The Scientific World Journal

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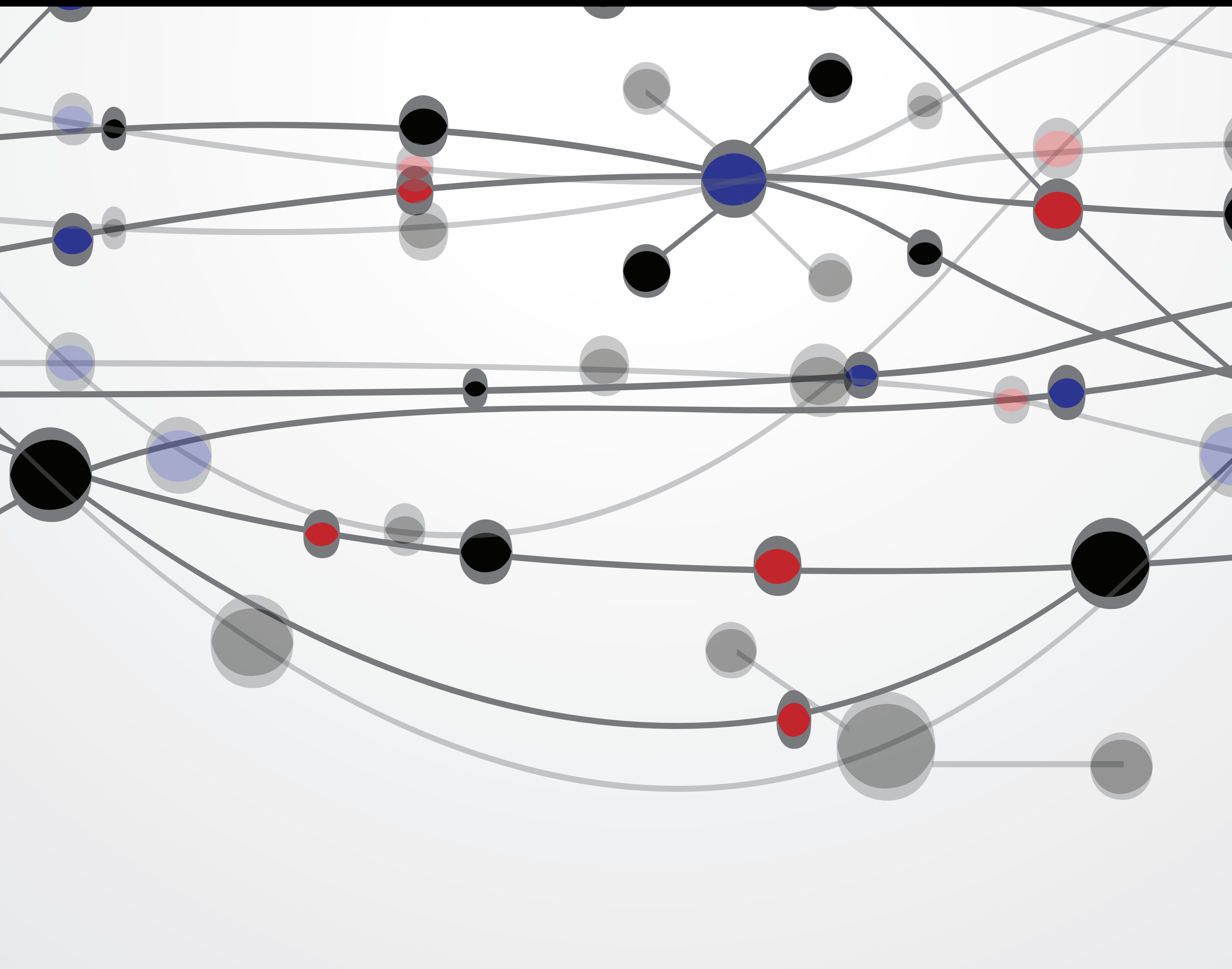
Guest Editors: Arianna Azzellino, Daniel Conley, Diego Vicinanza, and Jens Peter Kofoed



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Editorial

Marine Renewable Energies: Perspectives and Implications for Marine Ecosystems

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Countries with coastlines may have valuable renewable energy resources in the form of tides, currents, waves, and offshore wind. The potential to gather energy from the sea has recently gained interest in several nations [1–3], so Marine Renewable Energy Installations (hereinafter MREIs) will likely become very diffuse in the near future and determine a further transformation of our coastal seas.

Coastal zones are, in fact, already subjected to significant pressure from human activities, as a result of their high biological productivity and accessibility. It might be expected that the MRE sector development will add its impacts to those of the existing pressures.

Up to now the public concern about the environmental impacts of renewable energy projects has been a major factor behind the stalling or rejection of many planning applications for on-shore renewables developments. Siting renewables facilities in off-shore locations would appear to reduce this tension [4], but it cannot be forgotten that coastal ecosystems have already experienced major changes due to human activities, while the spatial conflicts of sea uses and demands are increasingly growing. In such a complex framework of existing uses, pressures, and foreseen developments, the MRE sector development makes urgent the use of Marine Spatial Planning approaches. Spatial decision support systems, through the efficient exchange of information between experts, stakeholders, and decision makers, offer the opportunity to guide the transition from the single sector management toward the integrated management of sea uses.

Concerning the marine realm, in fact, the integration of the resource planning has become a sought-after norm after the many failures of the traditional sectoral, single-issue management. Fisheries collapse, threats to marine biodiversity, and global climate change effects are all elements that require a greater integration in marine resource management and policies. Moreover, the greater awareness of the extent to which our marine habitats have become degraded, the widening of interests in—and users of—the marine space, including the general public, and the increased governmental commitment to a wider stakeholder participation in marine decision-making have created the ground for marine spatial planning becoming essential for analysing and allocating the spatial and temporal distribution of human activities in marine areas, in order to comply with fixed ecological, economic, and social objectives.

In this framework, the knowledge on the potential environmental risks that might be associated with the presence of MREIs, the prediction of the areas of particularly vulnerable environmental characteristics, and the early identification of conflictual uses will feed the spatial planning process and create the ground for mitigation actions or early negotiations between stakeholders.

To date only few studies have considered the potential environmental risks associated with the presence of MREIs.

The fact that many MRE devices are still in the experimental/trial phase is the reason why no data are available on the environmental effects of commercial developments and why presently it is not fully clear how to scale up from the limited observations on individual or small clusters of devices to commercial scale arrays.

The offshore wind industry, now extensive and well established, has already taught numerous lessons regarding monitoring methodologies and key receptors; however, to establish the baseline conditions of a site in order to evaluate impacts remains the critical point.

The articles contained in this special issue build further on the idea of the knowledge basis needed to accelerate the implementation of spatial planning decision support tools in the context of the management and, based on their particular field of expertise, provide a perspective on needs and opportunities offered by the MRE sector development.

The contributions consider various elements of the environmental impact assessment, spanning from the assessment of baseline conditions, the identification of control sites, the design of monitoring protocols, the need to combine the information derived by different MRE projects, and the perceived necessity to move towards adaptive management schemes that may benefit from the progress in the knowledge acquisition.

Effective and reliable decision-making needs sound research. In their article: "*Epibenthic assessment of a renewable tidal energy site*," E. V. Sheehan et al. provide a baseline benthic survey for the Big Russel in Guernsey, UK, a potential site for tidal energy development. They compared the abundance of organisms on different habitat types and the assemblage composition of sites within the Big Russel in order to assess the suitability of a previously suggested control site and other potential locations for devices. Their baseline survey is meant to be used to select control habitats with which to compare and monitor the benthic communities after installation of devices and contribute towards the optimal siting of any future installation.

A common feature of environmental impact assessment studies is the need to compare alternative scenarios, and this may be done by using a simulation approach or using the information derived from different MRE projects.

In their paper "*The environmental impact of a Wave Dragon array operating in the Black sea*," S. Diaconu and E. Rusu discuss the influence on the shoreline dynamics of a potential Wave Dragon installation in the Black sea. They use a simulation approach and evaluate the impact of the wave energy farm in the two representative scenarios: (1) scenario without any wave energy converter and (2) scenario of a Wave Dragon installation consisting of six wave energy converters. Their results show that the presence of the MREI has a significant influence near the wave farm that gradually decreases towards the coastline. They also analyse the influence of the WEC array on longshore currents, using a nearshore circulation model and found the longshore current velocities to be more affected by the presence of the wave farm than the significant wave height. The authors discuss also how effects may possibly impact the marine flora and fauna.

In their paper: "*Differentiating between underwater construction noise of monopile and jacket foundations for offshore windmills: A case study from the Belgian part of the North Sea,*" A. M. J. Norro et al. compare the underwater noise generated during the piling activities of steel monopiles at the Belwindwind farm (Blighbank) with that of jacket pinpiles at the C-Power project (Thorntonbank). Underwater noise is measured at various distances from the pile driving location. In their study, no significant differences are found between monopile and jacket pinpiles, having nearly identical spectra. The implications for the windmills construction are not insignificant, being the piling of the jacket pinpiles 2.5 timefolds more time consuming than monopile and requiring more energy. The implications of the underwater noise production are also evaluated in terms of radius of major behavioural disturbance for the sensitive species, the harbour porpoise, *Phocoena phocoena,* being found as almost the same for the two types of piling.

MREI may also produce positive impacts in the marine ecosystem, acting as artificial reefs, and offer the opportunity of strengthening MRE planning applications by combining energy production with other marine productions. In her review article "*Artificial reef effect in relation to offshore renewable energy conversion*," Langhamer discusses the opportunities offered by MREIs in terms of habitat enhancement for threatened or commercial interesting species. She describes why it is highly possible that offshore energy installations act as artificial reefs and may support both environmental and commercial interests. However, she points out that the lack of basic knowledge is very often the reason why artificial reefs may fail to enhance biomass production. Detailed ecological studies testing the enhancement potential of different types and dimensions of scour protection would be necessary, before developing management criteria (i.e., no-take zones for fisheries). Besides illustrating the economic opportunities of combining different farming systems (e.g., mussel farming and seaweed cultivation) with the existing offshore parks, Langhamer discusses how further research work may strengthen planning applications for future developments, based also on the cooperation of different MREIs, collecting environmental data using a Before-and-After-Control-Impact design, option that may significantly accelerate application processes and reduce the need to repeat studies.

Adaptive management is becoming a diffuse framework of choice for environmental management. Whether active (i.e., based on deliberate experimentation with alternative environmental management approaches whose impact is evaluated) or passive (based on a single management approach for which the impact is predicted and then monitored), the updating of the conceptual understanding of the impacts and the response of the natural systems to management interventions offer the opportunity to shape the management schemes (and in the monitoring itself) to what is suggested by evidences brought by the initial monitoring. In their paper "*An adaptive framework for selecting environmental monitoring protocols to support ocean renewable energy development*," E. J. Shumchenia et al. discuss an adaptive framework based on indicators of the likely changes to the marine ecosystems due to MREIs and develop decision trees to identify impacts, at both the demonstration and commercial scales, as function of type of energy (e.g. wind, tidal, or wave), structure (e.g., turbine), and foundation type (e.g., monopole). In their study, impacts are categorized by ecosystem component (i.e., benthic species, fish, birds, marine mammals, and sea turtles) and monitoring objectives are developed for each. In consideration of the poor knowledge about the baseline natural variability of the environmental indicators and the difficulties of separating impacts from the noise of the seasonal or interannual environmental variability, these authors propose an adaptive monitoring framework, as alternative to the more diffuse "static" type, since it might benefit from the progress in the knowledge acquisition and improved understanding of the impacts on marine resources deriving from the initial monitoring activity, which may, on its turn, greatly change the case specific monitoring needs and/or requirements.

All the papers in this issue are intended to advance more strategic and integrative thinking on how to apply an ecosystem-based spatial planning approach to better manage the integration of the MRE sector development into the existing framework of human sea uses. The growing concern over the threat of global climate change and the other environmental impacts of the worldwide reliance on fossil fuels have amplified the interest on renewable energies and drawn the attention on the immense stores of energy in the ocean [5]. Advocates of renewable energies endorse their multitude of economic and energy security benefits compared to other sources of conventional electricity generation and ground their reasons on the global benefit of reducing carbon emissions and on the collateral benefits of the lower consumption and pollution of water resources.

Notwithstanding, environmentalists and some environmental scientists have criticized the very diffuse wind energy installations, both terrestrial and marine, for their negative impacts on wildlife, and especially birds. In this respect we believe that the environmental concerns should not hinder the future of the MRE sector in absolute terms but instead foster the developing of guidelines to properly conduct the environmental impact studies, aiming to maximise the protection of the marine environment.

Sovacool [6] in a recent paper argues that conventional electricity systems, as nuclear power and fossil-fuelled power systems, have also a host of environmental and wildlife costs, particularly for birds. Through a coarse calculation of the avian fatalities of wind electricity, fossil-fueled, and nuclear power systems across the entire United States, Sovacool estimated that the risks to wildlife and birds, due to conventional electricity systems, are far greater than those from wind energy. His analysis reminds us that when dealing with environmental impact assessment issues that "by definition" need to be conducted using a relative scale of reference, we need always to consider the whole picture.

So if we are evaluating the avian fatalities due to wind energy installations, we cannot forget the higher number of avian deaths that may be accounted to fossil fuels as result of climate change global effects, or the other collateral impacts causing habitat alterations or contamination of land and water. We should not expect that low-emission, low-pollution energy sources will have no environmental impacts, but we have to assess instead that their impacts will be lower than the one of the conventional sources and acceptable in the perspective of the ecological sustainability.

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Research Article

The Environmental Impact of a Wave Dragon Array Operating in the Black Sea

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The present work describes a study related to the influence on the shoreline dynamics of a wave farm consisting of Wave Dragon devices operating in the western side of the Black Sea. Based on historical data analysis of the wave climate, the most relevant environmental conditions that could occur were defined, and for these cases, simulations with SWAN spectral phase averaged wave model were performed. Two situations were considered for the most representative patterns: model simulations without any wave energy converter and simulations considering a wave farm consisting of six Wave Dragon devices. Comparisons of the wave model outputs have been carried out in both geographical and spectral spaces. The results show that although a significant influence appears near the wave farm, this gradually decreases to the coast line level. In order to evaluate the influence of the wave farm on the longshore currents, a nearshore circulation modeling system was used. In relative terms, the longshore current velocities appear to be more sensitive to the presence of the wave farm than the significant wave height. Finally, the possible impact on the marine flora and fauna specific to the target area was also considered and discussed.

1. Introduction

The higher request concerning the implementation on large scale of the renewable energy imposed by the EU directives also implies a substantial enhancement of the renewable energy extraction all over Europe.

Wave energy is abundant and is more predictable than wind or solar energy. Although the amount of energy that can be extracted using wave technologies varies depending on the location and weather conditions, wave energy can be accurately predicted using numerical models within a window of a few days. Wave energy also offers much higher energy densities, allowing devices to extract more power from a smaller volume at consequently lower costs.

Shoreline energy converters have been tested for some years, and several successful devices have been installed. Nevertheless, the most exciting developments at the present time are in extracting renewable energy in the nearshore and offshore areas.

Combined wind-wave projects, also known as hybrids, hold great potential down the line when wave technologies become more established. At that point, wave production might compensate for the intermittency of the offshore wind, while economies of scale developed from offshore wind could accelerate cost reduction for wave components. Although nowadays discussion of hybrid offshore wind-wave projects is limited more to demonstrations or pilot projects, it is expected that in the near future the synergy between wave and wind energy would be better achieved and hybrid platforms will become fully operational and economically sustainable. Despite a certain degree of uncertainty related to the variability in the wave-wind climate, improvements in the accuracy of evaluating the environmental data in the coastal areas would enhance also the accuracy of the predictions that future energy convertors yield. Some economic advantages of combining the wave and wind power productions are presented in [1, 2].

The target of the present work is a coastal area located on the western side of the Black Sea, which is not considered an environment rich in wave energy. On the other hand, due to the technological developments regarding harvesting renewable energy resources, which are expected to be very high in the near future, this area can become interesting especially in relationship with the hybrid projects combining the marine energy from waves, wind, marine currents, thermal gradients, and differences in salinity.

Until now, several evaluations of the wave conditions and of the wave energy resources in the Black Sea have been made, and among these, the most relevant are those of presented in [3–6], where the presence of various hot spots from the point of view of the wave energy has been identified. These hot spots are areas near the coast where significant differences in terms of wave conditions usually appear.

Harvesting the wave energy and transform it into electricity implies wave energy convertors (WECs) that transform in the first stage the wave energy into mechanical energy, and then this is again transformed into electricity. Several types of devices as well as an overview on the WEC evolution are given in [7]. Sea waves generate high forces at low velocities, and the hydraulic systems seem to be the most appropriate devices to absorb the energy in such conditions. The device is fixed at a location with a mooring system. Electricity is transmitted to the sea bottom through a flexible cable and afterwards to the coast by a cable line. The waves depend on the characteristics of the wind that generates them, and in general the energetic conditions are significantly higher in the wintertime than in summertime. Both power production and cost are dependent on the layout of the farm. To develop a commercial technology, the impact of arranging WECs in a farm has to be investigated as well. An optimization of such a wave energy farm operating in the North Sea is presented in [8].

On the other hand, the implementation of the energy farms is depends of a correct evaluation of their impact on the coastline dynamics, because changes might appear in relationship with the energy and the direction of the waves as they propagate from the energy farm further towards the coast. The environmental impacts of the wave energy farms are yet insufficiently studied. Although this impact should not be expected as necessarily negative, since reducing the wave energy might produce benefits in several coastal areas, evaluating the sensitivity of the nearshore wave climate to the extraction of the renewable energy still represents a very important issue, and a lot of studies are required in this direction.

In this context, the objective of the present work is to evaluate the coastal impact of a WEC array composed of six Wave Dragon devices disposed in one line that would operate on the west side of the Black Sea.

Nørgaard et al. [9, 10] showed the importance of such devices, which can be used also to reduce the wave height along the shorelines. Different stiffness of the mooring system and reflector joints have been tested for different wave steepness and relative floating ratios assessing the influence of each of these parameters on the wave transmission.

Some other studies are those of Millar et al. [11] for the Wave Hub project or by Palha et al. [12] that studied the effect of a Pelamis wave farm on the shoreline wave climate which is situated close to the Portuguese coast and also by Ponce de Leon et al. [13] that studied the influence of a wind farm in the nearshore. The impact on the coastal dynamics is dependent both on the bathymetric features and on the particularities of the environmental matrix. For this reason, extended evaluations should be carried out in each coastal environment where a new structure or the energy farm will be installed. These factors affect the medium and long-term changes induced in the shoreline wave climate and dynamics.

From this perspective, the present study might represent a step forward to the investigation of the potential impact of the implementation of large-scale wave energy arrays by providing some insight in relationship with the influence of a Wave Dragon-based farm that would operate in the coastal environment. The present target area is located in the western side of the Black Sea close to the mouths of the Danube River, and this was found to be one of the most energetic parts of the western side of the sea [14]. Moreover, the results of the present work can be easily extrapolated to many other coastal environments.

2. Theoretical Background of the Numerical Models Considered

Since a deterministic approach of the sea waves is in general not feasible, the most adequate representation of the waves is based on the spectral concept. The wave spectrum represents the Fourier transform of the autocorrelation function of the free surface elevation. The spectral wave model considered in the present study is Simulating Waves Nearshore (SWAN, [15]). This is considered the state-of-the-art phase averaged shallow water wave model and solves the wave action density balance equation which can be expressed as

$$\begin{aligned} &\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}C_{gx}N + \frac{\partial}{\partial y}C_{gy}N \\ &\quad + \frac{\partial}{\partial \sigma}C_{\sigma}N + \frac{\partial}{\partial \theta}C_{\theta}N = \frac{S}{\sigma}, \end{aligned} \tag{1}$$

where N is the wave action density and C_{gx}, C_{gy}, C_σ, and C_θ represent the propagation speeds in the geographical space (x, y), in the frequency space (σ), and in the directional space (θ), respectively. S/σ represents the source and sink terms that account in deep water for processes as wave generation by wind, whitecapping dissipation, and nonlinear wave-wave interactions (quadruplets). In shallow water, additional processes as bottom friction, depth-induced breaking, and triad wave-wave interactions are also introduced. The model can be now utilized with either Cartesian or spherical coordinates; it has a parameterization to counteract the garden sprinkler effect, which is a characteristic of large areas and also includes a phase-decoupled diffraction approximation.

Many phenomena are generated from the wave energy dissipation in the surf zone by breaking, but for a practical application, the generation of the longshore currents is the most significant, obtaining considerable strength and being a significant factor in controlling the morphology of the beaches. They can also have an impact on human activities in the coastal zone. Calculation of the current velocity is usually based on radiation stress theory (Longuet-Higgins [16]), and various 1D, 2D, and 3D numerical models have been

Table 1: Characteristics of the computational domain defined for the SWAN simulations and the physical parameterizations activated.

SWAN model	Coordinates		$\Delta x \times \Delta y$ (m)		$\Delta\theta$ (°)	Mode/scheme	n_f	n_θ	$n_{gx} \times n_{gy} = n_p$			
	Cartesian		50×50		5	stat/BSBT	34	35	$355 \times 406 = 144130$			
Input/process	wave	wind	tide	crt	gen	wcap	quad	triad	diffr	bfric	setup	br
SWAN	X	X	0	X	X	0	X	X	X	X	X	X

developed to predict these currents. A widely known general prediction system for nearshore circulation is SHORECIRC (Svendsen [17]). This is a quasi-3D model that combines a numerical solution for the depth-integrated 2D horizontal momentum balance equations with an analytical solution for the 3D current profiles. The restrictions of the model are very mild, and the basic circulation equations solved can, therefore, in general be considered very accurate. In addition, such a model catches the nonlinear feedback between wave-generated currents and the waves that generate them. Nevertheless, the model works in the time domain and is quite expensive in terms of computational resources. A simpler, but considerably faster, model is Surf, or Navy Standard Surf Model (NSSM), [18]. This is a parametric one-dimensional model that estimates the wave-induced longshore currents by solving the following equation for the longshore current:

$$\tau_y^r + \rho \frac{\partial}{\partial x}\left[\mu h \frac{\partial V}{\partial x}\right] - \left\langle \tau_y^b \right\rangle + \tau_y^w = 0. \tag{2}$$

The first term in this equation, τ_y^r, represents the longshore directed radiation stress due to the incident waves, the second term represents the horizontal mixing term due to cross-shore gradients in the longshore current velocity V, the third term, τ_y^b, is the wave-averaged bottom stress, and the last term, τ_y^w, represents the longshore wind stress. The model includes a parametric relation for cross-shore growth, and dissipation of waves due to breaking and additional relations are included for estimating percent breaking, the number of lines of breakers, and breaker type. Because NSSM is one-dimensional several assumptions are utilized. In particular, the bottom contours are considered straight and parallel, the current depth uniform, and directional wave spectra narrow banded in frequency and direction.

Evaluations in the Italian nearshore of the waves and nearshore currents were performed by Conley and Rusu [19] with SWAN and NSSM models, and their results proved that this approach can be considered reliable for a wide range of coastal applications. In order to increase the properties of the two models and for simplicity and reliability, Rusu et al. [20] joined the two models in a user friendly computational tool named as the "Interface for SWAN and Surf Models" (ISSM).

The computational domain is illustrated in Figure 5. This is a rectangle with about 17.5 km in x-direction (cross shore) and 20 km in y-direction (long shore). The main characteristics and physical processes activated are presented in Table 1. In this table, Δx and Δy represent the resolution in the geographical space, $\Delta\theta$ is the resolution in the directional space, n_f is the number of frequencies in the spectral space, n_θ is the number of directions in the spectral space, n_{gx} is the number of the grid points in x-direction, n_{gy} is the number of grid points in y-direction, and n_p is the total number of grid points.

Some details will be given next in relationship with the implementation of the modeling conditions in the target area. The input fields considered are also indicated in Table 1 as follows: *wave* represents the wave forcing, *tide* is the tide forcing, *wind* represents the wind forcing, and *crt* is the current field. The physical processes activated are coded as follows: *gen* is the generation by wind, *wcap* indicates the whitecapping process, *quad* represents the quadruplet nonlinear interactions, *triad* indicates the activation of the triad nonlinear interactions, *diff* is the diffraction process (phase decoupled), *bfric* represents the bottom friction, *setup* is the wave-induced setup, and *br* indicates the activation of the depth-induced wave breaking.

3. Main Particularities of the WEC and of the Wave Conditions in the Target Area

The WEC considered in the present work is the Wave Dragon (Kofoed [21]). The basic idea of this wave energy converter device is to use well-known and well-proven principles of traditional hydropower plants in an offshore floating platform of the overtopping type.

The device elevates waves to a reservoir where water is passed through a number of turbines and in this way transformed into electricity. This is a typical terminator type WEC, for which the conservative approach is to assume that the devices will absorb all suitable wave energy across the full width of the reservoir.

The Wave Dragon (Figure 4) consists of two wave reflectors that direct the waves towards a curved ramp which overtops in a water reservoir and, therefore, has an increased potential energy compared to the surrounding sea. Thus, the Wave Dragon directly utilizes the energy of the water's motion.

To reduce rolling and keep the platform stable, the Wave Dragon must be large and heavy, having only one kind of *moving parts*: the turbines. This makes it to be a durable and resistant structure. This is essential for any device bound for operations offshore, where extreme conditions and fouling seriously affect any moving parts. If the waves do not interact with the ramp, they are reflected under its structure or diffracted away. Also, to improve the device performances, two reflectors are placed and hinged to the platform, which reflect the waves towards the ramp. The experiments showed that the ramp must be short to reduce the loss of energy, and due, the elliptical form to the overtopping increases significantly.

