determined by [41], considering, however, only the available offshore wind and wave energy resources.

In the present paper a methodological framework for identifying the most appropriate marine areas in Greece to deploy HOWiWaES is developed and presented. The framework is based on the combined use of MCDM methods and GIS. Initially, the unsuitable for the deployment/siting of HOWiWaES marine areas are identified based on a set of exclusion criteria related to utilization restrictions (including environmental constraints) as well as to economic, technical and social constraints. For this purpose, a GIS database is developed, where thematic maps are formed relevant to the aforementioned criteria. Eligible marine areas not satisfying exclusion criteria are, then, evaluated and ranked using AHP considering a set of evaluation criteria related to economic, technical and socio-political factors, and the most adequate areas for the siting of HOWiWaES in the Greek marine environment are, finally, determined. The remainder of this paper is organized as follows. Section 2 describes the AHP approach applied. Section 3 presents the study area and the data used, and provides the methodological framework of the HOWiWaES siting assessment applied in this study explaining both the exclusion and the evaluation criteria. In Section 4, the results of the present paper are presented and discussed in detail, while, finally, in Section 5, the main conclusions of this study are cited along with suggestions for future research and investigation.

2. AHP approach

AHP was initiated by Saaty [17] in the 1970s. The process includes the decomposition of a complex problem into a hierarchy with a goal at the top of the hierarchy, criterions at the levels of the hierarchy (sub-criterions at sub-levels of the hierarchy) and decision alternatives at the bottom of the hierarchy. Pairwise comparison of elements at each level of the hierarchy is performed with respect to each criterion on the preceding level. AHP is recognized in its ability to consider tangible and