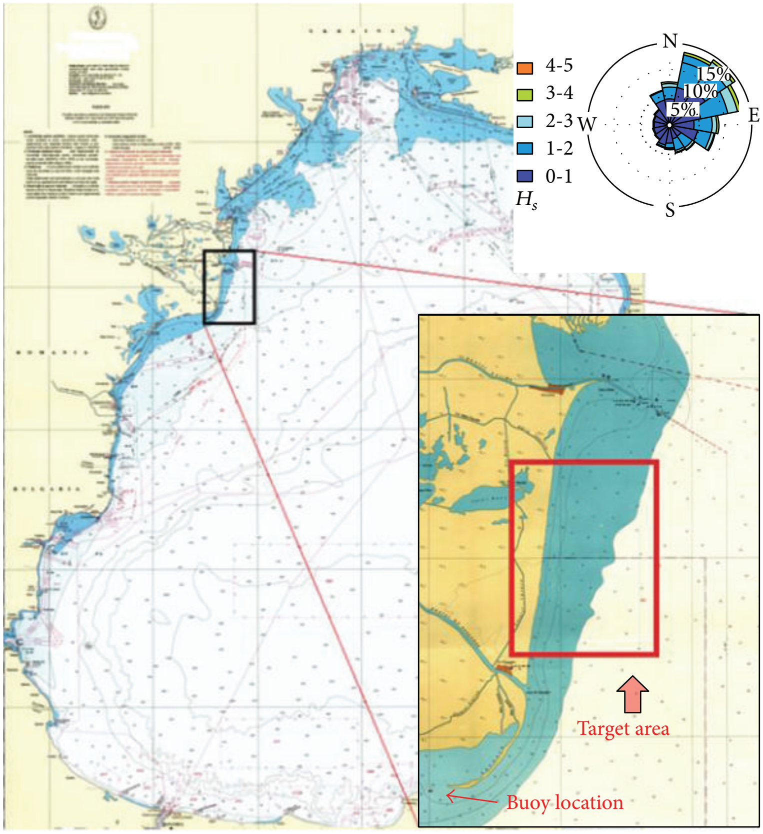


FIGURE 1: Location of the target area and the wave conditions resulting from an analysis of 5 years of data (2006–2011).

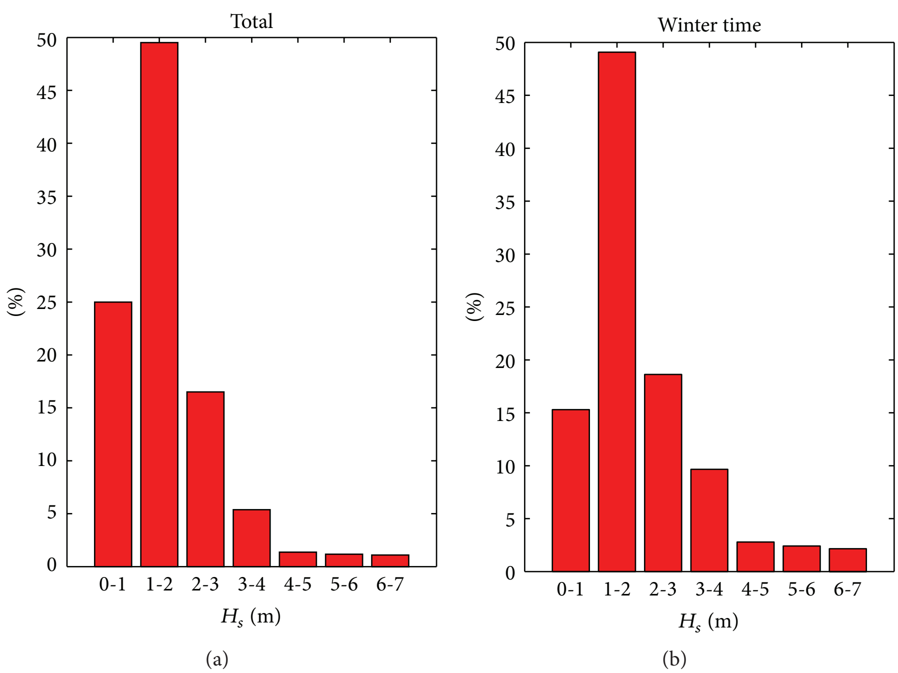


FIGURE 2: Analysis of the wave data measured at buoy close to the target area in the period 2006–2011: (a) Classes of significant wave height (H_s) for the total time interval; (b) H_s classes for wintertime.

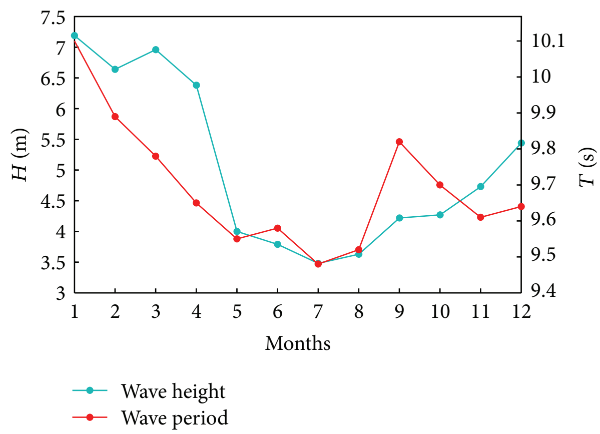


Figure 3: Analysis of the wave data measured at a buoy close to the target area in the period 2006–2011: H (m) monthly maximum wave height; T (s) monthly maximum wave period.

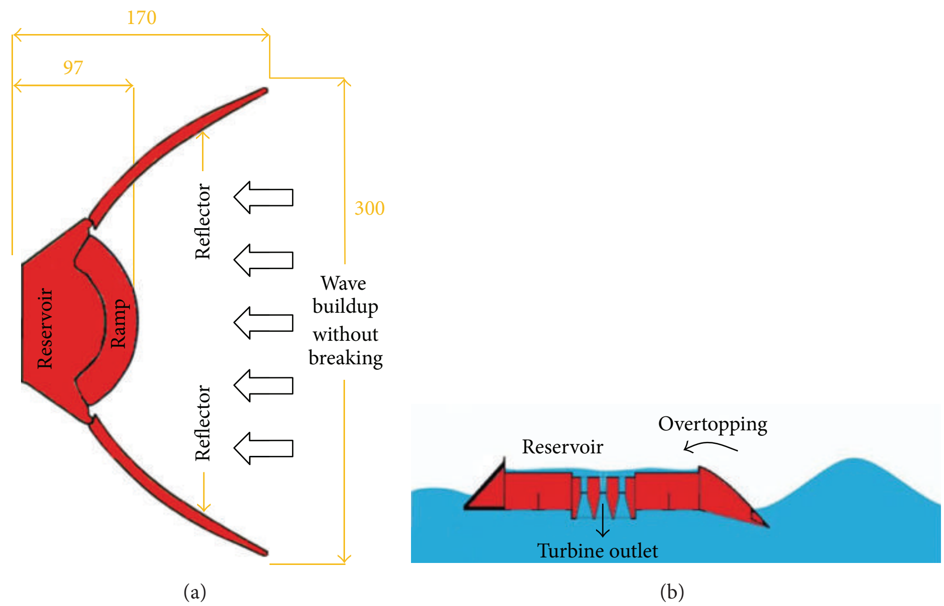


Figure 4: (a) Main structural elements of a Wave Dragon WEC in plain view—dimensions in meters; (b) cross-sectional view of the reservoir part of the Wave Dragon.

Some remarks on the wave energy potential of the Black Sea near the Romanian coasts together with a possible power take off system that can be placed here are given in [22]. Onea [23] made an estimation of the expected power provided by some wave energy devices operating in the western side of the Black Sea. This was based on the analysis of the wave data registered at the Gloria drilling unit for a five-year period (2001–2005). Considering the above data, diagrams for the bivariate distributions of the sea states occurrences, defined by the significant wave height and the energy period, were designed for both winter and total time. On this basis, the efficiency of different technologies for the extraction of the wave energy, including the Wave Dragon, was assessed. The above results showed that a Wave Dragon device would produce close to the target area about 600 kW electric power in winter time and about 400 kW for total time, respectively.

The device has a very complex design because there must be a perfect relationship between ramp, wave reflectors, wave height, the floating height of the device, and the amount of water overtopped and stored in the reservoir (Figure 4(b)). The components are all well-established technologies, and the Wave Dragon is a particular application combining these to produce electricity from the waves.

The target area considered in the present study is found to be among the most energetic sites from the western side of the Black Sea and is located at the south of Sulina channel, which

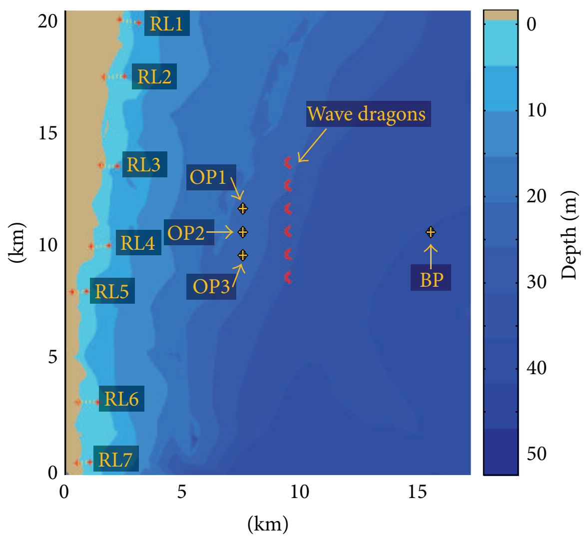


Figure 5: The computational domain considered for the simulations with numerical models. In the background the bathymetry is represented while in the foreground the Wave Dragon, the reference points, and the reference lines. BP indicates the boundary point, OP are the offshore points, and RL represent the reference lines considered in the analysis of the nearshore currents. Each offshore extremity point of the above reference lines is denoted as NP (nearshore point).

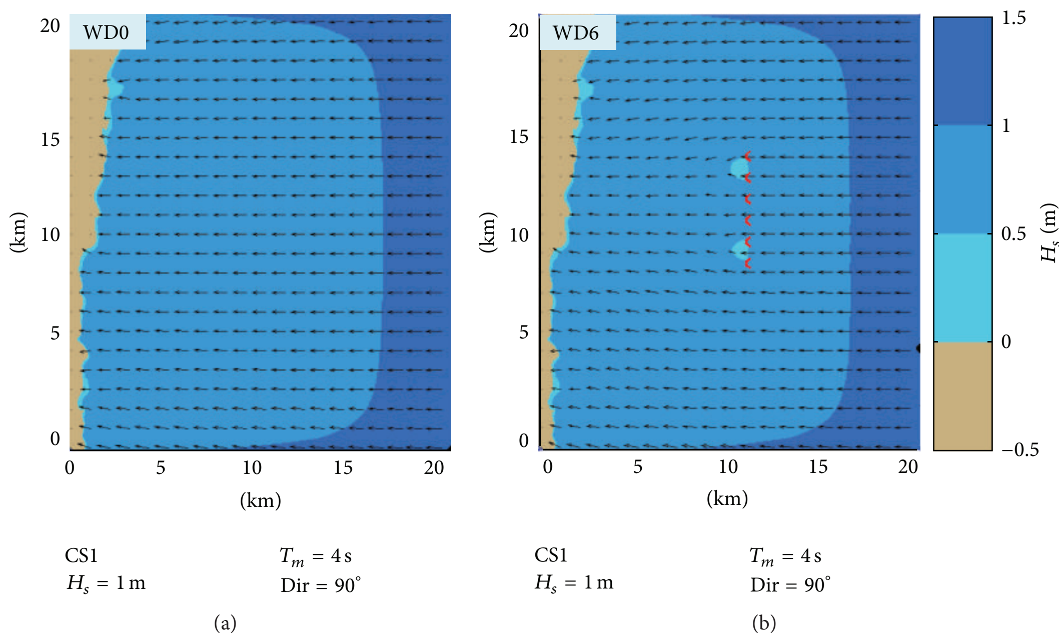


Figure 6: Evaluation in the geographical space of the impact on the wave field of a wave farm based on Wave Dragon WECs that operate in the target area. CS1—average to high energetic conditions and waves coming from east (90° in nautical convention). (a) SWAN simulation in the case without Wave Dragons (WD0). (b) SWAN simulation in the case when six Wave Dragons operate in line (WD6). The H_s scalar fields are presented in the background while in the foreground the wave vectors are indicated.

is also a very important navigation sector since it represents the main gate in the seventh Trans-European transportation corridor (Figure 1). It has to be highlighted also that in this region the wave fields are characterized by significant variations during the year.

The Romanian Black Sea littoral evolution of the sea-land interface, for a period of several decades, had registered some significant variation. Mateescu et al. [24] presented a study of the beach short-term response under the action of the marine factors in the actual geomorphologic conditions. The previously stated results indicate a significant coastal response process to the climate changes/sea level rise trend, with an obvious influence on the future development of the natural environment, as well as on the socioeconomic activities in coastal space. A study to determine various geomorphic types of landforms in order to create a web geomorphic classification development for the Black Sea coast has been made by Stanica et al. [25].

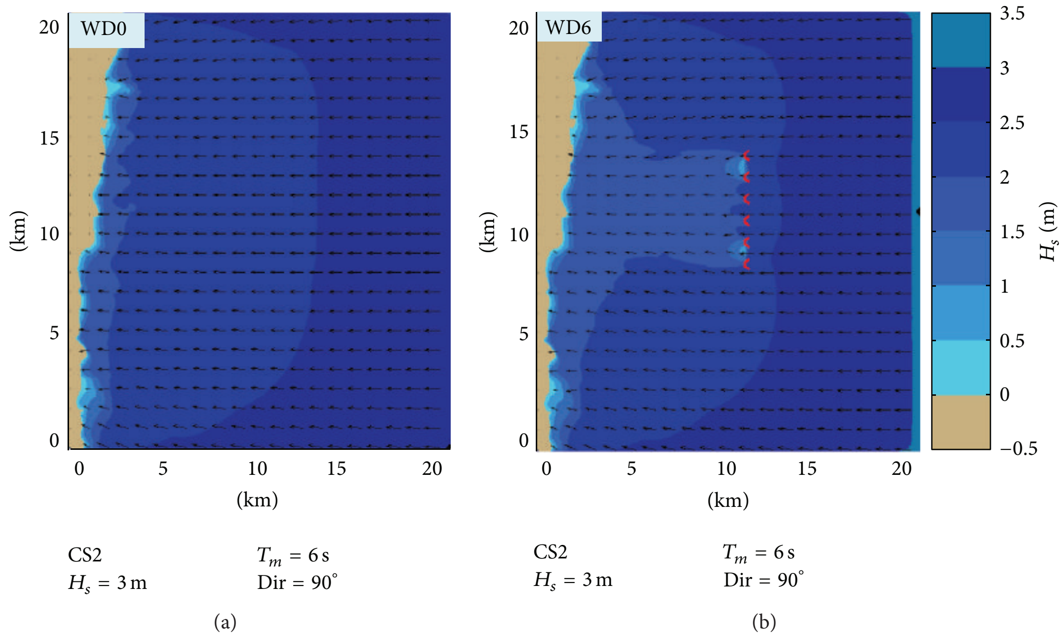


FIGURE 7: Evaluation in the geographical space of the impact on the wave field of a wave farm based on Wave Dragon WECs that operate in the target area. CS2—high energetic conditions and waves coming from east (90° in nautical convention). (a) SWAN simulation in the case WD0. (b) SWAN simulation for the case WD6. The H_s scalar fields are presented in the background while in the foreground the wave vectors are indicated.

The wave data analysis presented in this section considers data measured at a buoy which operated in the western sector of the Black Sea close to the target area (Figure 1). The measurements were made daily in the five-year time interval 2006 and 2011. The results were structured for total and winter time, respectively. In this work, winter time represents the time interval between October and March. Figure 1 shows together with the target area the directional distributions of the H_s classes as reflected by the buoy measurements. It can be observed that the lowest wave heights correspond to the western direction because of the presence of the coast in that side while the dominant wave direction is from the northeastern side. It can be also seen that from the same direction higher waves are usually coming in comparison with other directions. In Figure 2, the H_s classes are presented in percents in terms of the number of occurrences, illustrating in parallel the results for total time (a) and wintertime (b), respectively. The monthly maximum values of the significant wave heights and mean wave periods are shown in Figure 3.

The results show that the highest probability of occurring waves with significant heights, greater than 7 m is in the time interval between December and January. This possibility begins in September and lasts until the end of March. The same evolution can be seen for the significant wave heights in the classes 4-5 m, 5-6 m, and 6-7 m. Waves with significant wave heights in the range 1-2 m are present in a considerable proportion all over the year, with a minimum in March and a maximum in July. For the waves smaller than 1 m, the frequency of occurrence in summertime is almost double than in wintertime. The highest value of the significant wave is 7.08 m and corresponds to waves coming from the northeastern direction. As regards the wave periods, there are not so relevant differences between winter and total time.

4. The Expected Impact of the Wave Dragon Farm on the Marine Vegetation and Fauna That Characterize the Target Area

An important issue concerning the deployment and exploitation of the future energy farms relates to a correct assessment of their environmental impact, in general, and of their impact on the aquatic flora and fauna, in special.

It is thus very important to have a comprehensive picture of all the physical and biological characteristics of the area targeted in order to be able to assess correctly the consequences of the wave energy extraction. From this perspective, [26] studied the main physical-chemical characteristics correlated with the biological specificity of different species of multicellular algae along the Romanian Black Sea coast while [27] presented the evaluation of the conformity level for the marine environment of the Romanian marine areas designated for the main molluscs growth and exploitation.

The soils in the Black Sea basin are varied, and their distribution reflects the connection with the principal genetic factors (lithology, relief, climate, vegetation, and fauna) and the influence of the human activities by modifying the local conditions. From the same perspective, Stanica et al. [28] revealed the aspects that affected the natural processes of the Black Sea coast near the Sulina mouth by the human activities leading to erosion of the coast.

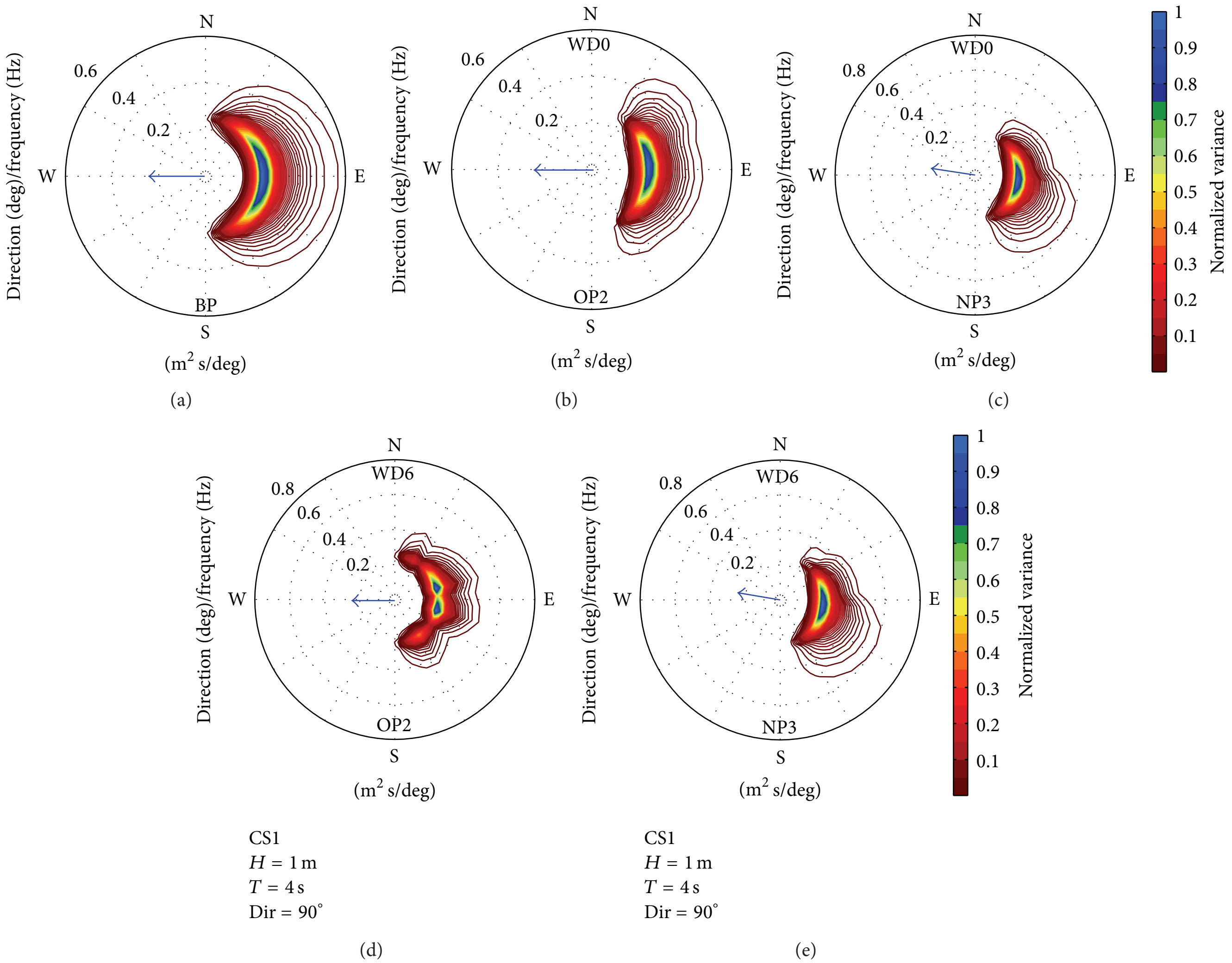


Figure 8: Evaluation in the spectral space of the impact on the wave field of a wave farm based on Wave Dragon WECs that operate in the target area for CS1. (a) BP for WD0. (b) OP2 for WD0. (c) NP3 for WD0. (d) OP2 for WD6. (e) NP3 for WD6.

Previous studies have found a higher proportion of plant species along the coastal area of the Black Sea. Anastasiu et al. [29] assessed the role of the harbours as gateways and reservoirs for alien plant species, the structure and invasion pattern of the alien plants, and test methods useful for effective monitoring programs; on the other hand Sava et al. [30] showed the influence of the nutrients on the macrophytic red algae of the Romanian Black Sea coast.

An overview of the turbot *Psetta maeotica* species that populate the Romanian Black Sea and the importance of the regional fishing potential under the aspect of market demand, both on the national and international level, is made in [31], while in [32] a study of the distributional patterns of the zoobenthos from the artificial hard substratum is presented.

Thus, in the global environmental context, it is assumed that the presence of a Wave Dragon farm would have a positive impact as an alternative to the use of polluting fossil fuels for generating electricity. These devices are a clean power generation technology with many environmental advantages: they have a very low visibility (Wave Dragon can be compared to a moored ship and will have a maximum height above mean sea level of 7 meters), the underwater noise generation is very low (so it cannot produce harm to the marine fauna due to noise), they have a modest "footprint" on the seabed from anchor block and the power cable duct, and there is no risk of spill (they use water hydraulics, and no toxic antifouling is used).

From this perspective, the impact of a single WEC on the marine environment is expected to be small, but the presence of a large number of converters in the same area working in an almost continuous way may cause eventually some environmental impact. Of course, this impact can be significantly attenuated: subsea cables and onshore cables impact can be avoided by identifying the important habitats for fisheries, benthos, and so forth and avoiding laying cables in these areas. Locations have to be chosen with respect to commercial and recreational fisheries, but we can notice positive effects on fish resources (this area will create a fishery exclusion zone, and the artificial reef effect will attract fish).

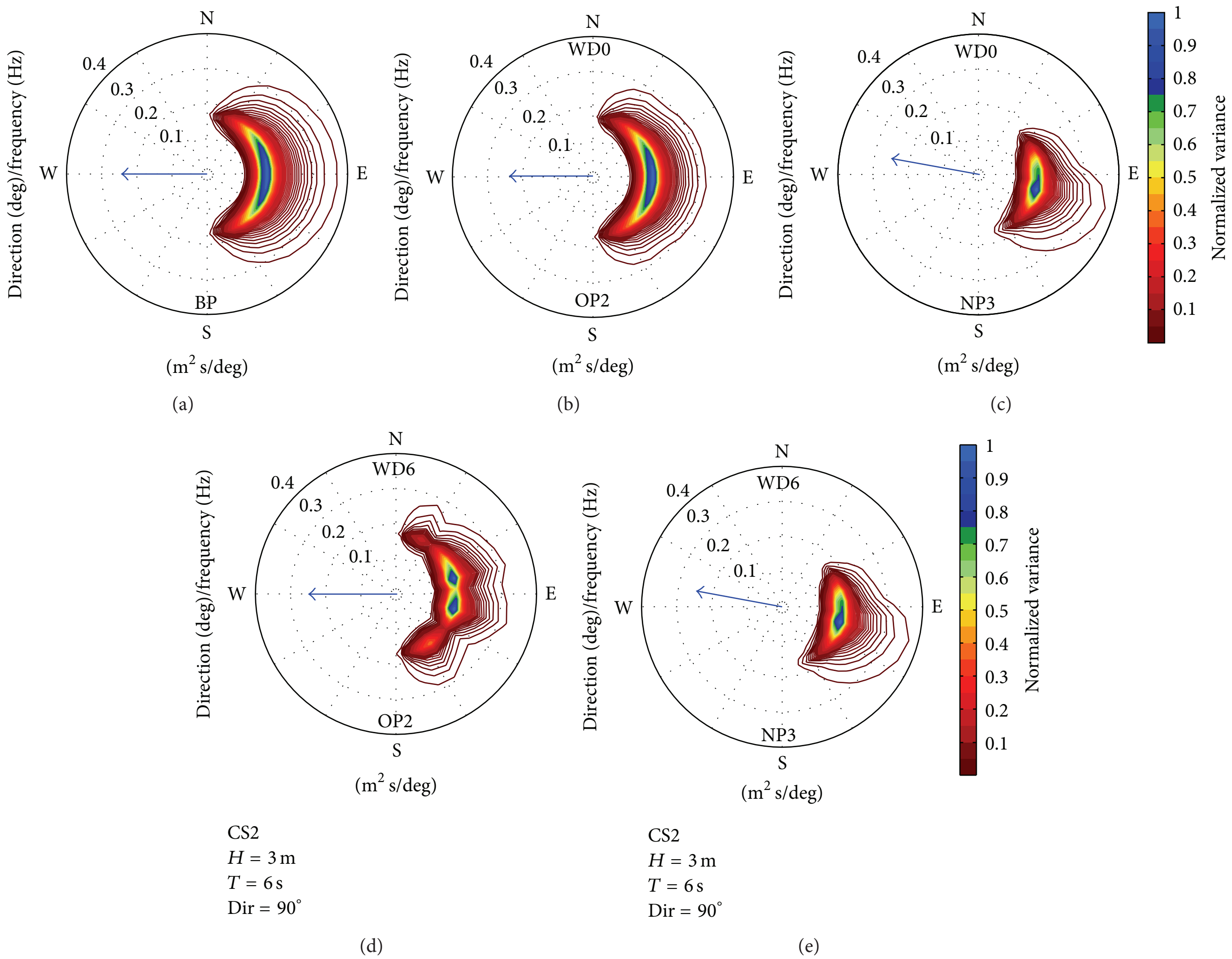


Figure 9: Evaluation in the spectral space of the impact on the wave field of a wave farm based on Wave Dragon WECs that operate in the target area for CS2. (a) BP for WD0. (b) OP2 for WD0. (c) NP3 for WD0. (d) OP2 for WD6. (e) NP3 for WD6.

Nevertheless, limited studies have been done regarding the wave energy farms impact and changes that these devices can make on the waves and current field. Wave Dragon farms will extract energy from waves and do some extended changes of the hydrodynamics behind the farm. Wave heights are expected to decrease behind a Wave Dragon farm. Changes in the hydrophysical regime due to the extraction of energy from the waves may cause an impact on coastal processes as erosion and sediment transport and a reduced recreational value, regarding surfing due to smaller waves. Therefore, the waves and current estimations are important aspects that must to be taken into account, and these aspects will be evaluated and discussed in the next section.

5. Model System Simulations and Discussion of the Results

As in the case of the attenuator type devices, the efficiency of the terminator devices is directionally dependent; that is, they must follow the direction of the wave propagation. Simulations with the SWAN model have been performed in various cases that reflect better the most relevant wave patterns in the target area.

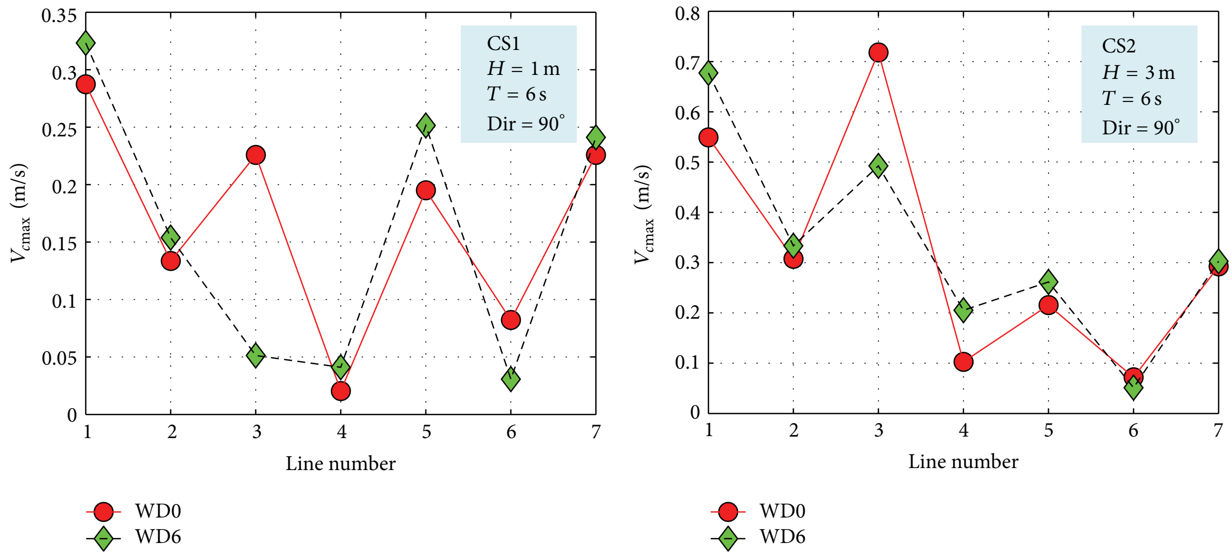
For accounting in the wave model of the Wave Dragon array geometry, the command obstacle that is available in SWAN was considered. The obstacle is subgrid in the sense that it is narrow compared to the spatial meshes, but its length should be at least one-mesh long. The location of the obstacle is defined by a sequence of corner points of a line. The obstacles interrupt the propagation of the waves from one grid point to the next. Such an obstacle will affect the wave field in three ways: it will reduce the wave height of waves propagating through or over the obstacle all along its length, it will cause waves to be reflected, and it will cause diffraction around its end. Therefore, the model can reasonably account for waves around an obstacle if the directional spectrum of incoming waves is not too narrow. There are several mechanisms for transmission of waves. In SWAN, this can be computed as transmission of waves

Table 2: CS1 ($H_s = 1$ m, $T_m = 4$ s, Dir = 90°), evaluation of the impact of the energy farms on the waves in the reference points OP1 (northern offshore point), OP2 (central offshore point), OP3 (southern offshore point), and in the point NP1–NP7. WD0: no energy converter, WD6: four Wave Dragon energy converters operating in line.

	WD	H_s (m)	E_{max} (m^2/Hz/deg)	Dir (deg)	DSPR (deg)	T_m/T_p (s)	Wlen (m)	P_x (m^3/s)	P_y (m^3/s)	F_x (N/m^2)	F_y (N/m^2)
BP	0	0.9	0.40	90.0	32.48	3.5/4	18.5	−0.13	0.00	−0.01	−0.00
	6	0.9	0.40	90.0	33.18	3.5/4	18.5	−0.13	−0.00	−0.01	−0.00
OP1	0	0.8	0.35	89.6	33.25	3.7/4	20.7	−0.10	−0.00	−0.00	−0.00
	6	0.7	0.32	91.4	33.57	3.7/4	20.4	−0.07	0.00	−0.00	0.00
OP2	0	0.8	0.31	90.0	33.23	3.7/4	20.7	−0.10	0.00	−0.00	−0.00
	6	0.7	0.31	89.3	33.81	3.7/4	20.5	−0.07	−0.00	−0.00	−0.00
OP3	0	0.8	0.35	90.4	33.23	3.7/4	20.7	−0.10	0.00	−0.00	−0.00
	6	0.6	0.30	93.1	38.28	3.7/4	20.6	−0.06	0.00	−0.00	0.00
NP1	0	0.8	0.34	80.4	30.00	3.5/4	17.1	−0.11	−0.02	0.13	0.03
	6	0.8	0.50	78.6	29.04	3.5/4	16.9	−0.11	−0.02	0.13	0.03
NP2	0	0.7	0.31	89.3	25.78	3.6/4	17.9	−0.09	−0.00	0.16	0.04
	6	0.6	0.32	86.2	26.05	3.6/4	17.6	−0.08	−0.00	0.14	0.03
NP3	0	0.7	0.34	98.8	25.54	3.5/4	15.1	−0.10	0.01	0.07	0.23
	6	0.7	0.34	99.8	24.95	3.5/4	15.0	−0.09	0.01	0.07	0.22
NP4	0	0.7	0.33	89.8	25.90	3.6/4	17.1	−0.09	−0.00	0.22	0.04
	6	0.6	0.28	90.3	27.85	3.6/4	16.8	−0.08	0.00	0.19	0.03
NP5	0	0.7	0.29	95.3	25.44	3.6/4	17.8	−0.08	0.01	0.14	−0.01
	6	0.6	0.29	98.3	26.13	3.6/4	17.5	−0.07	0.01	0.13	−0.00
NP6	0	0.7	0.29	85.4	25.90	3.6/4	17.3	−0.08	−0.01	−0.01	0.01
	6	0.6	0.29	87.3	25.60	3.6/4	17.1	−0.08	−0.01	−0.01	0.01
NP7	0	0.7	0.34	98.8	25.54	3.5/4	15.1	−0.10	0.01	0.07	0.23
	6	0.7	0.34	99.8	24.95	3.4/4	15.0	−0.09	0.01	0.07	0.22

Table 3: CS2 ($H_s = 3$ m, $T_m = 6$ s, and Dir = 90°), evaluation of the impact of the energy farms on the waves in the reference points OP1, OP2, OP3, and NP1–NP7.

	WD	H_s (m)	E_{max} (m^2/Hz/deg)	Dir (deg)	DSPR (deg)	T_m/T_p (s)	Wlen (m)	P_x (m^3/s)	P_y (m^3/s)	F_x (N/m^2)	F_y (N/m^2)
BP	0	2.7	5.27	90.0	32.28	5.4/6	42.7	−1.74	0.00	−0.10	−0.00
	6	2.7	5.27	90.0	32.94	5.4/6	42.7	−1.73	0.00	−0.10	−0.00
OP1	0	2.3	4.31	90.5	32.44	5.6/6	46.2	−1.38	0.02	0.04	−0.01
	6	1.9	3.81	92.2	32.67	5.5/6	45.6	−0.88	0.04	0.04	0.01
OP2	0	2.4	4.31	91.0	32.39	5.6/6	46.4	−1.38	0.03	0.03	−0.01
	6	1.9	3.70	90.3	33.00	5.5/6	45.8	−0.87	0.01	0.03	−0.00
OP3	0	2.4	4.32	91.5	32.43	5.6/6	46.5	−1.38	0.04	0.02	−0.03
	6	1.8	3.64	94.3	37.56	5.6/6	46.1	−0.74	0.06	0.04	−0.02
NP1	0	2.2	4.92	78.9	26.10	5.5/6	33.6	−1.31	−0.25	−0.77	−0.60
	6	2.2	5.02	77.2	25.23	5.5/6	33.4	−1.29	−0.29	−0.64	−0.55
NP2	0	1.8	4.55	89.2	19.58	5.6/6	33.1	−0.96	−0.01	0.06	0.23
	6	1.7	4.60	86.5	19.64	5.6/6	32.9	−0.85	−0.05	0.50	0.30
NP3	0	1.5	3.08	100.1	20.07	5.4/6	28.4	−0.56	0.10	−1.48	0.45
	6	1.5	3.10	100.4	19.81	5.4/6	28.4	−0.56	0.10	−1.47	0.46
NP4	0	1.6	3.90	93.9	18.68	5.6/6	29.4	−0.69	0.04	−3.26	−0.05
	6	1.5	3.15	93.8	20.22	5.6/6	29.2	−0.64	0.04	−2.54	−0.08
NP5	0	1.7	3.46	95.0	19.98	5.6/6	31.6	−0.79	0.06	−0.24	−0.14
	6	1.6	3.51	96.9	20.23	5.5/6	31.4	−0.72	0.08	0.18	0.00
NP6	0	1.7	3.63	83.6	18.51	5.6/6	31.8	−0.79	−0.10	−0.98	−0.31
	6	1.6	3.74	84.5	18.20	5.6/6	31.7	−0.78	−0.08	−0.89	−0.25
NP7	0	1.5	3.08	100.1	20.07	5.4/6	28.4	−0.56	0.10	−1.48	0.45
	6	1.5	3.10	100.4	19.81	5.4/6	28.4	−0.56	0.10	−1.47	0.46



(a) (b)

FIGURE 10: Evaluation of the impact of the energy farms on the maximum velocities of the nearshore currents along the reference lines considered. (a) CS1, (b) CS2.

TABLE 4: Evaluation of the impact of the energy farms on the waves in the reference points OP1, OP2, and OP3 for the wave conditions (a) $H_s = 1$ m, $T_m = 4$ s, and Dir = 30° and (b) $H_s = 1$ m, $T_m = 4$ s, and Dir = 150°.

	N	H_s (m)	E_{max} (m^2/Hz/deg)	Dir (deg)	DSPR (deg)	T_m/T_p (s)	Wlen (m)	P_x (m^3/s)	P_y (m^3/s)	F_x (N/m^2)	F_y (N/m^2)
(a) Direction: 30°											
BP	0	0.8	0.39	34.1	32.76	3.6/4	19.1	−0.06	−0.10	−0.00	−0.01
	6	0.8	0.40	33.9	33.10	3.6/4	19.1	−0.06	−0.10	−0.00	−0.01
OP1	0	0.8	0.35	32.2	31.52	3.7/4	20.4	−0.05	−0.09	−0.00	−0.00
	6	0.7	0.36	24.1	31.75	3.6/4	20.1	−0.03	−0.07	−0.00	−0.00
OP2	0	0.8	0.35	33.1	31.29	3.7/4	20.5	−0.05	−0.08	−0.00	−0.00
	6	0.7	0.35	27.2	32.50	3.6/4	20.2	−0.03	−0.07	−0.00	−0.00
OP3	0	0.8	0.34	34.2	30.93	3.7/4	20.6	−0.05	−0.08	−0.00	−0.00
	6	0.7	0.34	26.4	30.07	3.6/4	20.3	−0.03	−0.06	−0.00	−0.00
(b) Direction: 150°											
OP1	0	0.8	0.34	146.3	31.50	3.7/4	20.7	−0.05	0.08	−0.00	0.00
	6	0.7	0.33	152.2	32.59	3.7/4	20.4	−0.03	0.07	−0.00	0.00
OP2	0	0.8	0.34	147.1	31.70	3.7/4	20.6	−0.05	0.08	−0.00	0.00
	6	0.7	0.35	155.3	31.63	3.7/4	20.5	−0.03	0.07	0.00	0.00
OP3	0	0.8	0.35	147.9	31.95	3.7/4	20.5	−0.05	0.09	−0.00	0.00
	6	0.7	0.35	157.1	27.94	3.7/4	20.5	−0.03	0.08	−0.00	0.00

passing over a dam with a closed surface or as a constant transmission coefficient which was the choice in the present work. Together with the command obstacle, either specular reflection, when the angle of reflection equals the angle of incidence, or diffuse reflection, where incident waves are scattered over reflected direction, may be considered. In this way, the effect on the waves in front of the wave arrays might be also accounted for. To accommodate diffraction in SWAN simulations, a phase-decoupled refraction-diffraction approximation is implemented. It is expressed in terms of the directional turning rate of the individual wave components in the 2D wave spectrum. The approximation is based on the mild-slope equation for refraction and diffraction, omitting phase information. Therefore, this does not permit coherent wave fields in the computational domain. According to the technical data of the Wave Dragon device the transmission coefficient was set to 0.68 and the diffuse reflection coefficient to 0.2 (according to Harrington [33]).

5.1. Evaluations in the Geographical and in the Spectral Spaces. An in depth analysis of the wave conditions was performed. These correspond to two different situations that were considered in the present study, WD0 (without any

Table 5: Evaluation of the impact of the energy farms on the waves in the reference points OP1, OP2, and OP3 for the wave conditions (a) $H_s = 3$ m, $T_m = 6$ s, and Dir = 30° and (b) $H_s = 3$ m, $T_m = 6$ s, and Dir = 150°.

	N	H_s (m)	E_{max} (m^2/Hz/deg)	Dir (deg)	DSPR (deg)	T_m/T_p (s)	Wlen (m)	P_x (m^3/s)	P_y (m^3/s)	F_x (N/m^2)	F_y (N/m^2)
(a) Direction: 30°											
BP	0	2.6	5.12	35.0	32.51	5.4/5.8	43.8	−0.90	−1.30	−0.04	−0.05
	6	2.6	5.12	34.9	32.84	5.4/5.8	43.9	−0.90	−1.30	−0.04	−0.05
OP1	0	2.3	4.24	34.8	30.62	5.5/5.8	45.9	−0.70	−1.10	0.04	−0.04
	6	2.0	4.31	27.0	31.07	5.5/5.8	45.1	−0.40	−0.90	0.05	−0.02
OP2	0	2.2	4.17	36.0	30.24	5.5/5.8	46.0	−0.70	−1.00	0.03	−0.03
	6	1.9	4.12	30.6	31.61	5.5/5.8	45.2	−0.50	−0.80	0.04	−0.01
OP3	0	2.2	4.11	37.2	29.97	5.5/5.8	46.2	−0.70	−1.00	0.03	−0.05
	6	1.9	4.02	29.8	29.15	5.5/5.8	45.4	−0.40	−0.80	0.03	−0.03
(b) Direction: 150°											
OP1	0	2.2	4.01	143.4	30.12	5.5/5.8	46.1	−0.70	1.00	0.04	0.01
	6	1.9	3.95	148.8	31.38	5.4/5.8	45.5	−0.50	0.80	0.04	0.01
OP2	0	2.2	4.10	144.4	30.49	5.5/5.8	46.1	−0.70	1.00	0.03	0.02
	6	2.0	4.14	152.3	30.67	5.4/5.8	45.6	−0.40	0.80	0.05	0.01
OP3	0	2.3	4.21	145.7	30.79	5.5/5.8	46.0	−0.70	1.10	0.03	0.01
	6	2.0	4.23	154.9	26.79	5.4/5.8	45.9	−0.40	1.00	0.04	0.01

Table 6: Evaluation of the impact of the energy farms on the waves in the reference points OP1, OP2, and OP3 for the wave conditions (a) $H_s = 5$ m, $T_m = 8$ s, and Dir = 30°, (b) $H_s = 5$ m, $T_m = 8$ s, and Dir = 90°, and (c) $H_s = 5$ m, $T_m = 8$ s, and Dir = 150°.

	N	H_s (m)	E_{max} (m^2/Hz/deg)	Dir (deg)	DSPR (deg)	T_m/T_p (s)	Wlen (m)	P_x (m^3/s)	P_y (m^3/s)	F_x (N/m^2)	F_y (N/m^2)
(a) Direction: 30°											
BP	0	4.5	18.51	34.6	32.15	7.1/8.2	72.9	−3.70	−5.50	−0.08	−0.17
	6	4.5	18.51	34.4	32.52	7.1/8.2	73.0	−3.70	−5.50	−0.08	−0.17
OP1	0	3.9	15.12	39.9	29.34	7.2/8.2	73.2	−3.70	−4.30	0.43	−0.24
	6	3.3	13.65	32.3	30.60	7.2/8.2	72.0	−2.20	−3.40	0.43	−0.10
OP2	0	3.8	15.07	41.0	28.81	7.2/8.2	73.1	−3.60	−4.00	0.36	−0.16
	6	3.3	12.46	36.2	30.66	7.2/8.2	72.1	−2.30	−3.10	0.32	−0.07
OP3	0	3.8	14.97	42.5	28.63	7.2/8.2	73.4	−3.60	−3.80	0.30	−0.27
	6	3.1	11.93	35.5	28.12	7.2/8.2	72.3	−2.10	−2.90	0.25	−0.28
(b) Direction: 90°											
OP1	0	3.9	16.90	92.7	30.22	7.2/8.2	73	−5.80	0.30	0.40	−0.06
	6	3.1	14.48	94.1	29.96	7.2/8.2	72.3	−3.70	0.20	0.20	0.14
OP2	0	4	16.68	93.1	30.14	7.2/8.2	73.5	−5.90	0.30	0.30	−0.03
	6	3.2	14.02	91.8	30.66	7.2/8.2	72.8	−3.70	0.10	0.20	0.02
OP3	0	4	16.40	93.6	30.30	7.2/8.2	74.1	−5.90	0.40	0.30	−0.10
	6	3.0	13.42	96.1	35.52	7.2/8.2	73.3	−3.10	0.30	0.30	−0.10
(c) Direction: 150°											
OP1	0	3.8	15.29	139.9	27.89	7.2/8.2	72.9	−3.50	4.10	0.39	0.06
	6	3.3	13.96	144.5	29.51	7.2/8.2	71.7	−2.30	3.20	0.37	0.08
OP2	0	3.8	15.57	140.9	28.56	7.2/8.2	73.1	−3.50	4.30	0.36	0.05
	6	3.3	15.61	148.3	29.19	7.2/8.2	72.1	−2.20	3.50	0.40	0.08
OP3	0	3.9	15.87	142.5	28.78	7.2/8.2	73.3	−3.50	4.50	0.34	−0.10
	6	3.5	15.90	151.3	25.04	7.2/8.2	72.9	−2.30	4.10	0.42	0.10

device operating in the target area) and WD6 (with six Wave Dragon devices operating in line in the target area).

In Figure 5, some reference points are illustrated; the first reference point is denoted as BP and indicates the boundary point, and three other reference points are defined at 1.8 km down wave from the WD farm, and they have been denoted as offshore points (OP). Moreover, in order to assess the coastal impact of the wave farm by evaluating the wave-induced nearshore currents, seven reference lines (RL) were positioned along the entire coast and they are denoted as

Table 7: Evaluation of the impact of the energy farms on the nearshore currents in terms of maximum current velocities along the reference lines RL1–RL7 for $H_s = 1$ m, $H_s = 3$ m, $H_s = 5$ m, and three different wave directions (30°, 90°, 150°). The two configurations (WD0 and WD6) were considered in parallel.

Case study	Line config.	L1	L2	L3	L4	L5	L6	L7
H1D30	WD0	0.93	0.29	0.74	0.33	0.50	0.31	0.49
	WD6	1.16	0.40	0.75	0.33	0.53	0.30	0.48
H1D90	WD0	0.29	0.13	0.23	0.02	0.19	0.08	0.23
	WD6	0.32	0.15	0.05	0.04	0.25	0.03	0.24
H1D150	WD0	0.76	0.25	0.99	0.39	0.74	0.30	0.89
	WD6	0.73	0.24	0.97	0.38	0.74	0.30	0.89
H3D30	WD0	1.63	0.75	1.20	0.58	0.62	0.69	0.49
	WD6	1.63	0.75	1.28	0.63	0.64	1.66	0.48
H3D90	WD0	0.55	0.31	0.72	0.10	0.22	0.07	0.29
	WD6	0.68	0.33	0.49	0.21	0.26	0.05	0.30
H3D150	WD0	1.04	0.28	1.92	0.74	0.91	0.71	0.94
	WD6	1.01	0.26	1.89	0.76	0.93	0.36	0.94
H5D30	WD0	1.55	0.70	0.73	0.82	0.50	0.68	0.41
	WD6	1.55	0.70	1.04	0.86	0.52	0.67	0.40
H5D90	WD0	0.34	0.09	1.33	0.50	0.38	0.26	0.43
	WD6	0.41	0.15	1.25	0.53	0.40	0.26	0.43
H5D150	WD0	0.85	0.26	1.98	1.02	0.77	0.32	1.04
	WD6	0.82	0.24	2.04	1.14	0.77	0.32	1.04

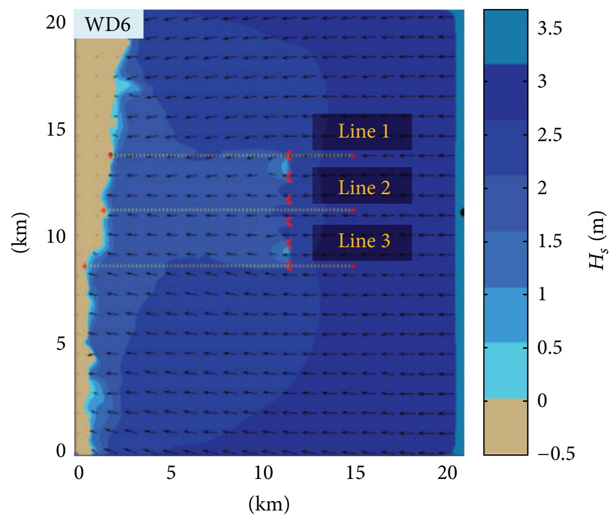


Figure 11: Evaluation of the impact of the energy farms on the maximum velocities of the nearshore currents along the reference lines considered. (a) CS1, (b) CS2.

RL1 to RL7. The extremities of each reference line from the offshore side denoted as nearshore points (NP), and these points were taken into consideration for analyzing in both geographical and spectral spaces the nearshore waves.

In Figures 6 and 7, the impact in the geographical space on the wave field of a wave farm based on Wave Dragon devices for two different case studies is presented: CS1 (H_s = 1 m, T_m = 3 s, and Dir = 90°) and CS2 (H_s = 3 m, T_m = 6 s, and Dir = 90°).

These cases were chosen because it has been observed that they present the highest differences between the two situations: with and without the energy farm. Thus, at the same time the two situations which were considered are presented in the figure, without any device deployed in the target area (WD0) and when six Wave Dragon devices operate in line (WD6), respectively.

CS1 corresponds to average wave conditions and Figures 6 and 7 show that in this case the impact is only locally visible,

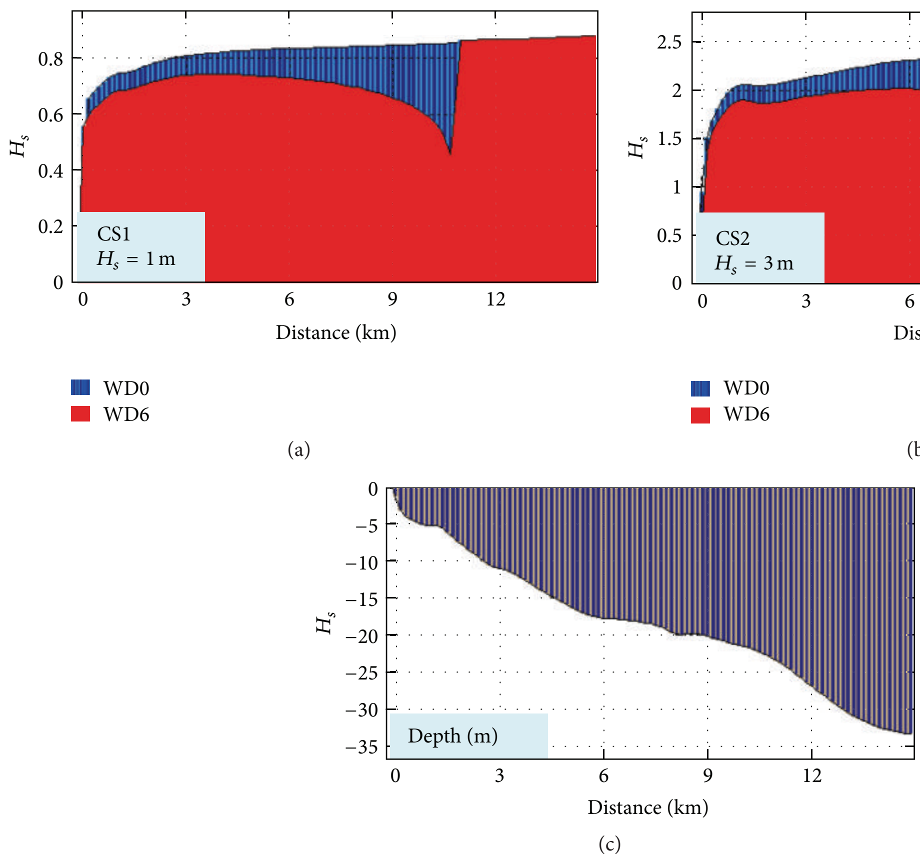


FIGURE 12: H_s variation along the reference line 1 without and with WD farm (WD0, WD6) for the two cases considered (CS1, CS2) and the variation of the water depth along the reference line.

the wave field being attenuated on a small area down wave the farm. Nevertheless, as the wave height increases, the impact propagates further towards the coast, like in CS2.

The evaluation in the spectral space of the Wave Dragon energy farm impact is illustrated in Figures 8 and 9 for the same two case studies (CS1 and CS2), where the 2D wave spectra were analyzed in parallel in the reference points OP2 and NP3 for the two different configurations considered (WD0 and WD6). In this figure a JONSWAP type spectrum was considered.

The boundary point (BP) presents the wave conditions unaffected in any way by the presence of the wave farm. Due to the presence of the Wave Dragons, the single-peak JONSWAP spectrum is transformed in a double peak spectrum immediately after the WEC array (as, e.g., in OP2), but this spectral shape does not propagate further in the geographical space, and at the level of the nearshore (the reference point NP3) no significant difference occurs in terms of the spectral shapes between the two different configurations considered (WD0 and WD6).

In Tables 2 and 3, a detailed data representation of the wave variation is given for CS1 and CS2, respectively. This represents the values of the wave parameters in all the reference points defined (BP, OP1, OP2, OP3, NP1, NP2, NP3, NP4, NP5, NP6, and NP7) for the two configurations considered (WD0 and WD6).

Some other relevant situations are presented in Tables 4, 5, and 6; this time the analysis is being focused only on the offshore points (OP1, OP2, and OP3) where the influence of the wave energy farm is in fact really relevant for the two situations mentioned before. The parameters considered in Tables 2, 3, 4, 5, and 6 are significant wave height (H_s), maximum variance (E_{max}), mean wave direction (Dir), directional spreading (DSPR), peak period (T_p), mean period (T_m), wavelength (Wlen), the components of the energy transport (P_x, P_y), and the components of the wave forces (F_x, F_y).

The results presented in the above tables show again that indeed relevant differences occur at the offshore reference points that were defined, while as regards the nearshore point NP1–NP7, these differences are significant attenuated.

5.2. Assessment of the Impact on the Shoreline Dynamics. Various phenomena are generated by the energy dissipation in the coastal environment, and the most relevant are the nearshore currents because they contribute to the sediment transport affecting directly the coastal dynamics. It is thus very important to find out how an energy farm will affect the nearshore circulation patterns by its presence in the marine environment and to estimate which will be the medium to

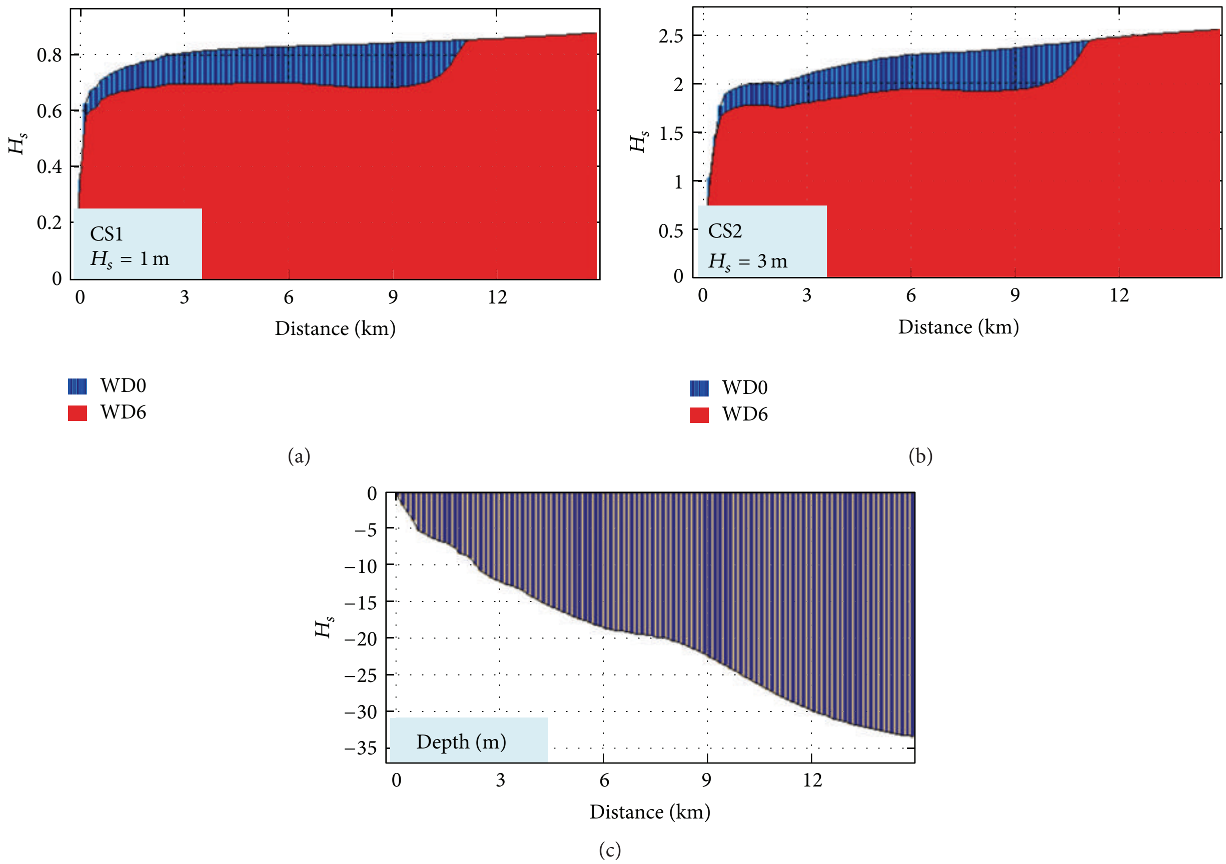


FIGURE 13: H_s variation along the reference line 2 without and with WD farm (WD0, WD6) for the two cases considered (CS1, CS2) and the variation of the water depth along the reference line.

the long-term impact on the coastal dynamics of the energy farm.

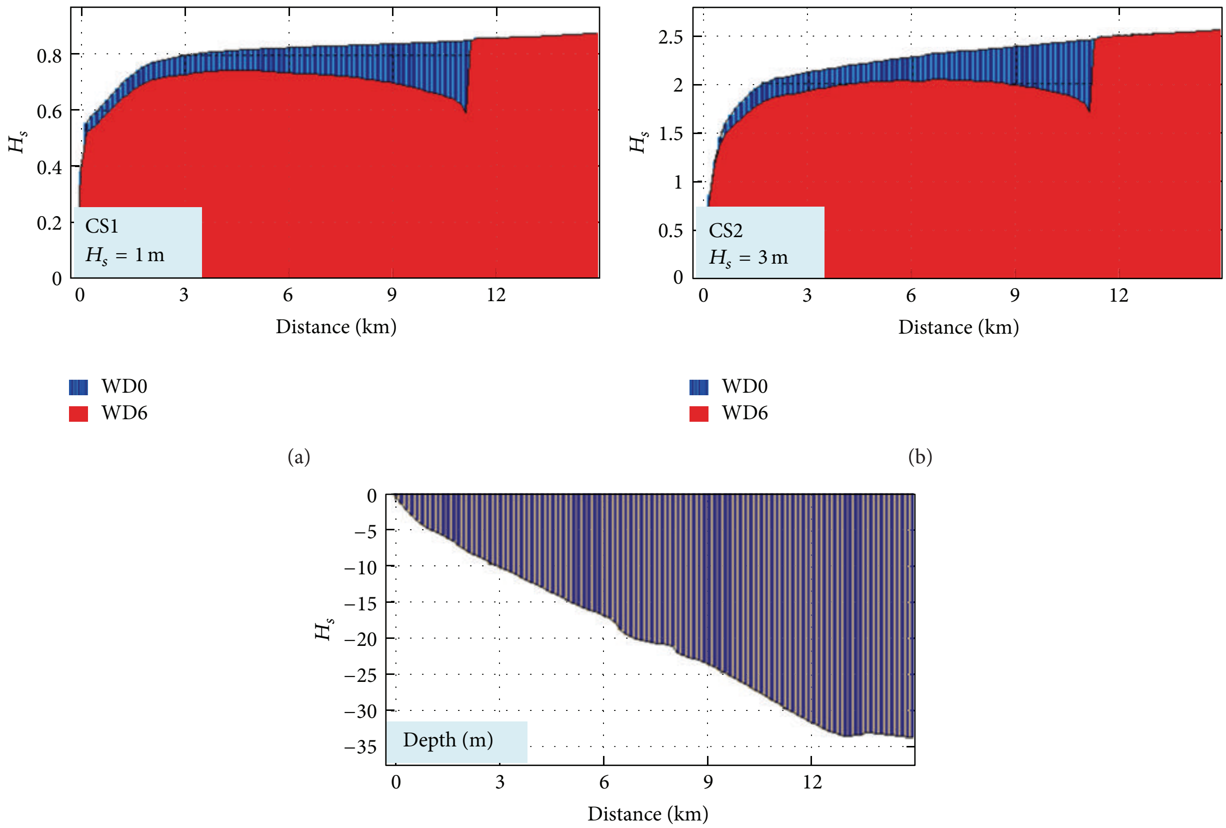
The nearshore currents were evaluated along the reference lines RL1–RL7, for the two different configurations considered (WD0 and WD6). The results concerning the maximum longshore current velocity are presented in Table 7. Table 7 presents the results corresponding to $H_s = 1$ m, $H_s = 3$ m, and $H_s = 5$ m at three different wave directions (30°, 90°, and 150°).

The maximum values of the velocities of the nearshore currents along the reference lines are illustrated in Figure 10 for both case studies considered (CS1 and CS2). As the results show, the influence of the wave farm over the nearshore currents appear in all the points but in general is not very high. From the analysis of data from the simulations, it has been observed that the most sensitive direction is that normal to the shoreline (90°) and the highest decrease of the current velocity appears in NP3.

An additional issue is related to the assessment of the evolution of the waves after their impact with the body of the WD farm structures. For that, the H_s variations have been analyzed along three reference lines passing through the wave energy farm in different locations, as illustrated in Figure 11.

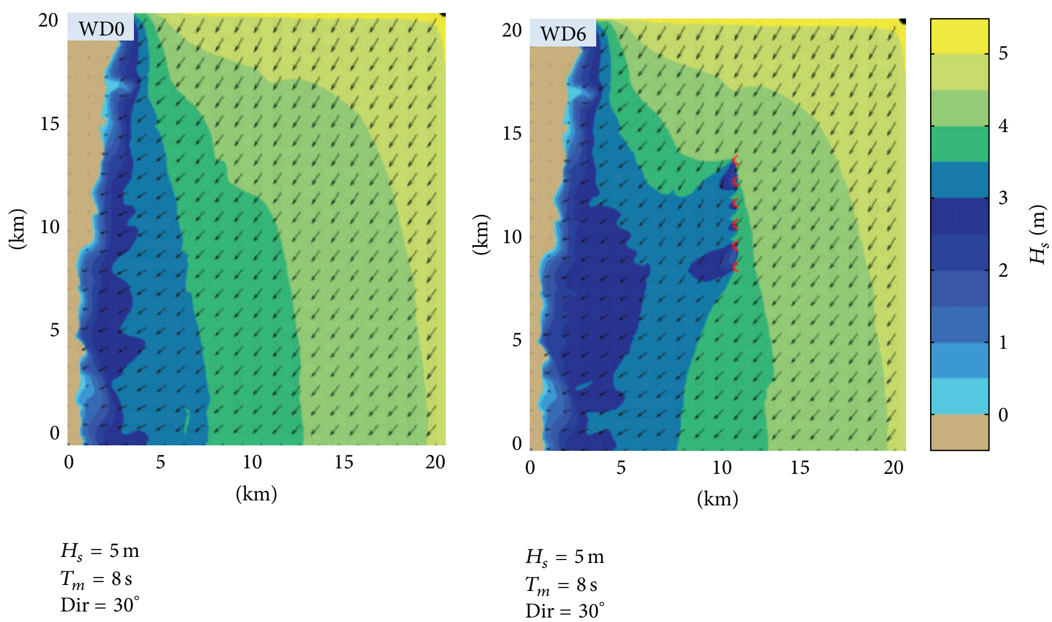
The results are presented in Figure 12 (for line 1), Figure 13 (for line 2), and Figure 14 (for line 3). They all present the evolution of the waves for the two situations WD0 (blue) and WD6 (red). The bathymetric variation along the reference lines is also illustrated in each figure. As it can be seen, the most relevant impact occurs at the reference line 1 in both cases (CS1, CS2), and the lowest is at the reference line 2 due to the fact that the line is passing between two devices while in the other two cases the lines pass directly through the body of one WD.

Finally, in order to complete the picture, another case study that was analyzed will be presented. It considers the following conditions on the external boundaries: $H_s = 5$ m, $T_m = 8$ s, and Dir = 30°. Thus, Figure 15 illustrates the impact in the geographical space on the wave field and Figure 16 the evaluation in the spectral space of the impact on the wave field of the Wave Dragon farm. In this case study, the maximum values of the velocities of the nearshore currents along the reference lines are illustrated in Figure 17. In such situation, the results of the modelling system indicate that the presence of the energy farm leads this time to an increase of the nearshore currents in most places. Finally, Figure 18 presents the H_s variation along the three reference lines



(a) (b) (c)

FIGURE 14: H_s variation along the reference line 3 without and with WD farm (WD0, WD6) for the two cases considered (CS1, CS2) and the variation of the water depth along the reference line.



(a) (b)

FIGURE 15: H_s variation along the reference line 3 without and with WD farm (WD0, WD6) for the two cases considered (CS1, CS2) and the variation of the water depth along the reference line.

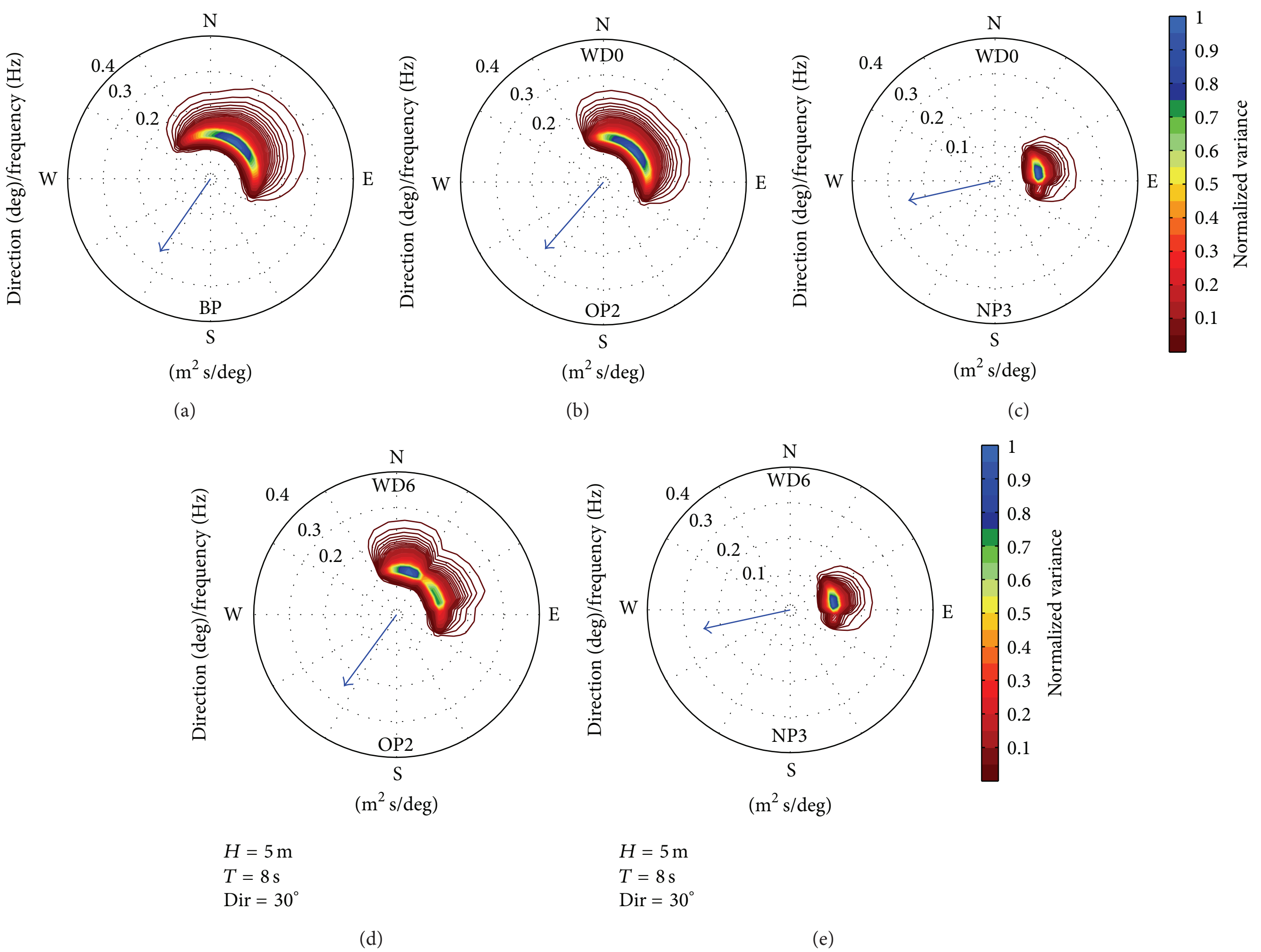


Figure 16: Evaluation in the spectral space of the impact on the wave field of a wave farm based on Wave Dragon WECs that operate in the target area for an additional case study defined by the parameters $H_s = 5$ m, $T_m = 8$ s, Dir = 30°. (a) BP for WD0. (b) OP2 for WD0. (c) NP3 for WD0. (d) OP2 for WD6. (e) NP3 for WD6.

previously considered, for the two different situations without and with the WEC array.

6. Concluding Remarks

According to the EU requirements, 20% of the electric energy produced in Europe should be provided until 2020 by renewable energy sources. In this connection, the marine environment represents a vast space depositing a huge amount of renewable energy. Nevertheless, the most important problem related to harvesting the energy in the marine environment is represented by the high cost of the electric power produced. As regards the wave energy extraction, the most significant step in the direction of reducing the energy cost is represented by the implementation of large WEC arrays. Thus, large scale WEC deployments are expected in the near future, and a very important issue related to this perspective is to evaluate correctly the possible coastal impact of these new power plants operating in the nearshore. In this context, the present work presents an evaluation of the changes induced in the coastal wave climate by an array of six Wave Dragons. The target area considered is located in the western side of the Black Sea, but the methodology can be easily extended to any coastal environment.

As regards the wave transformation, the modelling system considered in these evaluations is based on the SWAN spectral model, which represents an adequate framework for accounting the wave changes due to the presence of the energy farm. Evaluations were carried out in both geographical and spectral spaces for various relevant wave patterns. The results show that while immediately after the farm drastic changes occur in the wave fields, thus gradually attenuate towards the coast. In order to assess better the changes taking place in the spectral shapes due to the energy farm, transformations of theoretical JONSWAP spectra were followed for each case study considered. The results usually show that the single-peaked wave spectra are usually changed by the wave farm to double-peaked spectra immediately down wave the farm, but the spectra become again single-peaked at the level of the breaking line. This is also due to

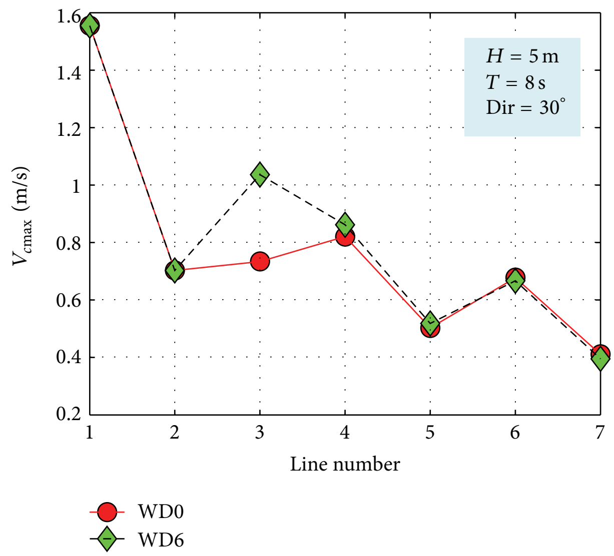


FIGURE 17: Evaluation of the impact of the energy farms on the maximum velocities of the nearshore currents along the reference lines considered for an additional case study defined by the parameters $H_s = 5$ m, $T_m = 8$ s, and Dir = 30°.

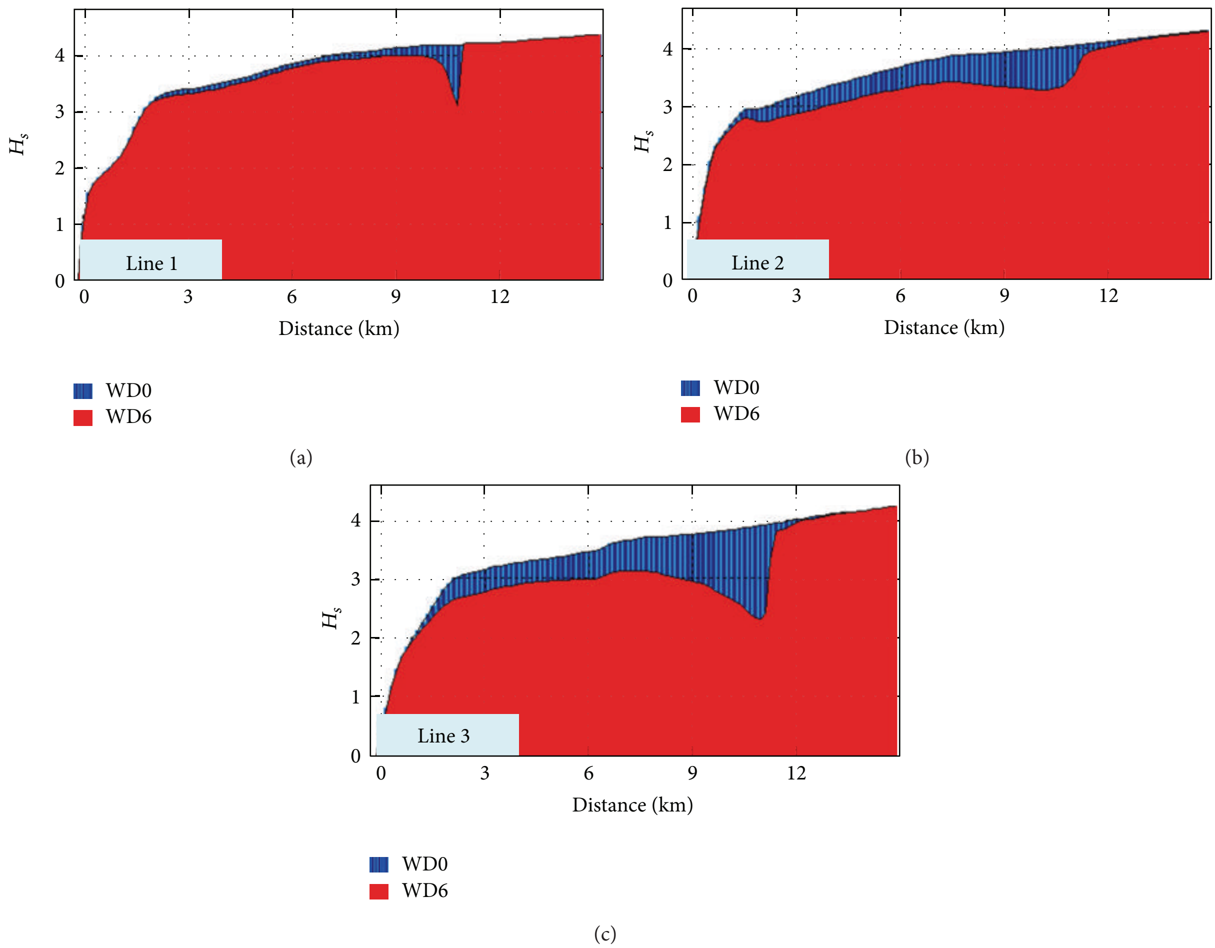


FIGURE 18: H_s variation along the three reference lines without and with the WEC array (WD0 and WD6) for the wave conditions corresponding to the parameters: $H_s = 5$ m, $T_m = 8$ s, and Dir = 30°.

the relatively large distance between the shoreline and the location of the wave farm.

In order to assess better the changes at the level of the shoreline dynamics, the modelling system ISSM that joins SWAN with the 1D surf models was considered. This allowed an evaluation of the longshore currents. The results show that although the nearshore waves are not very much affected by the presence of the WD farm, the maximum current velocities may, however, have significant variations. These variations are most evident at the central nearshore points. The results show also that the longshore current velocity is a more sensitive parameter to the presence of the energy farm than the significant wave height.

Since in general the presence of the energy farm has led to slight decreases of the wave conditions, its influence at the level of the shoreline dynamics is expected to be rather positive. Nevertheless, a very interesting result coming from the present work is that sometimes the presence of the energy farm may lead locally to enhancements of the longshore current velocity which means that due to the specific features of the site some coastal processes might be also accentuated. The work is still ongoing and larger WEC arrays, both of one and two lines, are being considered, which means that more accentuated changes might be expected for such configurations.

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Research Article

Differentiating between Underwater Construction Noise of Monopile and Jacket Foundations for Offshore Windmills: A Case Study from the Belgian Part of the North Sea

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Steel monopiles, jackets requiring four steel pinpiles, and gravity-based foundations were applied in offshore wind farms in the Belgian part of the North Sea. This paper compares the underwater noise generated during the piling activities of steel monopiles at the Belwind wind farm (Blighbank) with that of jacket pinpiles at the C-Power project (Thorntonbank). Underwater noise was measured at various distances from the pile driving location. The underwater noise was quantified by its zero to peak sound pressure level (L_{z-p}), unweighted sound exposure level (SEL), cumulative SEL, and 1/3 octave spectra. No significant differences in L_{z-p} could be demonstrated (monopile L_{z-p}: 179–194 dB re 1 μPa, jacket L_{z-p}: 172–189 dB re 1 μPa). SEL showed no statistical difference between monopile and jacket and varied between 145 and 168 dB re 1 μPa^2s. Furthermore, near identical spectra were measured for both types of piling. Piling of the jacket pinpiles took, however, about 2.5 times the time of the monopile. When standardised to megawatt installed per foundation both types of piling scored near equally. As an illustration, the radius of major behavioural disturbance (L_{p-p} = 155 dB re 1 μPa) in the harbour porpoise *Phocoena phocoena* was estimated by a model at 16 km for monopiles and at 8 km for jacket.

1. Introduction

The European Marine Strategy Framework Directive obliges every member state to achieve or maintain good environmental status, under which also the introduction of energy including underwater noise is considered a main concern [1]. An indicator for impulsive sound and a second indicator concerning the evolution of background noise are introduced. Clarification and details can be found in [2].

One of the major concerns in excessive underwater noise emissions is linked to offshore wind farms, as this industry is relatively new to the marine environment [3], is developing fast, and is highly diverse in technology used [4]. As such, at present, major attention is paid to the underwater noise generated during the construction, operation, and (future) dismantlement of offshore wind farms [3]. Here, four different phases should be distinguished in relation to the life cycle of an offshore wind farm: (1) the before implantation phase-reference situation, (2) the construction phase, (3) the operational phase, and (4) the dismantlement phase [5].

For the Belgian part of the North Sea (BPNS), the underwater noise emissions were documented for the first three phases, with reference sound pressure levels (SPL) of about 100 dB re 1 μPa at the Thorntonbank and Blighbank [6, 7]. So far, seven wind farms are planned for the BPNS, of which four have been granted both a domain concession and environmental permit. Two wind farms have actually been constructed. The first six windmills (C-Power project, phase 1; Thorntonbank) were built on concrete gravity based foundation (GBF), while in a second and third phase jacket foundations, involving the piling of four pinpiles per jacket, were used. In a second wind farm (Belwind project, Blighbank) only monopile foundations were applied. During the operational phase finally [8], a 20 dB re 1 μPa increase in mean

SPL emitted in case of a steel monopile foundation (totalling 120 dB re 1 μPa at 100 Hz) was measured, while hardly any increase in underwater noise was observed in case of GBFs.

This paper focuses on the differences in underwater noise emissions by two different types of piling, that is, piling of large monopiles (further called: monopiling) and the piling of the jacket foundation pinpiles (further called: jacket piling). In addition to zero to peak level (L_{z-p}), the best measures for comparing noise from pile driving also include sound exposure level (SEL), as the latter is better related to the energy emitted by the piling. Comparison of both piling activities therefore focused on both L_{z-p} and SEL. We finally also compared their noise spectra and attenuation functions. As an illustration and for the harbour porpoise that is the only marine mammal present in high density in Belgian waters, some computations related to the impact of underwater noise levels are proposed.

2. Materials and Methods

Analysis focused on the quantification of the discontinuous impulsive pile driving-generated underwater noise. Underwater noise was measured at various distances (250–14000 m) from the pile driving location during the installation of steel monopiles and jackets at the Blighbank and Thorntonbank site, respectively. Zero to peak sound pressure level (L_{z-p}), unweighted sound exposure level (SEL), cumulative SEL, and 1/3 octave spectra were computed in order to quantify the underwater noise emitted during the construction phase.

2.1. Measurement Methodology. Measurements of wind farm construction noise were performed from a drifting rigid hull inflatable boat (RHIB) in the vicinity of the piling site [7]. To avoid interaction with the hydrophone, the engine, radar, and echosounder were turned off. The geographic position and time of measurement were recorded with a handheld GPS GARMIN GPSMap60 at a frequency of one position every 5 seconds. The clock of the recorder was synchronised beforehand with the GPS-time (UTC). At the start and the end of each measurement a reference signal was recorded.

Several recordings of few minutes each (1 to 5 min.) were performed at different locations on September 26 2009 (monopile A02) and January 15 2010 (monopile B10) at the Blighbank and on the May 11 (jacket CG3) and the of July 12 2011 (jacket CB6) at the Thorntonbank site (Table 1). Weather conditions encountered during fieldwork featured a wind force of 1–3 BF and a sea state of 1 to 2.

2.2. Acoustic Measurement Equipment. For every measurement, a Brüel & Kjær hydrophone (type 8104) was deployed at a depth of 10 m. A Brüel & Kjær amplifier (Nexus type 2692-0S4) was connected between the hydrophone and the recorder in order to allow for an amplification and filtration of the signal. A reference signal was used together with the output sensitivity of the Nexus to calibrate the amplitude of the recorded signal. The signal was recorded using an audio MARANTZ Solid State Recorder (type PMD671). It was operated with the highest possible sampling rate of 44100 Hz. The signal was recorded in WAVE format (.wav) on Compact Flash cards of 2 GB (Sandisk Ultra II). Batteries powered all equipment.

Table 1: Geographic position, peak level (L_{z-p}), and distance from the piling location of the underwater noise measurements at the Blighbank site (monopiles A02 and B10) and at the Thorntonbank site (jackets CG3 and CB6).

Position start recording (WGS84) Latitude	Longitude	Peak level (dB) L_{z-p}	Distance (m) from piling location
Monopile A02			
51°40.39′	2°50.03′	177	~3000
51°39.41′	2°50.64′	177	~4820
51°38.25′	2°51.25′	166	~6990
Monopile B10			
51°34.59′	2°57.31′	159	~14150
51°38.52′	2°48.16′	185	~1580
51°38.50′	2°47.44′	193	~770
Jacket CG3			
51°33.92′	2°58.94′	192	~250
51°51.34′	2°58.36′	187	~500
51°33.96′	2°58.93′	196	~250
Jacket CB6			
51°33.07′	2°53.94′	182	~600
51°32.96′	2°52.59′	175	~1700
51°32.65′	2°53.42′	172	~750
51°32.22′	2°53.01′	171	~1600

2.3. Response Variables. It is very common in underwater acoustics to use values expressed in a logarithmic scale (decibels). In order to characterize extreme level values of a transient signal like the one associated with pile driving the peak sound pressure level is often used. This terminology is not totally unambiguous and we prefer to use L_{z-p} that is defined by [9] as

$$L_{z-p} = 10\log_{10}\frac{p_{z-p}^2}{p_{\mathrm{ref}}^2} \quad \text{in dB re } 1\,\mu\text{Pa}. \tag{1}$$

For impulsive sound, however, the unweighted SEL better characterises the energy produced by a given stroke, extracted from a complete piling event. SEL is computed as defined by [9]. The SEL is the level of a continuous sound during the integration period and having the same sound energy as the impulse:

$$\begin{aligned} \mathrm{SEL} &= 10\log\left(\frac{1}{T}\int_{T1}^{T2}\frac{p(t)^2}{p_0^2}dt\right) \\ &= 10\log\frac{E}{E_{\mathrm{ref}}} \quad \text{in dB re } 1\,\mu\text{Pa}^2\text{s}, \end{aligned} \tag{2}$$

where T is 1 second, $T1$ and $T2$ are, respectively, the start and the end of the integration time window (the complete stroke being included in this window), $p(t)$ is the sound pressure

Table 2: Summary statistics of the piling activities of monopile A02 and B10 and jacket foundations CB6 and CG3, targeted in this study, as well as the averages and total (where appropriate) for the 56 monopiles installed at the Blighbank (source: Belwind) and the 49 jacket installed on the Thorntonbank (source: C-Power).

	Monopile piling activities (pile diameter = 5 m)					Jacket piling activities (pinepile diameter = 1.8 m)				
	Unit	A02	B10	Average	Total	Unit	G3	B6	Average	Total
Pile length	m	55	63	54		m	48	21	37	—
Mass	t	401	453	375		t	96	46	77	—
Number of strokes required		2114	3848	2982	168550		13321	4288	9476	464328
Average energy per stroke	kJ	642	839	706		kJ	436	321	412	
Duration of piling	min	64	163	120	6779	min	405	162	319	15646
Net piling frequency	Number of strokes/minute	42	39	40		Number of strokes/minute	About 40	About 40		
Total energy	MJ	1356	3224	2084	118909	MJ	5805	1376	3909	191531

signal, and p_0 is the reference sound pressure of 1 μPa. When more than one noise pulse is generated as is the case for pile driving, it is possible to compute a cumulative sound exposure level. For a series of strokes, the cumulative SEL is computed following the definition given by [10], advising not to rely only on cumulative SEL but also to include the total number of blows and the frequency of piling. Measurements made at various distances were normalized to a reference distance of 750 m using the equation [11, 12]:

$$L_{\text{norm}} = L_{\text{measured}} + 15\log_{10}\left(\frac{\text{distance}}{750}\right). \tag{3}$$

This normalization has been used in this study in order to allow for an appropriate comparison of noise characteristics collected at various distances from the source using a normalized transmission loss [11, 12] permitting comparison with other sites.

The third octave band spectrum of the underwater sound pressure level was computed according to the norm IEC1260. All these computations were made using dedicated routines developed using the MATLAB environment.

A Kruskal-Wallis test, followed by Dunn's *post hoc* multiple comparison tests, was used to identify statistically significant differences in the underwater noise emitted by the different foundation types. More specifically, Dunn's *post hoc* test as applied by Statistica 10 compares the difference in the sum of ranks between two columns with the expected average difference (based on the number of groups and their size). For each pair of columns, Prism reports the P value as >0.05, <0.05, <0.01, or <0.001. The calculation of the P value takes into account the number of comparisons made. If the null hypothesis is true (all data are sampled from populations with identical distributions, so all differences between groups are due to random sampling), then there is a 5% chance that at least one of the posttests will have $P < 0.05$. The 5% chance does not apply to each comparison but rather to the entire family of comparisons.

2.4. Piling Activity Details. For the piling of the 56 monopile foundations at the Blighbank, a hammer IHC hydrohammer S1200, operated from the support vessel Svanen, was used. The hammer featured a maximum power of 1200 kJ. The average energy used for each stroke was 706 kJ (Table 2). For the installation of the 49 jacket foundations at the Thortonbank, the piling of 196 pinpiles was required. The hammer used was an IHC hydrohammer S-800 featuring a maximum power of 800 kJ for a nominal power of 720 kJ. Average energy used for each stoke was 412 kJ. The hammer log did not record a time stamp for every blow along with the other information, hampering a direct comparison between the records and the hammer log.

2.5. Major Behavioural Disturbance Levels for Marine Harbour Porpoise. Even if underwater noise produced by human activities is known to produce effect to the marine life, including fishes or birds, we propose an illustration to compare our data and model results with known level for the most common marine mammal present in Belgian water. For the harbour porpoise *Phocoena phocoena,* a major behavioural disturbance level, is found above $L_{p-p} = 155$ dB re 1 μPa [13].

2.6. Regression Model for Noise Propagation. A linear regression model based on the ordinary least square (OLS) was computed from the data presented at Table 1:

$$\begin{aligned} L_{z-p} &= -27.4\log(d) + 270.7\text{ dB} \qquad \text{for monopile} \\ L_{z-p} &= -27.4\log(d) + 259,5\text{ dB} \qquad \text{for jacket,} \end{aligned} \tag{4}$$

in which d is the distance to the source. It has a transmission loss of 27.4log (d) ranging within the 95% confidence interval from 30.5 to 24.3log (d). That model is further modified by the addition of an absorption term making use of absorption coefficient of 0.0004 dB/m as proposed by [13] and the final model reads

$$\begin{aligned} L_{z-p} &= -27.4\log(d) + 270.7\text{ dB} - 0.0004d \\ &\qquad \text{for monopile} \\ L_{z-p} &= -27.4\log(d) + 259,5\text{ dB} - 0.0004d \\ &\qquad \text{for jacket.} \end{aligned} \tag{5}$$

TABLE 3: Normalized @ 750 m zero to peak sound pressure level (L_{z-p}) in dB re 1 μPa. Normalized @ 750 m mean and maximum sound exposure levels (SEL) in dB re 1 $\mu Pa^2 s$.

	Record	Norm. L_{z-p} @ 750 m	Norm. mean SEL @ 750 m	Norm. max. SEL @ 750 m
Monopile A02	1	186	161	164
	2	189	164	166
	3	180	160	164
Monopile B10	1	194	162	166
	2	190	168	162
	3	179	163	166
Jacket CG3	1	185	168	174
	2	189	168	178
	3	186	168	175
Jacket CB6	1	180	155	159
	2	172	145	151
	3	176	150	152
	4	180	152	157

3. Results

3.1. Underwater Noise Sound Pressure and Exposure Levels. The highest normalised L_{z-p} of 194 dB re 1 μPa was observed for the piling of the B10 monopile at the Blighbank, while for the piling of the jacket pinpiles a maximum of 189 dB re 1 μPa was observed (CG3) at the Thorntonbank (Table 3). The lowest L_{z-p} value of 172 dB re 1 μPa was observed for the piling of the jacket CB6, while the lowest L_{z-p} for monopiles was 179 dB re 1 μPa. The piling of the jacket foundation CG3 and the piling of the monopile A02 exert similar normalized L_{z-p} values of about 186 dB re 1 μPa. Some lower normalized L_{z-p} (by 15 to 20 dB re 1 μPa) is observed for the piling of the jacket CB6.

Normalized maximum SEL values range between 151 and 178 dB re 1 $\mu Pa^2 s$. The maximum observed normalised SEL for jacket foundation piling was 178 dB re 1 $\mu Pa^2 s$ (CG3), while the maximum observed normalized SEL for monopiles (B10) was some 10 dB lower with a maximum of 166 dB re 1 $\mu Pa^2 s$. Normalized mean SELs show similar behaviour with the highest value of 168 dB re 1 $\mu Pa^2 s$ measured at CG3 and the lowest value for jacket piling of 145 dB re 1 $\mu Pa^2 s$ (CB6). Normalized mean SELs for both steel monopile are in between with 168 dB re 1 $\mu Pa^2 s$ for B10 and 164 dB re 1 $\mu Pa^2 s$ for A02. Whereas statistically significant differences were detected between the four piling events for normalized maximum SEL (Kruskal-Wallis test: $P = 0.016$) and mean SEL ($P = 0.020$), *post hoc* multiple comparisons revealed differences only between the two jacket piling events ($P = 0.008$ and $P = 0.018$, resp.).

3.2. Underwater Noise Spectra. For both monopile and jacket piling, the strongest underwater noises were emitted between 60 to 2000 Hz. Moreover, while the shape of the spectra are similar in the frequency domain 100 to 500 Hz, the spectra showed more isolated peaks for the jacket piling than for the monopiling, for which only one larger peak was found. The decay of the spectra showed a similar slope for both foundation types.

TABLE 4: Characterization of the monopile and jacket piling activities. Normalized maximum sound exposure level (norm. max. SEL @ 750 m).

Foundation type	Monopile (3 MW)	Jacket (6 MW)
Average no. of blow/foundation	3010	9476
Average no. of blow/MW installed	1021	1612
Average energy (MJ)/blow	0.7	0.4
Average energy (MJ)/foundation	2123	3909
Average energy (MJ)/MW installed	721	665
Norm. max. SEL @750 m (dB re 1 $\mu Pa^2 s$)	166	178
Average duration of piling (min)/foundation	120	319
Average duration of piling (min)/MW installed	41	55
Average piling frequency (blow/min)	25	30

On average, a jacket foundation required about three times more blows per foundation (Table 4) than a monopile. When that parameter was normalized to MW installed, 57% more blows/MW installed were needed for jacket foundations than for monopile. Moreover, the average piling time required was higher for a jacket foundation than for a monopile (factor 2.5) and remained somewhat higher when normalized to MW installed (factor 1.3).

3.3. Noise Propagation and Attenuation. For both farms, the propagation model (Figure 2) is used to compute the extent of the zone wherein noise levels exceeded the major behavioural disturbance level for harbour porpoises.

The simple model used is an approximation of the exact situation. That zone of the North Sea features complex geomorphology on a shallow water environment that may induce more complicated propagation and attenuation for underwater sound waves. Nevertheless, when taking into account the variability found on the production of the noise itself (Table 2), the first approximation that is represented by the model is acceptable for the purpose of an estimation of a radius of major behavioural disturbance for marine mammals around a construction place.

The zone of major behavioural disturbance for harbour porpoises was estimated by the model to a radius of 8 km around the jacket piling location, while that radius extended to 16 km from the monopile piling location.

3.4. Cumulative Sound Exposure Level. The mean number of strokes required for the complete piling of one monopile foundation was 3010 strokes (Table 4). As 3010 strokes represent an increase of the normalized @750 m mean SEL of 35 dB ($10 \log_{10}(3010)$), the mean cumulative SEL for monopile was estimated at 196 dB re 1 $\mu Pa^2 s$. The mean duration of piling for one foundation was 120 min. A mean number of 9476 strokes were required for the installation of one jacket foundation. This represented an increase of 40 dB, giving a cumulative normalized SEL of 196 dB re 1 $\mu Pa^2 s$ @750 m. The mean duration of piling for one jacket was 319 min. The same cumulative SEL values were, hence, observed for both foundation types, but the disturbance time for jacket foundations lasted for longer than that for monopile foundations.

4. Discussion

As expressed earlier, the piling work linked to the installation of the jacket foundation requires the piling of four pinpiles, while the monopile design requires the piling of only one large monopile. Jacket foundations may, however, accommodate larger turbines than monopiles [4]. A less powerful hammer can be used for the installation of the jacket foundations than that for the monopile foundations. However, a jacket design requires longer piling time than the monopile design (mean time of 319 min for jacket against 120 min for monopile), but at lower noise levels with a normalized L_{z-p} of maximum 194 dB re 1 μPa for a monopile against 189 dB re 1 μPa for a jacket. The installation of jacket foundations, hence, impacts a smaller zone, but for a longer period of time.

In terms of energy, the total piling energy needed to achieve the complete construction of the C-Power project, phases 2 and 3 at the Thorntonbank (49 jacket foundations), was just above 0.19 TJ (Table 2), while the same figure for the Belwind wind farm implanted at the Blighbank and featuring 56 monopile foundations was 0.12 TJ. The overall message is that more energy was used and, therefore, transmitted to the environment for the installation of the new C-Power wind farm than that for the installation of the Belwind wind farm. This is further confirmed by the SEL data (Table 3) featuring a maximum value for the normalized SEL of 178 dB re 1 μPa^2s for the C-Power project wind farm against 166 dB re 1 μPa^2s for the Belwind wind farm.

When underwater noise is generated by pile driving, the size of the pile, power of the pile driver (hammer), and sedimentological and geological properties are important variables, affecting the effective underwater noise produced. For similar sediment properties, using a larger pile driver would generate less noise because of a lower impact velocity applied when hammering [11]. It could also be economically more efficient to use a large pile driver operated at 2/3 of its nominal power than a smaller one used at its maximum power. The use of a less powerful hammer (800 kJ) for pinpiling (versus 1200 kJ for monopiling) in conjunction with the use of smaller pinpiles produced lower L_{z-p} values than those for the monopiling at the Blighbank (some 5 dB re 1 μPa @750 m). The higher SEL identified for the piling of jacket CG3 (Table 2) in comparison with the piling of the jacket CB6 is most probably related to the use of the hammer at a higher power, even if we cannot demonstrate that relation due to the unavailability of a timestamp for every blow. However, to conclude the differences observed between pinpiling and monopiling, a significant difference was found within the pinpiling group (Table 3). This significant difference can be explained by the fact that the piling of one of the jackets (CB6) required only a third of the mean energy used for the installation of the other jackets (Table 2). This could indeed be related to the small scale local differences in sedimentological and geological properties.

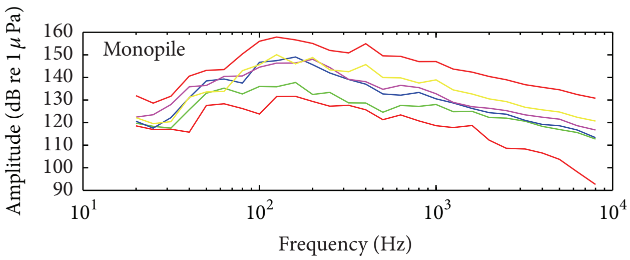
Nevertheless, when renormalizing these data to the installed power, the message is different with a little lower average energy per MW used for the jacket foundation (665 MJ/MW) than that for the monopile foundation (721 MJ/MW). While jacket piling used less piling energy per MW, the average duration of piling per installed MW remained 26% higher with 55 minutes for a jacket and only 41 minutes for a monopile. However, an even better normalization would be obtained when standardising to the MW produced instead of the MW installed. Such standardisation would, however, be premature at this moment, since the wind farms are either operational for a short period of time (Belwind) or not yet operational at all (C-Power, phases 2 and 3).

For both monopiling and jacket installed in the BPNS, cumulative SEL of 196 dB re 1 μPa^2s @750 m was found. Comparison with the available data for the Q7 wind farm [10] located in Dutch waters and featuring 4 m diameter monopiles was possible after a renormalization at 750 m. Some 13 dB higher cumulative SEL was computed (209 dB re 1 μPa^2s). Unfortunately, other comparisons based on that variable are difficult to make since primary data are missing. Adapted from [11], zero to peak levels ranging between 185 and 199 dB re 1 μPa for a pile diameter ranging between 3,3 and 4,7 m were observed in various wind farms located in German and UK waters. These results are of the same order of magnitude and coherent with what was observed in the BPNS wind farms.

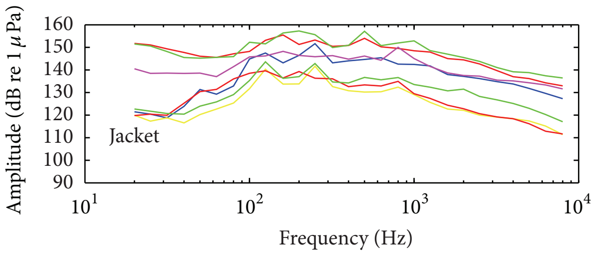
Some of the levels observed here for both the monopile or jacket type foundations installation exceed the 185 dB re 1 μPa permitted by the Belgian MSFD descriptor 11. This indicates that future offshore wind farms will need to take mitigating measures during construction. Different methods exist [11, 14]. One of these is the air bubble curtain method [15] that could reduce the levels (both L_{z-p} and SEL) by about 14 dB. These values were obtained inside a port and such technique remains to be validated at sea, with, for example, strong tidal current. A current of 1 m/s, which is not uncommon for the BPNS, may indeed induce a drift of the bubble curtain of about 70 m for a bottom depth of 20 m [11]. New difficulties may arise when the sleeve may be in contact with the pile due to the tidal current. For bubble curtains, size of the bubble has an impact on sound insulation [14, 15]. A second method often preferred by the industry for sound isolation is the use of pile sleeves made from various material including foam or air [11, 14]. This last method can achieve a sound reduction of 20 to 25 dB for low frequencies where the maximum noise is produced (Figure 1). These methods, if they were used in conjunction with piling works, would have reduced the produced noise to levels below the Belgian MSFD requirements.

5. Conclusion

(i) While jacket foundations involved smaller diameter pinpiles and while the emitted noise levels normalized at 750 m L_{z-p} values are lower than those for monopiling, therefore impacting a smaller zone, the overall energy needed for the complete piling was 58% higher for the 49 jackets than for the 56 monopiles.



(a)



(b)

FIGURE 1: 1/3 octave spectra of the underwater noise of the Blighbank monopiling and the C-Power jacket piling.

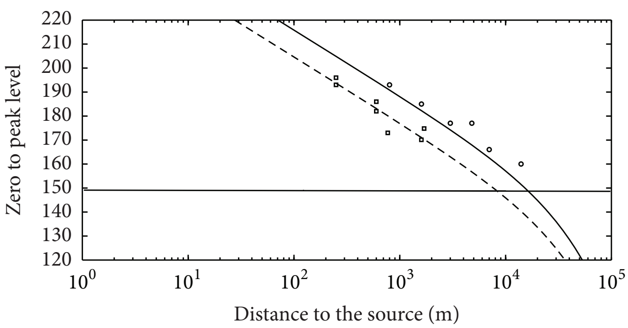


FIGURE 2: Application of the propagation model to jacket piling (dashed line) and monopiling (plain line). Squares and circles are the measured L_{z-p}, respectively, for jacket and monopile (Table 1) while the horizontal line at 149 dB re 1 μPa represents the level (L_{z-p}) for major behavioural disturbance for harbour porpoise [13].

The normalized @750 SEL was also higher for jacket than for monopile foundation piling.

(ii) When normalized to installed MW the figure is inversed and average energy needed by installed MW is 8% lower for jacket than for monopile.

(iii) Finally, for both maximum and mean normalized @750 m SEL, no statistically significant difference on the emitted underwater noise between pinpiling and monopiling could, however, be observed.

(iv) The radius for major behavioural disturbance was modelled to reach 16 km for monopile and 8 km for jacket.

(v) Some measurements are above the Belgian MSFD requirements and those for monopile as well as for jacket. Use of mitigation measures could have reduced the produced noise below these requirements.

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Research Article

Epibenthic Assessment of a Renewable Tidal Energy Site

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Concern over global climate change as a result of fossil fuel use has resulted in energy production from renewable sources. Marine renewable energy devices provide clean electricity but can also cause physical disturbance to the local environment. There is a considerable paucity of ecological data at potential marine renewable energy sites that is needed to assess potential future impacts and allow optimal siting of devices. Here, we provide a baseline benthic survey for the Big Russel in Guernsey, UK, a potential site for tidal energy development. To assess the suitability of proposed sites for marine renewable energy in the Big Russel and to identify potential control sites, we compared species assemblages and habitat types. This baseline survey can be used to select control habitats to compare and monitor the benthic communities after installation of the device and contribute towards the optimal siting of any future installation.

1. Introduction

Widespread concern over global climate change as a result of fossil fuel use has resulted in an increased interest in renewable energy [1]. Wave and tidal energy developments are receiving increased attention despite the technology being less advanced compared to offshore wind technology because it has great potential in countries with suitable conditions [2–4]. Even though the global environmental benefits of renewables are clear, their local impacts must also be quantified, so that future installations can be effectively managed [5].

Often, species assemblages in locations that are suitable for renewable energy installations are not well understood as these high energy environments are difficult and dangerous to study [6]. As the industry is in its infancy, little is also known about the environmental impacts that are likely to result. A marine renewable energy installation can cause physical disturbance during construction, operation, and decommissioning [7]. Inger et al. [5] suggested that the impacts are likely to be both positive and negative. Installations may act as artificial reefs [8] and provide refuge and feeding grounds for marine fauna. Safety exclusion zones surrounding installation sites are likely to exclude benthic trawling and dredging which damage the sea bed [9] and therefore act as *de facto* Marine Protected Areas (MPAs) [5, 10]. Conversely, the infrastructure associated with these developments may entangle marine organisms, create noise and/or cause scouring of the seabed [5, 7, 11]. Guernsey, Channel Islands, UK, has been identified as a candidate area for tidal energy extraction; however, the lack of benthic data in potential tidal energy sites such as Pentland Firth, Scotland, UK [12], and Guernsey, Channel Islands, UK [13], has prompted calls for baseline surveys as a high priority.

The islands of Guernsey (termed the Bailiwick) are situated in the bay of St Malo in the English Channel approximately 30 miles off the northern coast of France (Figure 1). The tidal currents around the Bailiwick are some of the strongest in the world, and the exposure to wave action from the Atlantic Ocean make this area a good prospective location to harness marine renewable energy [13]. Guernsey aims to generate 20% of its electricity from renewable sources by 2020 in line with EU targets [13] by locating tidal devices in "the Big Russell" (Figure 1), a channel where very little is known about the benthic assemblages. In order to predict

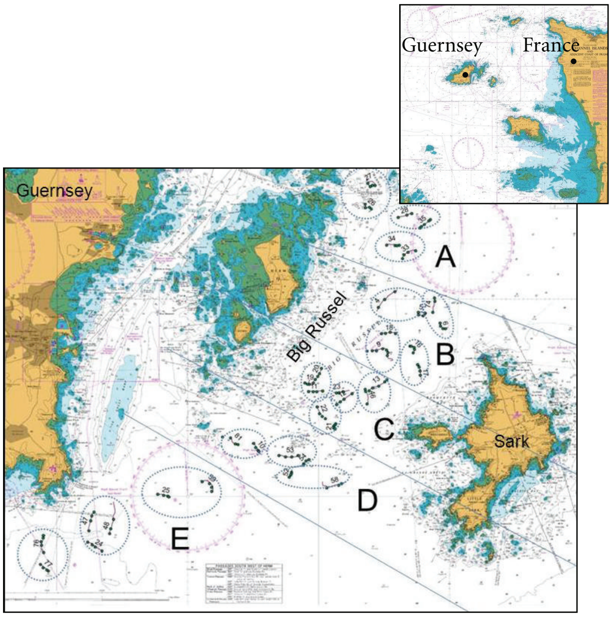

Figure 1: The Bailiwick of Guernsey off the north coast of France. The Big Russel channel is on the eastern side of Guernsey. The channel was divided into Locations (A, B, C, D, and E) and Areas (dotted lines), which comprise 2 or 3 sites (black filled in circles).

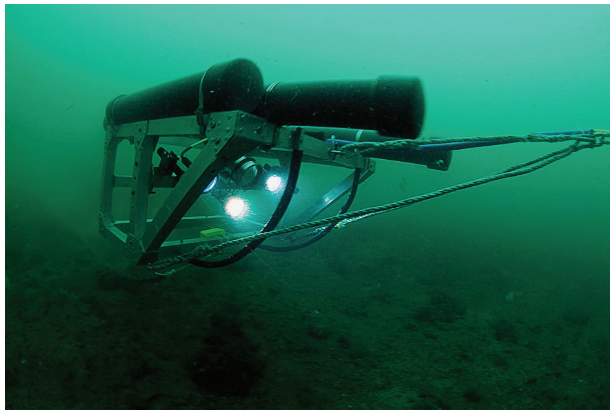

Figure 2: The towed flying array mounted with high definition video.

the impact of future energy developments and allow managers to locate developments in areas of least impact, a benthic survey was undertaken.

The aim of the survey was to document the epibenthos in the Big Russel to provide a baseline of species composition in an area where tidal development may occur, and to identify suitable control areas for any future tidal development impact assessments. The survey also provided a reference list of species that can be used for future impact assessments for developers seeking consent to deploy devices on the sea bed.

2. Methods

2.1. Study Site. Sites were selected across the Big Russel to include the parts which had been identified as potential locations for the development of tidal energy, and to identify suitable control areas for future impact assessment (Figure 1). Sites were also selected south of the Big Russell, as this was thought most likely to provide suitable controls away from those areas proposed for development in the main channel.

To enable quantitative comparison of the species assemblages throughout the north east to south west of the channel, transects were distributed across 5 "locations" A–E (Figure 1). To examine the small scale variability of the species assemblages within each "location" and increase our ability to estimate the species variability for any given part of the Big Russel, two to three transects (sites) were sampled per area. For each site, a transect was filmed for approximately 200 m with a field of view of 0.5 m width (Figure 2). A total of 36 transects were selected for video analysis based on the clarity of the footage.

2.2. Field Sampling. Transects were videoed in September 2010 from a 15 m fishing trawler. The survey employed a method of filming the seabed using a High Definition (HD) video camera mounted on a towed "flying array" described by Sheehan et al. [6] (Figure 2). The flying array is an aluminium sled that floats above the seabed, which makes it suitable for sampling epibenthos over variable seabed relief. A piece of chain is used to control height above the seabed and a drop weight is attached to the tow rope to provide extra stability and minimize the effect of the pitch and roll of the boat.

The system comprised an HD video camera (Surveyor-HD-J12 colour zoom titanium camera, 6000 m depth rated, 720p: resolution 1280×720 (0.9 megapixels)) positioned at a 45° angle to the seabed, three LED lights, mounted either side and below the camera, and two green laser pointers. The two laser pointers were mounted on the frame either side of the camera at a fixed distance apart to allow calibration of the field of view during video analysis. The flying array was deployed over the stern of the boat and an umbilical connected the camera to the surface control unit allowing control of the camera focus, zoom, and light intensity [6]. The boat was carefully controlled and towed the camera slowly (approx. 0.4 knots) over the seabed in up to 2.4 knots of tidal flow.

This method is cost effective, allowing large areas to be surveyed rapidly (e.g., Stevens and Connolly, [14]). It also has minimal impact on the seabed, which is essential for studies where there is interest in documenting change over time as it avoids confounding the results with impacts resulting from the survey method. The use of HD video provides data of a high quality, and also a data archive for future use.

2.3. Video Analysis. Video footage was analysed in two stages. To enumerate the abundant/encrusting species, including sponges, hydroids and algae, frame grabs were extracted at 5 s intervals and overlaid with a digital quadrat (3Dive Frame Extractor Software). Frames were viewed and those that were not clear of obstruction, well focused and had the lasers within acceptable margins of the screen, were deleted (see Sheehan et al., [6] for details). Ten frame grabs were haphazardly selected from the video throughout the length of the transect and all taxa within the frame identified and counted. Taxa were identified to the highest taxonomic level. Taxonomically similar species, which could not be distinguished with confidence, were grouped (e.g., branching sponges, gobies, and hydroids). The area sampled was corrected for every frame based on the position of the laser dots, giving density units of ind·m^{-2}. To quantify the infrequent/conspicuous species including crustaceans, soft corals, and sea stars, counts were made from the entire video transect. Species counts were determined by viewing the video and recording all identifiable taxa that passed within the "gate" made by the two laser pointers (see the species list in the Supplementary Material available online at http://dx.doi.org/10.1155/2013/906180).

2.4. Statistical Analyses. Permutational multivariate analysis of variance (PERMANOVA+ in the PRIMER v6 software package, [15]) was used to determine whether assemblages of organisms were different between locations and areas based on Bray Curtis similarity matrices [16]. PERMANOVA is robust to datasets with many zeros and allows testing interactions in multivariate data. It has significant advantages over conventional MANOVA in that it makes no assumptions about underlying data distributions and is robust to unbalanced designs [17]. All analyses were done twice; firstly the common/encrusting fauna quantified from the ten frame grabs were averaged to avoid pseudoreplication and to increase the precision at which the epibenthic assemblage could be quantified. Secondly, an analysis was done for the infrequent/conspicuous fauna that were quantified from the entire video tow.

To examine spatial differences between assemblages there were three factors: Location (A–E), Area (random and nested in Location), and Site (random and nested in Area). Significant differences were further examined using pairwise tests. SIMPER was used to explain which taxa contributed most to differences between assemblages [18].

Multivariate assemblage data were visualised using nonmetric multidimensional scaling (nMDS) ordinations, one for the abundant/encrusting species (frame grabs), and one for the infrequent/conspicuous fauna (video dataset).

Potential habitat/taxa associations were then visualised by plotting frame grab assemblage data averaged over site, coded by the dominant habitat type for each site on nMDS ordination. The densities of the ten most abundant taxa for the three dominant habitats were also summarised in a table.

3. Results

The benthic community in the Big Russel was clearly affected by strong tides as throughout the channel the sessile fauna were typically cropped and low lying, and fishes were often observed travelling backwards, or fighting to swim towards rocky overhangs, presumably, to escape the tidal currents.

The area surveyed ranged from sandy plains in Location A in the north east (site 28) to bedrock and rocky pinnacles in Locations C and D. The largest proportion of frames (36.34%) was rock, with 31.34% composed entirely of bedrock. Cobbles and boulders were the next most common habitats, occurring in 27.05% and 18.43% of frames, respectively, and 13.68% of the frames comprised combined habitat.

Table 1: (a) PERMANOVA to compare the assemblage composition of the abundant/encrusting fauna based on Bray Curtis similarities. Data were dispersion weighted and square root transformed. (b) Pairwise tests for Location differences. P values in bold type are significant.

(a)

Source	df	MS	Pseudo-F	P (perm)
Location Lo	4	2246.6	1.9995	**0.0029**
Area Ar(Lo)	11	1125.4	1.2587	0.0825
Site (Ar(Lo))	16	894.08	No test	
Total	31			

(b)

Location pairings	P (perm)
A and B	0.1719
A and C	0.1233
A and D	0.4978
A and E	0.4014
B and C	0.1127
B and D	**0.0270**
B and E	**0.0107**
C and D	**0.0218**
C and E	**0.0047**
D and E	**0.0470**

A total of 74 taxa were identified during the survey, 39 in the video transects, and 59 in the frame grabs (full species list in Supplementary Material, Table 1). The most abundant species identified in the video transects was dead man's fingers *Alcyonium digitatum* followed by ross coral *Pentapora fascialis*. The most common taxa in the frame grabs were hydroids (grouped), which were present in 87.5% of the frames, followed by turf (hydroids and bryozoans < 1 cm), which was present in 75.5% of the frames. Other species observed included ballan wrasse *Labrus bergylta*, common cuttlefish *Sepia officinalis*, spiny spider crab *Maja squinado*, red gurnard *Aspitrigla cuculus*, bloody henry sea star *Henricia oculata,* edible crab *Cancer pagurus*, jewel anemone *Corynactis viridis*, and edible sea urchin *Echinus esculentus*. In the north of Big Russel where it is sandy we also observed flatfishes such as brill *Scophthalmus rhombus*.

The assemblage composition of benthic fauna in the Big Russel was highly variable. Locations were significantly different to each other for frame grab and video transect analyses ($P < 0.05$, Tables 1 and 2). Pairwise tests for the abundant/encrusting assemblage composition showed that Location A was not significantly different to any other Location. B and C were also not different to each other, suggesting that assemblages of the abundant and/encrusting fauna in the northern part of the channel were fairly similar. Conversely, locations in the southern end of the channel were significantly different to each other ($P < 0.05$) (Table 1) showing greater variability than in the northern end.

Table 2: (a) PERMANOVA to compare the infrequent/conspicuous species assemblage based on Bray Curtis similarities. Data were dispersion weighted and square root transformed. (b) Pairwise tests for Location. *P* values in bold type are significant.

(a)

Source	df	MS	Pseudo-F	*P* (perm)
Location Lo	4	5036.5	2.8667	**0.0006**
Area Ar(Lo)	12	1725.4	2.1951	**0.0001**
Site Si(Ar(Lo))	19	786.02	No test	
Total	35			

(b)

Location pairings	*P* (perm)
A and B	0.0565
A and C	**0.0146**
A and D	0.4946
A and E	0.2627
B and C	**0.0343**
B and D	**0.0298**
B and E	**0.0092**
C and D	**0.0145**
C and E	**0.0032**
D and E	0.0501

The assemblage composition of the infrequent/conspicuous fauna was also similarly significantly different between locations ($P < 0.05$) (Figure 3(a)).

The areas in each Location were not significantly different, showing that differences between species assemblages varied along the north east-south west gradient rather than between the sides of the channel. This has important implications for the future selection of control areas with regards to tidal energy impact assessment. Control areas will be best selected for across the channel rather than up or down stream of the devices.

Across all Locations in the Big Russel, the most abundant sessile taxa identified from the frame grab analysis were hydroids (grouped), turf, and unidentified sponges.

Prominent taxa in each location were red algae in Locations A, B, and C; bryozoan *Flustra foliacea* contributed towards the similarities between areas in Location B, keel-worm *Pomatoceros triqueter* in Location D, and the bryozoans *Cellepora pumicosa* and *Pentapora fascialis* in Location E.

From the video analysis, the most frequently observed taxa of the infrequent/conspicuous species in the Big Russel were the spiny sea star *Marthasterias glacialis* and the bloody henry sea star *Henricia oculata*, which contributed towards the similarities between areas in all locations. Varying abundances of dead man's fingers *Alcyonium digitatum* and the crabs; the spiny spider crab *Maja squinado*, the velvet swimming crab *Necora puber,* and the edible crab *Cancer pagurus* all contributed to differences along the north east-south west gradient between locations (Table 3).

Table 3: SIMPER analysis to determine the taxa whose abundance contributes most to the similarities seen between Locations for (a) abundant/encrusting and (b) infrequent/conspicuous.

(a)

Frames	Av. abund.	Contrib. percentage
Location A		
Grouped hydroids	0.63	16.19
Turf algae	0.65	14.62
Encrusting sponge 4	0.5	11.54
Red algae	0.42	10.97
Encrusting sponge 1	0.52	9.78
Encrusting sponge 2	0.48	7.76
Location B		
Grouped hydroids	0.93	20.14
Turf algae	0.68	13.2
Encrusting sponge 1	0.6	11.51
Red algae	0.61	11.02
Flustra foliacea	0.55	10.37
Encrusting algae 2	0.48	9.18
Location C		
Grouped hydroids	0.97	21.31
Turf algae	0.77	14.53
Red algae	0.48	9.26
Encrusting sponge 4	0.45	8.57
Encrusting sponge 1	0.46	7.5
Encrusting sponge 2	0.38	5.9
Location D		
Grouped hydroids	0.92	20.81
Turf algae	0.82	17.61
Pomatoceros triqueter	0.7	12.96
Encrusting sponge 2	0.52	8.31
Encrusting sponge 1	0.5	6.78
Nemertesia antennina	0.38	5.2
Location E		
Turf algae	0.8	16.76
Encrusting sponge 4	0.8	15.86
Hydroids (grouped)	0.73	15.15
Cellepora pumicosa	0.73	13.6
Encrusting sponge 1	0.7	12.53
Pentapora foliacea	0.67	11.85

(b)

Video transects	Av. abund.	Contrib. percentage
Location A		
Marthasterias glacialis	1.45	24.71
Alcyonium digitatum	0.8	13.37
Henricia oculata	0.81	9.7
Ammodytes tobianus	0.34	8.8
Pentapora foliacea	0.63	8.68
Cancer pagurus	0.52	6.22
Location B		
Marthasterias glacialis	1.66	17.76
Henricia oculata	1.55	13.8
Cliona celata	1.19	12.4

(b) Continued.

Video transects	Av. abund.	Contrib. percentage
Cancer pagurus	1.32	11.1
Ctenolabrus rupestris	1.21	10.92
Necora puber	1.05	8.37
Location C		
Marthasterias glacialis	1.93	15.88
Henricia oculata	1.72	15.04
Polymastia boletiformis	1.25	10
Alcyonium digitatum	1.15	8.81
Cancer pagurus	0.97	8.23
Branching sponge 1	1.05	8.05
Location D		
Marthasterias glacialis	1.18	18.36
Pentapora foliacea	1.39	14.06
Henricia oculata	1.01	13.35
Branching sponge 2	1.45	12.06
Polymastia boletiformis	1.1	8.88
Branching sponge 4	0.95	6.67
Location E		
Branching sponge 2	1.3	15.75
Marthasterias glacialis	1.41	15.59
Henricia oculata	0.99	11.54
Pentapora foliacea	1.04	10.41
Alcyonium digitatum	0.65	7.02
Maja squinado	0.78	5.85

Despite the PERMANOVA results indicating differences between both the abundant/encrusting fauna and the infrequent/conspicuous fauna, the nMDS ordinations suggested that the pattern was different between the two groups (Figure 3). A clear gradient can be seen for the infrequent/conspicuous fauna that shows distinct grouping for each location, with locations situated next to their geographical neighbour. There are no discernible patterns, however, for the common/encrusting fauna.

3.1. Habitats in the Big Russel. The dominant habitat types identified were rock and boulders and cobbles. Sand was the dominant habitat type in some frame grabs in the north of the channel and is therefore included as a dominant habitat type despite being relatively rare throughout the rest of the Big Russel.

The habitat type supporting the greatest abundance of taxa was rock (50 taxa), but the mean abundance of individuals was greatest on the boulders and cobbles (74.33 individuals site^{-1}). Frames dominated by sand were by comparison species poor (12 taxa and 11 individuals site^{-1}). Some taxa were found to dominate across all habitat types but their abundance was greater in frames where rock, boulders, or cobbles were present (Table 4).

Epifauna were only present in sandy habitats when the frame contained hard substrata. With the exception of the sand eel *Ammodytes tobianus* the species present in sandy habitats were those associated with rocky substrata.

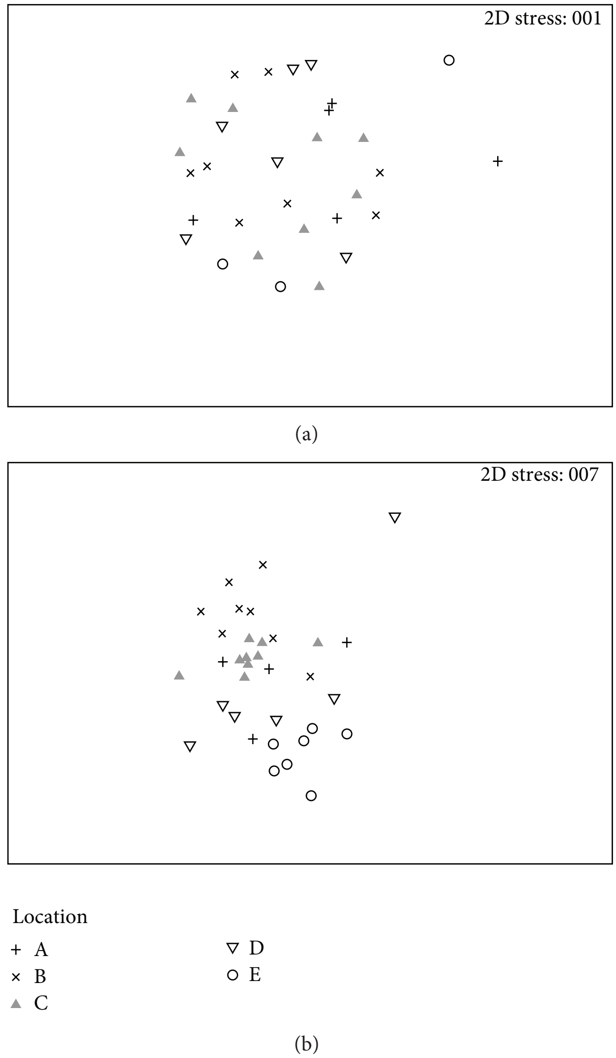

Figure 3: (a) nonmetric Multidimensional Scaling (nMDS) ordination of Bray-Curtis similarities of assemblage composition of the abundant/encrusting between Locations (A–E). (b) nMDS ordination of the Bray-Curtis similarities of assemblage composition of the infrequent/conspicuous fauna between Locations (A–E). Data were dispersion weighted and square root transformed.

The differences between species assemblage composition averaged over site from the frame grab data can be partially explained by habitat type. Sites where boulders and cobbles dominated the frames show some aggregation of species assemblage composition. Sites where rock dominated the frames also show similarities between species assemblage composition. Site 26 (Location A), which was dominated by rock and sand, was dissimilar to all other sites (black diamond on the left side of the ordination, Figure 4).

4. Discussion

The extent of the benthic features in the high tidal energy site, the Big Russell, was successfully recorded. Using the "flying array" a range of epifauna were enumerated from flatfishes

Table 4: The ten taxa from frame grab analysis with the greatest abundance where rock, boulders and cobbles, and sand were the dominant habitat type. Data are percentage of frames containing each taxa for each habitat type (%). Gravel and pebbles were excluded as they did not dominate the habitat in any frame.

Rock		Boulders and Cobbles		Sand	
Taxa	Percentage	Taxa	Percentage	Taxa	Percentage
Turf	72.17	Hydroids (grouped)	72.73	Hydroids (grouped)	20.00
Hydroids (grouped)	65.41	Turf	65.16	Red algae	20.00
Encrusting sponge 1	61.77	*Pomatoceros triqueter*	50.19	Encrusting sponge 4	15.00
Pomatoceros triqueter	51.77	Encrusting sponge 4	31.32	Turf	15.00
Encrusting sponge 2	50.10	*Flustra foliacea*	28.05	*Alcyonium digitatum*	5.00
Encrusting sponge 4	33.54	Encrusting sponge 1	26.40	*Ammodytes tobianus*	5.00
Encrusting sponge 3	33.33	Encrusting sponge 2	25.58	*Calliostoma zizyphinum*	5.00
Nemertesia antennina	30.00	*Nemertesia antennina*	24.63	*Dendrodoa grossularia*	5.00
Alcyonium digitatum	25.20	*Pentapora fascialis*	20.15	*Halecium halecinum*	5.00
Red algae	23.74	*Alcyonium digitatum*	19.71	*Nemertesia antennina*	5.00

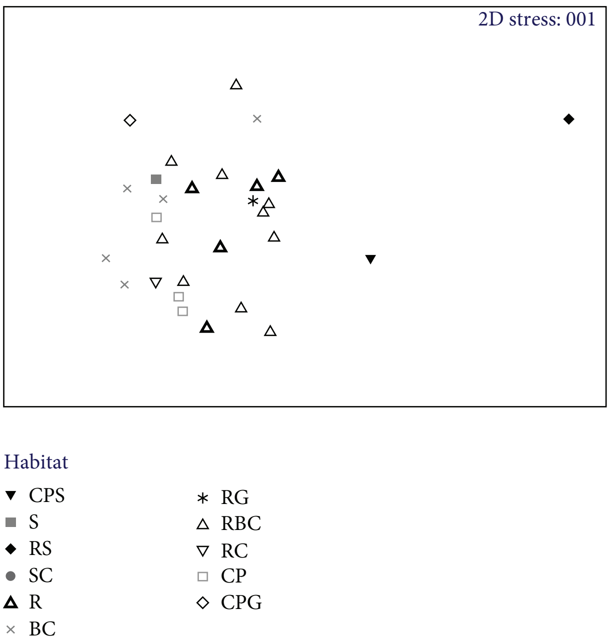

Figure 4: nonmetric Multidimensional Scaling (nMDS) ordination showing the similarities between abundant/encrusting species assemblages at different sites based on habitat type. Habitat type is the dominant type per tow calculated from the frame analysis (R (rock), B (boulders), C (cobbles), P (pebbles), G (gravel), and S (sand)).

on the sandy plains in the north of the channel to crustaceans and bryozoans on the heterogeneous reef habitat in the main channel. Overall, 74 epifaunal taxa were counted.

Areas which were composed entirely of bedrock were those with the greatest number of species. Cobbles and pebbles supported the second greatest abundance of species followed by boulders and cobbles. In the sandy habitat (e.g., Location A), although few mobile fauna such as flatfish were recorded, supplementary sampling would be required to fully assess the habitat as the greatest abundance of fauna in sedimentary habitats occurs below the surface, "infauna" [19], which the video does not sample. Quantification of infauna would require dredges or a grab to take physical samples [20].

Some taxa such as turf and hydroids were found to dominate across all hard substrate habitat types. Due to the tide swept environment, fauna associated with the hard habitat types were characterised by species such as encrusting sponges, dead man's fingers *Alcyonium digitatum*, ross coral *Pentapora fascialis,* and hornwrack *Flustra foliacea* which grow close to the substratum.

The Guernsey Regional Environmental Assessment (REA) identified that seagrass beds and maerl beds were the priority habitats for protection in Guernsey. Neither of which were identified during this study. Furthermore, no UK Biodiversity Action Plan (BAP) species have been identified here. It is important to note, however, that this method does not sample all benthic fauna. Species such as the BAP species cup coral *Leptopsammia pruvoti* are commonly found under overhangs and in small crevices [21] and are therefore not likely to be identified through a study using a towed camera that flies above the benthos.

Based on this survey, it is difficult to assess the implications of the placement of future tidal devices without knowledge of the type and size of the devices. Observations of the extremely heterogenous seabed comprising sandy patches, cobbles, boulders, and rocky pinnacles in an area known for extreme tides and waves suggest that the benthic faunal assemblages are already living in a diverse and hostile environment. Deployment of devices in the north where there are sandy patches would introduce additional hard habitat for epifauna to colonise [22]. Construction throughout the channel may cause localised disturbance to fauna, but ultimately, devices are likely to act as artificial reefs like other anthropogenic structures [23–25] providing increased habitat complexity that benthic mobile fauna such as crustaceans could use as a refuge [26] and fishes may use to escape tidal currents in this high energy environment. The risks associated with the devices such as collision are not likely to affect those benthic organisms discussed here, but should be considered for larger pelagic species [27].

Deployment of marine renewable devices not only introduces impacts to the benthos but is also known to relieve other human impacts such as the effects of trawling and dredging [5, 9, 28, 29]. However, after observing the seabed in the Big Russel it was clear that fishing using static gear, in particular pots, was most common rather than the use of more destructive towed gears. The rocky pinnacles and reefs that were observed provide the perfect complex habitat for benthic fauna but would certainly snag and break most towed fishing gears.

Location E had been suggested as a potential control area away from the likely area for tidal development by the Guernsey Renewable Energy Team. The assemblage of organisms found in Location E was statistically different to all the other Locations and so it would not be comparable to locations in the main channel. Despite the PERMANOVA results indicating differences between both the abundant/encrusting fauna and the infrequent/conspicuous fauna, the nMDS ordinations suggested that the pattern was different between the two groups. A clear latitudinal gradient was seen for the infrequent/conspicuous fauna that shows distinct grouping within each location, which are separated and situated next to their geographical neighbour on the nMDS. There were no discernible patterns, however, for the common/encrusting fauna. Unlike the infrequent/conspicuous taxa, and as a result of using flying HD video, many of the abundant/encrusting taxa could not be identified to species. For example, "turf," "hydroids," and "sponges" and so any potential existing differences that may exist at the species level through the channel may not occur at the observed lower level of taxonomic resolution. To resolve this problem, future analyses may be best combined across video analysis methods to give an estimate of overall assemblage. Future impact assessments can also use this study to preselect a subset of indicator species that represent the response of different groups of organisms that share life history traits [30]. An example of a life history trait could be "Recoverability from disturbance" where dead man's fingers *Alcyonium digitatum* could be used as an indicator species for those with "Low recoverability," edible crabs *Cancer pagurus* have "Medium recoverability," and the great scallop *Pecten maximus* are quick to recover from disturbance and so represent species with relatively "High recoverability" [30].

The species assemblage changed over the latitudinal gradient, and so depending on the location of future developments, the most suitable, comparable un-impacted controls would likely be found in a similar latitude to the development.

This study has provided a baseline assessment of the epibenthos of the Big Russel. The results can be used to inform the optimal siting of future tidal energy devices in the channel and as a baseline for future impact assessment.

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Research Article

An Adaptive Framework for Selecting Environmental Monitoring Protocols to Support Ocean Renewable Energy Development

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Offshore renewable energy developments (OREDs) are projected to become common in the United States over the next two decades. There are both a need and an opportunity to guide efforts to identify and track impacts to the marine ecosystem resulting from these installations. A monitoring framework and standardized protocols that can be applied to multiple types of ORED would streamline scientific study, management, and permitting at these sites. We propose an adaptive and reactive framework based on indicators of the likely changes to the marine ecosystem due to ORED. We developed decision trees to identify suites of impacts at two scales (demonstration and commercial) depending on energy (wind, tidal, and wave), structure (e.g., turbine), and foundation type (e.g., monopile). Impacts were categorized by ecosystem component (benthic habitat and resources, fish and fisheries, avian species, marine mammals, and sea turtles) and monitoring objectives were developed for each. We present a case study at a commercial-scale wind farm and develop a monitoring plan for this development that addresses both local and national environmental concerns. In addition, framework has provided a starting point for identifying global research needs and objectives for understanding of the potential effects of ORED on the marine environment.

1. Introduction

At present, there is a great need to better understand the potential effects of offshore renewable energy developments (ORED) on the marine environment [1–3]. While the development of commercial-scale ORED in the United States has lagged well behind development in Europe [4], construction on multiple projects is likely to begin within the next few years in U.S. waters [5]. Because of differences between Europe and the U.S. in terms of regulatory requirements, environmental settings, and species present at development sites [6], there is a considerable need for U.S.-specific guidance to ensure thorough data collection as ORED projects develop to evaluate effects and assess potential impacts. In this paper, we use the word "effect" to refer to a change in the environment without respect to magnitude or direction (i.e., moderate or severe, positive or negative [1]). When the effect is better characterized and a magnitude and direction can be assigned, we refer to it as an "impact." A scientific framework exists for detecting and characterizing effects, but more work is needed in order to describe and assess impacts [1].

Data collection at ORED sites should be guided by a framework that identifies the unique impacts associated with ORED [7], then selects and helps implement a suite of standardized environmental monitoring protocols relevant to each development type. Standardized protocols improve impact assessment by following a single methodology at multiple sites, permitting comparison and aggregation of data [8]. Building a uniform database of environmental impacts will allow us to better refine our understanding of drivers and stressors acting at ORED sites, improve the Environmental Impact Statement (EIS) process, and refine monitoring requirements in the future as certain impacts are suggested to be either negligible or worthy of concern. This knowledge can be used to encourage development in areas where known impacts are expected to be minimal. In addition, reducing the existing uncertainty about environmental impacts related to ORED will likely ease public concern about development and therefore improve the siting process. Such a framework should also assist in answering regulatory questions about siting and scale by ensuring that relevant data are collected, therefore reducing uncertainty in decision making.

Monitoring an effect or an impact means that the monitoring protocol must be designed to measure change against some baseline condition or management objective [9, 10]. This change may be measured temporally, as in between seasons or years, before and after construction, or spatially, including measuring differences between an affected and a control area. Designing a study that can both provide conclusive evidence of an impact (or lack thereof) and separate this impact from the noise of seasonal or interannual environmental variability can be problematic [11]. Furthermore, not all of the potential impacts will be directly observable. For example, observations of underwater ORED structures will not likely be continuous. Therefore, in order to determine if a foundation has an impact on seabed structure, for example, discrete measurements of seabed volume will be made and compared through time. In this example, measured changes in seabed volume serve as a representative of the impact of the foundation on the seabed and in this way are considered to be an indicator of that impact. In general, indicators can be used as a means to quantitatively track change in the context of ecosystem-based management goals [12–14]. Developing indicators of change at ORED sites would be immensely helpful to impact assessments and, if developed across disciplines (e.g., biology, geology, physical oceanography), enable an overall assessment of the condition of the ecosystem. Building support for an indicator as a representative of an ecosystem attribute or function is an iterative process that can be conducted as monitoring data are collected at ORED sites. At first, where few data exist, qualitative "reference directions" can be used to track change [10]. As a database is built, changes can be quantified and thresholds can be identified relative to impacts at particular developments. In rare cases where the natural variability of a parameter has already been characterized, statistical tools may be used to determine appropriate thresholds or even the sampling protocols themselves (e.g., power analyses [15–17]). In most cases, however, very little is known about natural variability and environmental monitoring efforts will be measuring natural change commingled with the effects of ORED. A monitoring framework that considers all of these concerns is essential.

To address these concerns, an adaptive, rather than a static, monitoring framework for ORED is most appropriate. Firstly, there are many points of weakness in the general understanding of the impacts of ORED on marine resources that could greatly change monitoring needs and/or requirements. For example, the impacts of indirect effects (e.g., alteration to food webs) and wholly unanticipated effects are unknown [1]. Data regarding these points may only become available at a later stage of ORED maturity, but current monitoring protocols and regulations should be prepared in anticipation of these types of effects. Next is the current understanding of linkages between effects and indicators. We can agree conceptually that certain environmental/biological parameters are indicative of an ecosystem change, but in many cases we have no estimate of thresholds of concern for these parameters (e.g., how much of a reduction can occur in a bird population before mitigation needs to take place?). Just as experience in ecosystem-based fisheries management has helped propose appropriate thresholds for indicators of fisheries status [9], experience in managing OREDs will help clarify the assumptions made between effects and indicators. An adaptive framework is also essential in a field where new technologies are developing and emerging at a rapid pace.

In this paper we propose an adaptive monitoring framework based on indicators of the likely changes to the ecosystem due to ORED. We developed the framework to be used by offshore renewable energy developers and U.S. management and regulatory agencies in order to standardize the design and methodologies used to collect data at ORED sites. The framework and protocols were developed to be scientifically valid and easy to understand and follow by nonscientists. In order to do so, we reduced the complexity of impact assessment by developing decision-support tools that guide users towards monitoring objectives. As scientists, we were challenged with the task of maintaining scientific rigor in the framework while simultaneously acknowledging the pressures on management and regulatory agencies to encourage developments and keep costs low. The resulting framework is adaptive, flexible and can be implemented at any ORED site in U.S. waters.

2. Methods

Offshore renewable energy development is here defined as the construction and operation of one or more devices designed to harness power from the marine environment (wind, tidal, and wave power considered here) and includes any necessary infrastructure, including subsea cables, the vessels necessary to construct or install an ORED, and the footprint of a project. This paper considers the effects of ORED on the benthic habitat and resources, marine mammals, sea turtles, fish, and avian species. We also considered the effect of ORED on one human use—fishing activity—because of the inextricability of the effects on fishing activity from effects on fish themselves, and the resulting concerns of fishermen about potential effects on their livelihood. We examined renewable energy developments at two scales, 1 = "demonstration" and 2 = "commercial/multiple commercial." At Scale 1, three or fewer devices are part of a "farm"; Scale 2 constitutes a farm or farms of around 100 devices and greater.

A literature review was conducted of potential positive and negative environmental effects (see Appendix A, supplementary material available online at doi:10.1100/2012/450685 for works cited) using the Programmatic Environmental Impact Statement (PEIS) for Alternative Energy Development developed by the Minerals Management Service in 2007 as a reference point [18]. Potential impacts were categorized by the five affected ecosystem components, the anticipated level of effect (minor, moderate, major), and the level of certainty (high, medium, low) at each scale of development and for each technology type within an ORED "impact matrix" (Supplementary Appendix B). The descriptions and thresholds for impact levels were derived from the definitions used in the PEIS [18]: minor—should not influence or have only small impacts on the affected resource, activity, or community; moderate—impacts could moderately influence the resource, activity, or community, generally or for particular species; major—impacts could significantly influence the resource, activity, or community, generally or for particular species. Here, we used the word "certainty" to refer to the amount of evidence available from studies conducted on a particular effect. High certainty indicates that there was a large body of literature documenting or studying an impact. It is important to note that "certainty" does not refer to the chance that an impact will occur. The chance of an impact occurring is more appropriately described as likelihood, a concept that was not addressed in this study. Therefore, where we describe an effect with a high certainty of major impact, this can be interpreted as "*if* the named effect occurs, *then* the magnitude of the impact on environment will be major."

Suites of similar potential impacts were aggregated by energy resource, foundation type, and scale of development in order to define "Impact scenarios." An Impact scenario is applicable to multiple development situations in order to distill and focus the monitoring and management actions required for ORED. Impact scenarios describe the major and moderate negative impacts of ORED on five ecosystem components—benthic habitat and resources, marine mammals, sea turtles, fish, and avian species.

We developed two types of decision trees to serve as decision-support tools, to help users determine which impacts are relevant when their development criteria are implemented, and to evaluate alternatives. The first decision tree, the "Impact decision tree," determines the approximate magnitude of impacts from ORED on each ecosystem component considering three factors—energy type, foundation type, and development scale. The second type, "Component decision trees," is a suite of finer-scale decision trees for each of the ecosystem components that determine which monitoring protocols are recommended given a more specific suite of characteristics related to the development type (e.g., stage of development). We took this approach because each ecosystem component experiences different levels of impact due to different drivers. For example, different foundation types would differentiate several types of effect for benthic habitat and resources but are not likely to do the same for avian species.

A chart-based/graphic format was rejected in favor of a text-based/key format. In the adopted format, the user answers a series of questions about the development project and is guided through the decision tree and toward an eventual "answer" based on the responses to the questions. For the Impact decision tree, the "answer" is an Impact scenario, an associated list of the ecosystem components that may experience major and moderate negative (i.e., adverse) impacts from ORED, a short description of the type of impacts, and an estimate of the certainty regarding these impacts. For each scenario, the lists of major negative potential impacts were ranked by proportion and magnitude of total impacts so that #1 reflects the component with the most negative impacts. To provide more detail on potential adverse impacts, all moderate impacts and levels of certainty are also provided for each scenario. The lists of moderate impacts are not prioritized or ranked and are listed as they appeared in the impact matrix (Supplementary Appendix B).

For the Component decision trees, the "answer" is a list of monitoring objectives. At the University of Rhode Island we have developed a series of monitoring protocols to address each of these objectives. We also developed a case study in order to demonstrate how a manager or regulator may use these tools to develop an ORED monitoring plan. The case study consists of a Scale 2 wind-turbine farm composed of around 200 jacketed structures. We describe the resulting Impact scenario and list the major and moderate impacts that monitoring should address. To demonstrate the next step, we present an example monitoring protocol that addresses monitoring of benthic habitat and resources.

3. Results

From the renewable energy impact matrix, literature review, and expert judgment, we assembled a short list of the potential effects for each ecosystem component considered to be of greatest importance. For each effect, we propose an indicator that is recommended for use as a monitoring target (Table 1).

3.1. The Monitoring Framework. We developed an adaptive and reactive monitoring framework that incorporates the use of environmental indicators to track change (Figure 1). Currently, we have the ability to characterize a baseline condition and assign reference directions to indicators; for example, increases in sediment grain size at every turbine should accelerate monitoring for scour. Reference directions are useful when data are insufficient to establish more quantitative reference levels, but they only provide an indication of a trend and do not specify when a threshold of irreversible harm has been reached [10]. In an adaptive monitoring framework, data are synthesized to produce more quantitative metrics and thresholds for environmental indicators of ORED effects. In a reactive monitoring framework, evidence of an effect should be used to accelerate study of that effect, perhaps by multiple methodologies (refer to Figure 1). Suites of ORED effect indicators would not only provide a clearer

Table 1: Potential effects of offshore renewable energy developments in the United States considered to be of greatest importance based on results of a literature review and expert judgment (see Supplementary Appendix A). Effects are organized by ecosystem component and are paired with a proposed indicator of that effect.

	Impact/monitoring objective	Indicator
Benthic habitat and resources	Changes to seafloor morphology and structure (compared to preconstruction)	Increase or decrease in seabed volume
	Changes in median grain size, or organic content	(i) Deposition: decrease in median grain size, increase in organic content, increase in seabed volume (ii) Scour: increase in median grain size, decrease in organic content, decrease in seabed volume
	Turbidity during construction/decommissioning	Change in water column turbidity
	Change in target species abundance and distribution (e.g., species of importance)	Change in abundance, diversity, % cover, multivariate community composition
	Current speed/direction inside and outside farm	Change in residual flow rates
	Reef effects, colonization on foundations	Increase in % cover, biomass of epifaunal organisms; increase in presence of nonnative species
	Change in density, diversity, dominance structure of infauna	Change in abundance, diversity, % cover, multivariate community composition
Fish	Reef or aggregation effects	Increase in fish abundance around devices, shift in species composition, increase in presence of nonnative species
	Changes to abundance/distribution caused by disturbance or habitat alteration	Increase or decrease in fish abundance; increase or decrease in target species; shift in species composition; change in density, diversity, and dominance structure of fish species; increase in presence of nonnative species
	Blade strikes/pressure gradients (tidal power)	Observation of blade strike incidents
	EMF effects	Not feasible to monitor directly—changes in fish abundance, behavior, or species composition are indicators
	Installation or operational noise effects	Not feasible to monitor directly—changes in fish abundance, behavior, or species composition are indicators
Fisheries	Catchability (catch per unit effort) during construction	Catch per unit effort increases or decreases for target species
	Catchability (catch per unit effort) during operation	Catch per unit effort increases or decreases for target species
	Loss of access to grounds	Changes in numbers of vessels fishing near or inside of the renewable energy area, change in the presence of fixed fishing gear inside of or around a renewable energy installation
	Changes in species distribution	Shift in species composition, increase in presence of nonnative species
	Reef effects (aggregation)	Increase in fish abundance around devices; shift in species composition; increase in presence of nonnative species
Avian	Displacement/attraction	Increase or decrease in avian species-specific densities postconstruction in development area
	Barrier effects—effects on foraging, roosting, migratory movements	Migrating or commuting birds avoiding developed areas
	Collision mortality	Birds found dead or injured due to direct collision with infrastructure above the water
Marine mammals and sea turtles	Vessel strikes	Detection of dead or injured animals
	Noise generated during construction	Detection of dead or injured animals; changes in distribution, abundance, or behavior of populations
	Disturbance or injury during all stages of development, including from vessels	Detection of dead or injured animals; changes in distribution, abundance, or behavior of populations
	Noise generated during operation	Changes in distribution, abundance, or behavior of populations

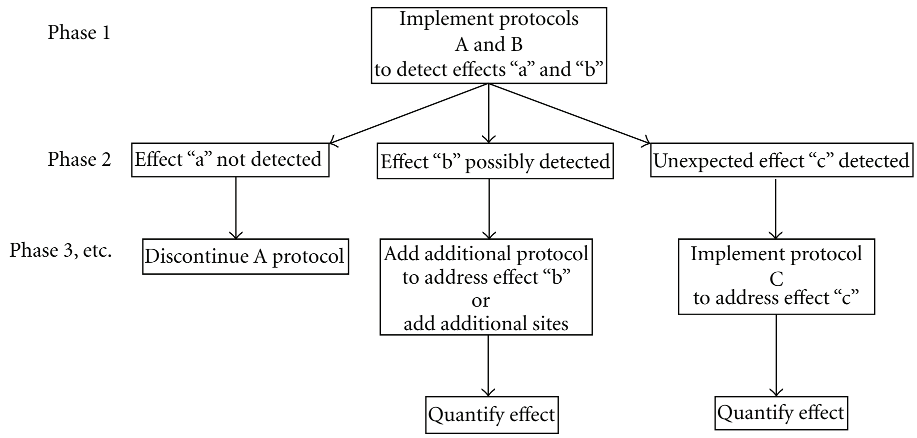


Figure 1: Proposed adaptive and reactive monitoring framework.

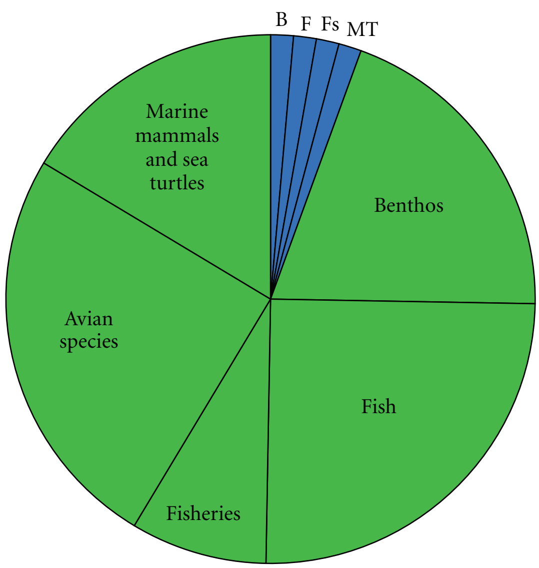


Figure 2: Pie chart representing the proportion of impacts for each ecosystem component for Impact scenario i1, demonstration-scale projects, categorized by whether the effect is positive (blue), minor negative (green), moderate negative (yellow), or major negative (red). B = Benthic habitat and resources; F = Fish; Fs = Fisheries; A = Avian species; MT = Marine mammals and sea turtles.

path for goal setting for developers but would encourage regulatory monitoring protocols to contribute to our general understanding of the natural variation of marine ecosystems and how human activities can be integrated and harmonized.

3.2. Impact Decision Tree. The Impact decision tree determines the approximate magnitude of impacts from ORED on each ecosystem component for a broad range of development types and scenarios. For each combination, a bar graph shows the relative number of potential impacts and their magnitudes (Table 2). Even though there are 39 possible scenarios that result when combining the three factors, our decision tree reduces these to six main Impact scenarios.

3.3. Impact Scenarios. Impact scenarios are very brief descriptions of the major environmental concerns regarding categories of ORED with similar environmental impacts. Below, the Impact scenarios are accompanied by pie charts representing the total number of impacts for each scenario, categorized by whether the impact is positive (blue), minor negative (green), moderate negative (yellow), or major negative (red). Each of these sections of the pie is further broken down by ecosystem component.

(i1) All Demonstration Scale Projects (Figure 2, Table 3). These projects are described as "Scale 1". The current literature suggests that any renewable energy development, if completed at the demonstration scale, will not have moderate or major impacts on the ecosystem components examined here. Therefore, we list the potential minor impacts and their certainty in the Impact decision tree. Of the suite of minor impacts, benthic habitat and resources, avian species, and fish species share an equally high proportion. Across ecosystem components, impacts with the highest certainty tend to be physical and chemical disturbances, such as disturbance from device installation, attraction to devices, or chemical spills. Impacts with low certainty include noise (except for marine mammals and sea turtles where the certainty for this impact is high), changes to energy regimes, and changes in organism energetic expense. Electromagnetic field (EMF) impact is the only impact that has low certainty consistently across all ecosystem components. Only those potential impacts with high certainty are listed in the decision tree; where certainty is low, it may be impossible to detect any impact at this magnitude.

(i2) Wind Turbine Developments Involving Pile Driving (Figure 3, Table 4). This scenario includes monopile wind turbine developments and jacketed- or tripod-mounted turbines at development Scale 2. If the proposed development will not utilize pile driving to install the jacketed or tripod structures, then Impact scenario i3 is more appropriate. The impacts that make this scenario unique are the presence of turbines above the water surface, the piles drilled into the seabed, and the noise associated with this activity. Therefore,

Table 2: The impact decision tree. Each step of the key is followed until an Impact scenario is reached, denoted by "i#". A bar graph is shown with each Impact scenario displaying the proportion of impacts, color-coded by direction (positive or negative) and magnitude (none, minor, moderate major). Data is derived from the literature review (Supplementary Appendix A) and renewable energy impact matrix (Supplementary Appendix B).

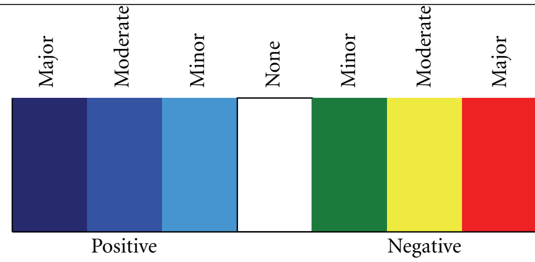
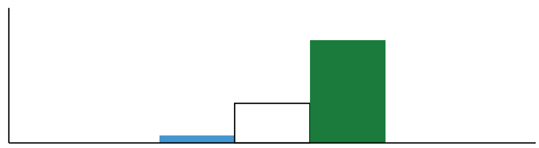
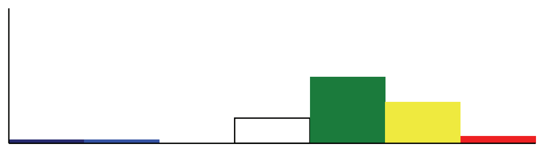
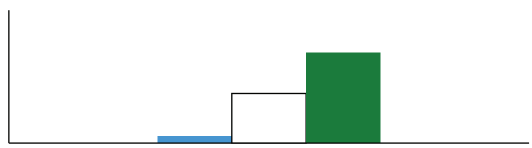
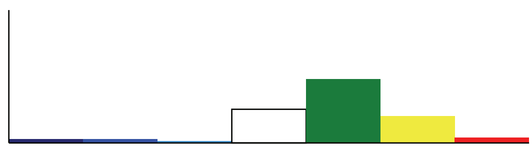
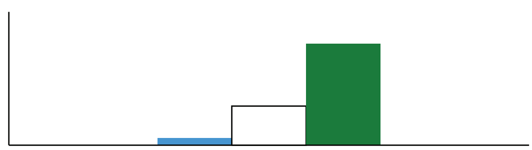
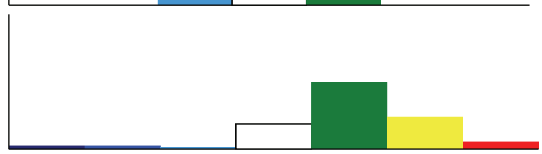
Determine which ecosystem components may experience impacts from renewable energy development:		
The energy resource is		
Wind		Go to A
Tidal		Go to B
Waves		Go to C
(A) The wind turbine foundation is		
Monopile		Go to A1
Gravity		Go to A2
Tripod/lattice		Go to A3
Floating mooring		Go to A4
(A1) The monopile wind turbine project scale is		
Demonstration	Go to i1	
Commercial/multiple commercial	Go to i2	
(A2) The gravity wind turbine project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i3	
(A3) The tripod/lattice wind turbine project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i2	
(A4) The floating mooring wind project scale is		

Table 2: Continued.

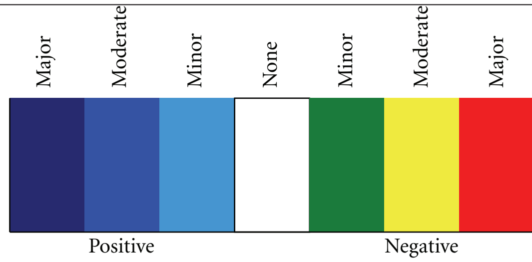
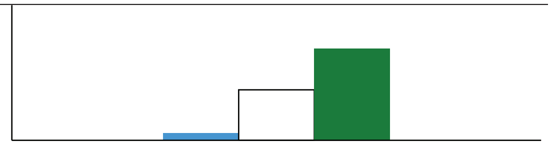
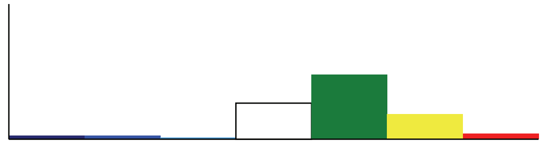
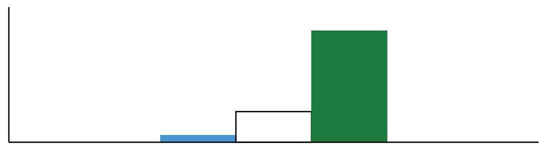
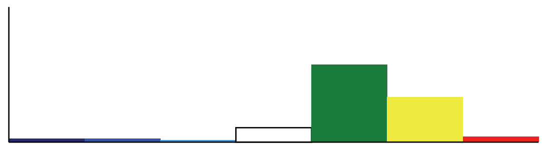
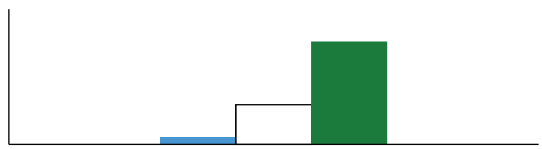
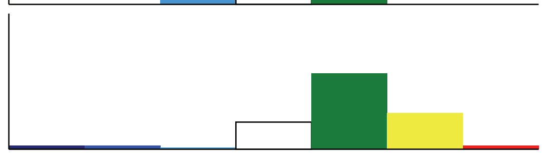
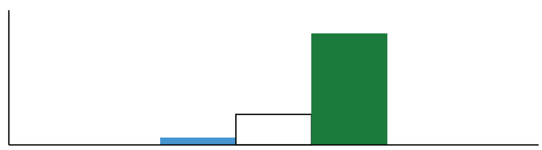
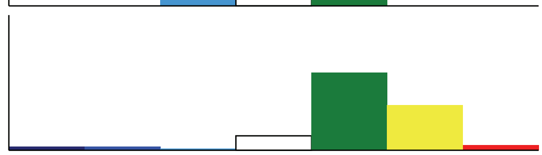
Determine which ecosystem components may experience impacts from renewable energy development:		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i3	
(B) The tidal turbine type is		
Open, bottom mounted		Go to B1
Open, floating mooring		Go to B2
Shrouded, bottom mounted		Go to B3
Shrouded, floating mooring		Go to B4
(B1) The open rotor, bottom-mounted tidal turbine project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i4	
(B2) The open rotor, floating mooring tidal turbine project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i5	
(B3) The shrouded rotor, bottom-mounted tidal turbine project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i4	

Table 2: Continued.

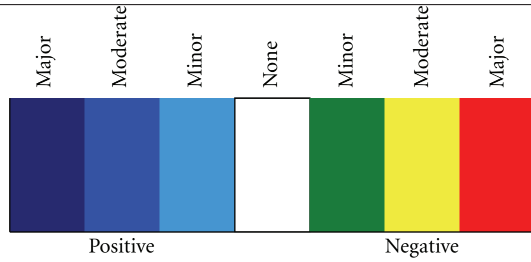
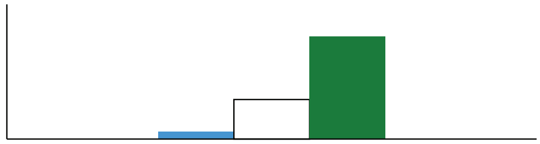
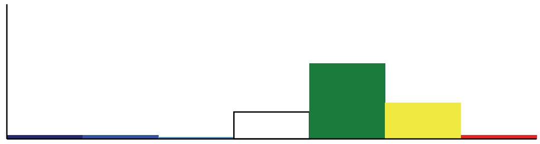
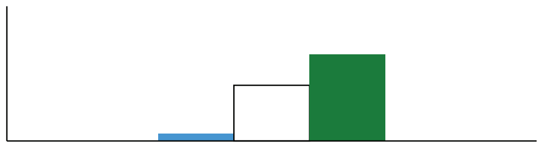
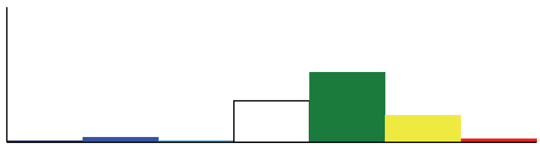
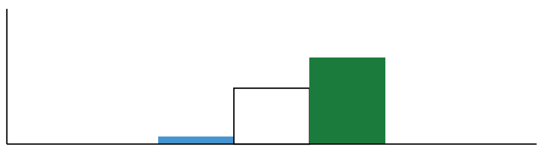
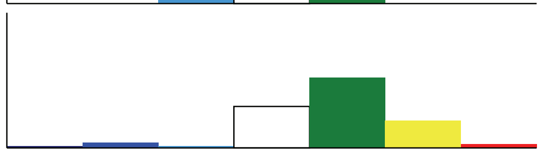
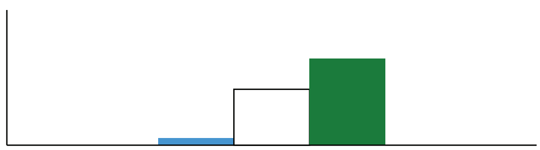
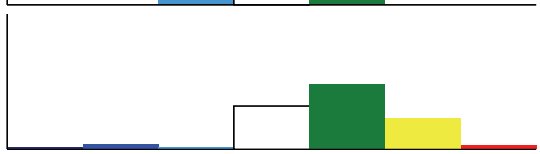
Determine which ecosystem components may experience impacts from renewable energy development:		
(B4) The shrouded rotor, floating mooring tidal turbine project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i5	
(C) The wave device type is		
Point absorber		Go to C1
Wave attenuator		Go to C2
Oscillating water column		Go to C3
Oscillating wave surge converter		Go to C4
Overtopping		Go to C5
(C1) The point absorber project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i6	
(C2) The wave attenuator project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i6	
(C3) The oscillating water column device project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i6	

Table 2: Continued.

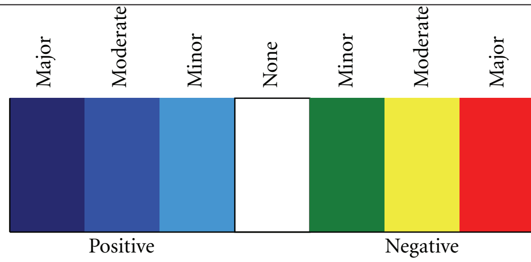
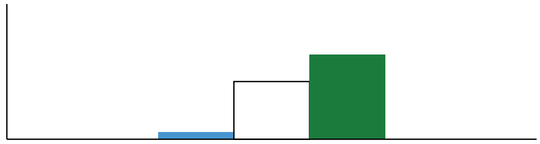
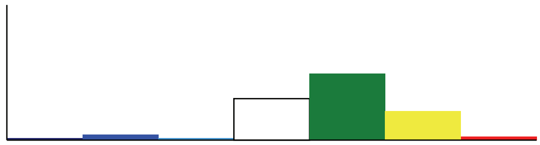
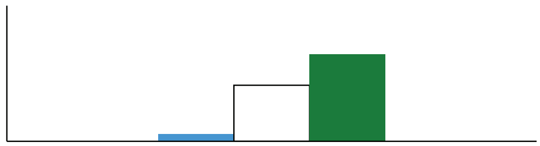
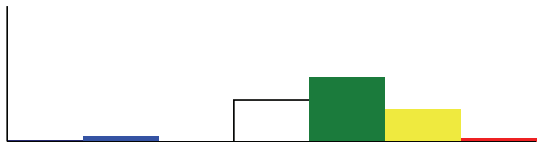
Determine which ecosystem components may experience impacts from renewable energy development:		
(C4) The oscillating wave surge converter project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i6	
(C5) The overtopping device project scale is		
Demonstration	Go to i1	
Commercial/Multiple commercial	Go to i6	

Table 3: A description of the potential impacts resulting from demonstration scale projects. See text, Section 3.3, for a narrative summary of this development scenario. Minor impacts are listed in the order they appear in the renewable energy impact matrix.

(i1) Demonstration scale projects		
Component (not ranked)	Minor impact	Certainty
Benthic habitat and resources	(i) Disturbance from installation/removal of device (including turbidity)	(i) High
	(ii) Disturbance from installation or removal of power cable (including trenching)	(ii) High
	(iii) Scour around structures	(iii) High
	(iv) Smothering by excavated sediments	(iv) High
	(v) Reef effects	(v) High
	(vi) Diffusion/flaking of marine coating	(vi) High
	(vii) Chemicals discharged during installation or removal	(vii) High
	(viii) Resuspension of pollutants in sediments	(viii) High
Fish species and fishing activity	(i) Disturbance from installation or removal of device	(i) High
	(ii) Disturbance from installation or removal or power cable	(ii) High
	(iii) Reef effects	(iii) High
	(iv) Loss of access to grounds during construction	(iv) High
	(v) Loss of access to grounds during operation	(v) High
Avian species	(i) Displacement or attraction to structure above surface of the water (wind turbines)	(i) High
	(ii) Displacement or attraction to structure below the surface of the water	(ii) High
	(iii) Disturbance from installation of device or transmission cable	(iii) High
	(iv) Collision with rotating turbine blades	(iv) High

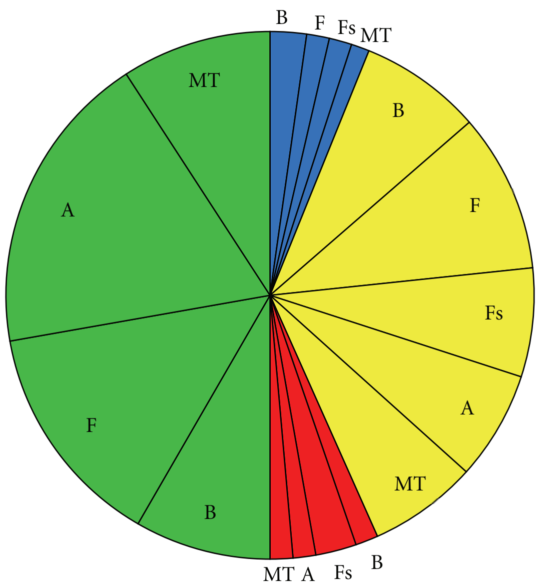


Figure 3: Pie chart representing the proportion of impacts for each ecosystem component for Impact scenario i2, wind turbine projects involving pile driving, categorized by whether the effect is positive (blue), minor negative (green), moderate negative (yellow), or major negative (red). B = Benthic habitat and resources; F = Fish; Fs = Fisheries; A = Avian species; MT = Marine mammals and sea turtles.

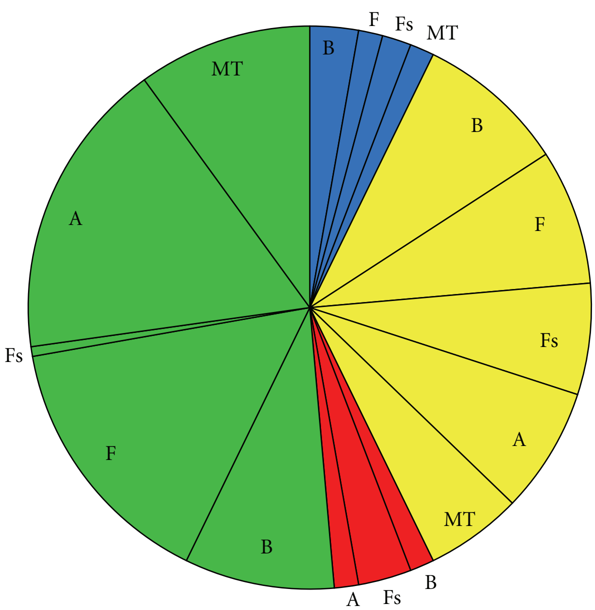


Figure 4: Pie chart representing the proportion of impacts for each ecosystem component for Impact scenario i3, wind turbine project involving no pile driving, categorized by whether the effect is positive (blue), minor negative (green), moderate negative (yellow), or major negative (red). B = Benthic habitat and resources; F = Fish; Fs = Fisheries; A = Avian species; MT = Marine mammals and sea turtles.

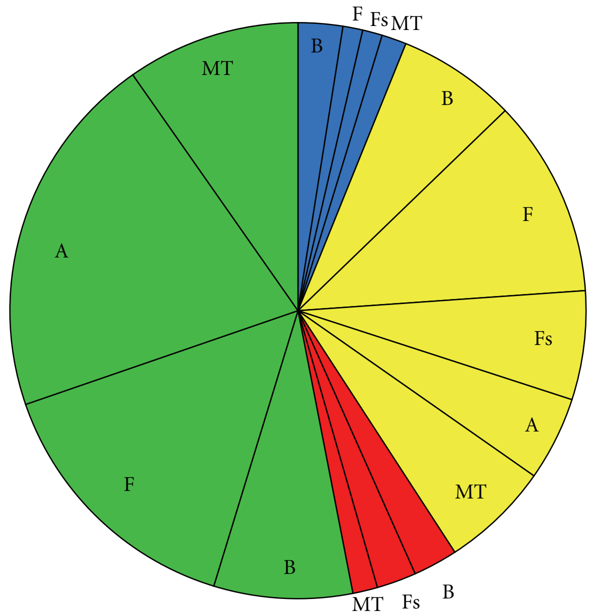


Figure 5: Pie chart representing the proportion of impacts for each ecosystem component for Impact scenario i4, bottom-mounted tidal turbine projects, categorized by whether the effect is positive (blue), minor negative (green), moderate negative (yellow), or major negative (red). B = Benthic habitat and resources; F = Fish; Fs = Fisheries; A = Avian species; MT = Marine mammals and sea turtles.

the expected major impacts include noise, scour and/or deposition around the structures, displacement or attraction to structures, and loss of access to mobile-gear fishing grounds. Notable moderate impacts include resuspension of pollutants, loss of access to recreational and fixed gear fishing grounds, decreased catchability (fisheries), damaged/lost fishing gear, and collisions and strikes for avian species, marine mammals, and sea turtles. Reef effects are likely for benthic habitat and resources and fish species at these developments.

(i3) Wind Turbine Developments Involving No Pile Driving (Figure 4, Table 5). Floating mooring or gravity-base foundations present a different suite of impacts for wind turbine developments at Scale 2. A major impact in scenario i2—noise during construction—is now absent. The suite of remaining negative impacts for each ecosystem component is very similar to i2, with the exception of benthic habitat and resources. Gravity-base foundations incur a moderate negative impact through physical disturbance to the sediment, where in i2 this impact is classified as minor. Reef effects are likely for benthic habitat and resources and fish species at these developments.

(i4) Bottom-Mounted Tidal Turbine Projects (Figure 5, Table 6). For tidal turbine developments, the profile of impacts tended to differ more based on the foundation type than on whether the rotor is shrouded or open.

Table 4: A description of the potential impacts resulting from wind turbine projects involving pile driving. See text, Section 3.3, for a narrative summary of this development scenario. Ecosystem components are ranked by their proportion of the major impacts. Moderate impacts are listed in the order they appear in the renewable energy impact matrix.

(i2) Wind turbines involving pile driving		
Priority	Major impacts	Certainty
(1) Fish species and fishing activity	Loss of access to grounds during construction and operation (mobile gear)	High
(2) Avian species*	Displacement or attraction to structure above water surface	High
(3) Benthic habitat and resources	Scour and/or deposition	High
(4) Marine mammals and sea turtles*	Noise from pile driving	Medium
Component	Moderate impacts	Certainty
Benthic habitat and resources	(i) Resuspension of pollutants in sediments	(i) High
	(ii) Chemical spills, discharge	(ii) Medium
	(iii) Disturbance from installation of cable	(iii) Medium
	(iv) Changes to current/wave regime	(iv) Medium
Fish species and fishing activity	(i) Chemical spills	(i) Medium
	(ii) Operational noise	(ii) Medium
	(iii) Noise from preconstruction seismic surveys	(iii) Medium
	(iv) Noise from pile driving	(iv) Medium
	(v) Noise from pile cutting during device removal	(v) Medium
	(vi) EMF	(vi) Low
	(vii) Habitat/community composition alteration	(vii) Medium
	(viii) Decreased catchability during construction and operation	(viii) Medium
	(ix) Loss of access to grounds during construction and operation (fixed gear and recreational)	(ix) High
	(x) Changes in species distribution	(x) Low
	(xi) Damaged/lost gear	(xi) High
Avian species	(i) Displacement or attraction to structure below water surface	(i) Medium
	(ii) Collision with rotating turbine blades	(ii) High
	(iii) Pressure gradients around rotor	(iii) Medium
	(iv) Leakage of lubricants/fluids, release of maintenance chemicals	(iv) Medium
	(v) Large chemical spills	(v) High
Marine mammals and sea turtles	(i) Entanglement with mooring lines or cables	(i) Medium
	(ii) Strikes with installation or support vessels	(ii) High
	(iii) Operational noise	(iii) Medium
	(iv) Noise from pile cutting during device removal	(iv) High

*Denotes that higher priority may be given to this component due to national/regional/local regulatory objectives and obligation.

Potential major impacts at these developments include changes to hydrodynamics, scour and/or deposition around devices/moorings, loss of access to mobile-gear fishing grounds, and noise from pile driving. If the proposed development will not utilize pile driving to install the tidal turbines, then Impact scenario i5 is more appropriate. Notable moderate impacts include physical disturbance to the sediment; collisions/strikes to rotor blades for fish species, avian species, marine mammals, and sea turtles; the effects of rotor wake/pressure gradients to fish and avian species; collisions/strikes with construction or support vehicles for marine mammals and sea turtles; decreased catchability and damaged/lost gear for fisheries.

(i5) Floating Mooring Tidal Turbine Projects (Figure 6, Table 7). Floating mooring foundations present a different suite of impacts for tidal turbine developments at Scale 2. A major impact in scenario i4—noise during construction—is now absent. The suite of remaining negative impacts for each ecosystem component is very similar to i4 with exceptions for benthic habitat and resources and fisheries. The impacts from sediment disturbance in this scenario are downgraded to minor, as are the impacts surrounding decreased catchability.

(i6) Wave Energy Projects (Figure 7, Table 8). In general, wave energy developments are not as well studied as tidal

Table 5: A description of the potential impacts resulting from wind turbine projects involving no pile driving. See text, Section 3.3, for a narrative summary of this development scenario. Ecosystem components are ranked by their proportion of the major impacts. Moderate impacts are listed in the order they appear in the renewable energy impact matrix.

(i3) Wind turbines involving no pile driving		
Priority	Major impacts	Certainty
(1) Fish species and fishing activity	Loss of access to grounds during construction and operation (mobile gear)	High
(2) Avian species*	Displacement or attraction to structure above water surface	High
(3) Benthic habitat and resources	Scour and/or deposition	High
Component	Moderate impacts	Certainty
Benthic habitat and resources	(i) Resuspension of pollutants in sediments	(i) High
	(ii) Disturbance from installation/removal of device (turbidity)	(ii) Medium
	(iii) Chemical spills, discharge	(iii) Medium
	(iv) Disturbance from installation of cable	(iv) Medium
	(v) Changes to current/wave regime	(v) Medium
Fish species and fishing activity	(i) Chemical spills	(i) Medium
	(ii) Operational noise	(ii) Medium
	(iii) Noise from pre-construction seismic surveys	(iii) Medium
	(iv) Noise from pile cutting during device removal	(iv) Medium
	(v) EMF	(v) Low
	(vi) Habitat/community composition alteration	(vi) Medium
	(vii) Decreased catchability during construction and operation	(vii) Medium
	(viii) Loss of access to grounds during construction and operation (fixed gear and recreational)	(viii) High
	(ix) Changes in species distribution	(ix) Low
	(x) Damaged/lost gear	(x) High
Avian species	(i) Displacement or attraction to structure below water surface	(i) Medium
	(ii) Collision with rotating turbine blades	(ii) High
	(iii) Pressure gradients around rotor	(iii) Medium
	(iv) Leakage of lubricants/fluids, release of maintenance chemicals	(iv) Medium
	(v) Large chemical spills	(v) High
Marine mammals and sea turtles	(i) Entanglement with mooring lines or cables	(i) Medium
	(ii) Strikes with installation or support vessels	(ii) High
	(iii) Operational noise	(iii) Medium

*Denotes that higher priority may be given to this component due to national/regional/local regulatory objectives and obligation.

or wind developments. Therefore, we caution against the interpretation that the pie chart suggests that wave energy developments have a lower proportion of potential major and moderate impacts than any other development type. Major impacts at Scale 2 wave energy projects are changes in hydrodynamics, scour, and/or deposition around devices and loss of access to mobile-gear fishing grounds. Notable moderate impacts include loss of access to fixed-gear and recreational fishing grounds, damaged/lost fishing gear, chemical spills, and collisions/strikes with construction or support vehicles for marine mammals and sea turtles. Specifically, oscillating wave surge converters have higher potential impacts over the other types (moderate versus minor) for operational noise on fish species, marine mammals, and sea turtles, and for sediment disturbance on benthic habitat and resources. Overtopping devices pose increased potential impacts over other types (moderate versus minor) on avian species for displacement or attraction to the device because of the above-water structure.

3.4. Component Decision Trees. The Component decision trees take component-specific concerns into consideration and terminate with a manageable number of recommended monitoring protocols and templates (Tables 9, 10, 11, 12, and 13). For example, the benthic environment decision tree (Table 9) describes 24 total monitoring scenarios but condenses them into a maximum of four monitoring templates. We have two separate decision trees for marine mammals and sea turtles, but one set of monitoring protocols, as in many cases a single protocol can be used to monitor both components. After working through the Impact decision

TABLE 6: A description of the potential impacts resulting from bottom-mounted tidal turbine projects. See text, Section 3.3, for a narrative summary of this development scenario. Ecosystem components are ranked by their proportion of the major impacts. Moderate impacts are listed in the order they appear in the renewable energy impact matrix.

(i4) Bottom-mounted tidal turbine projects		
Priority	Major impacts	Certainty
(1) Benthic habitat and resources	(i) Changes in hydrodynamics (ii) Scour and/or deposition	(i) Medium (ii) High
(2) Fish species and fishing activity*	Loss of access to grounds during construction and operation (mobile gear)	High
(3) Marine mammals and sea turtles*	Noise from pile driving	Medium
Component	Moderate impacts	Certainty
Benthic habitat and resources	(i) Resuspension of pollutants in sediments (ii) Disturbance from installation/removal of device (turbidity) (iii) Chemical spills, discharge (iv) Disturbance from installation of cable (v) Changes to current/wave regime	(i) Low (ii) High (iii) Medium (iv) Medium (v) Medium
Fish species and fishing activity	(i) Collision/blade strike (ii) Pressure gradients around rotor (iii) Chemical spills (iv) Operational noise (v) Noise from pre-construction seismic surveys (vi) Noise from pile driving (vii) Noise from pile cutting during device removal (viii) EMF (ix) Habitat/community composition alteration (x) Decreased catchability during construction and operation (xi) Loss of access to grounds during construction and operation (fixed gear and recreational) (xii) Changes in species distribution (xiii) Damaged/lost gear	(i) Medium (ii) Medium (iii) Medium (iv) Medium (v) Medium (vi) Medium (vii) Medium (viii) Low (ix) Medium (x) Medium (xi) High (xii) Low (xiii) High
Avian species	(i) Collision with rotating turbine blades (ii) Pressure gradients around rotor (iii) Leakage of lubricants/fluids, release of maintenance chemicals (iv) Large chemical spills	(i) Medium (ii) Medium (iii) Medium (iv) High
Marine mammals and sea turtles	(i) Entanglement with mooring lines or cables (ii) Strikes with installation or support vessels (iii) Operational noise (iv) Noise from pile cutting during device removal	(i) Medium (ii) High (iii) Medium (iv) High

*Denotes that higher priority may be given to this component due to national/regional/local regulatory objectives and obligation.

tree, the user should then select the recommended Component decision trees in order to determine specifically which monitoring objectives will apply to that technology type.

3.5. Monitoring Protocols. The Component decision trees terminate with a total of 30 monitoring objectives across all ecosystem components. Monitoring protocols have been developed to address each of these objectives at the University of Rhode Island, but for brevity, the benthic habitat and resources monitoring protocol for seabed scour and/or deposition is presented.

4. Case Study: Commercial Wind Farm

This test case was conducted using a hypothetical wind farm in the Wind Energy Area defined by BOEM in federal waters off the Massachusetts and Rhode Island coasts. A wind farm being planned for this area may include around 200 turbines with jacketed structures. Ecological concerns for this development include the sensitivities of local bird populations (scoters, red-throated loons), important commercial fisheries (demersal fish, lobsters), and the occasional presence of endangered marine mammals (particularly North Atlantic right whales).

Table 7: A description of the potential impacts resulting from floating mooring tidal turbine projects. See text, Section 3.3, for a narrative summary of this development scenario. Ecosystem components are ranked by their proportion of the major impacts. Moderate impacts are listed in the order they appear in the renewable energy impact matrix.

(i5) Floating mooring tidal turbine projects		
Priority	Major impacts	Certainty
(1) Benthic habitat and resources	(i) Changes in hydrodynamics (ii) Scour and/or deposition	(i) Medium (ii) High
(2) Fish species and fishing activity*	Loss of access to grounds during construction and operation (mobile gear)	High
Component	Moderate impacts	Certainty
Benthic habitat and resources	(i) Resuspension of pollutants in sediments	(i) Low
	(ii) Chemical spills, discharge	(ii) Medium
	(iii) Disturbance from installation of cable	(iii) Medium
	(iv) Changes to current/wave regime	(iv) Medium
Fish species and fishing activity	(i) Collision/blade strike	(i) Medium
	(ii) Pressure gradients around rotor	(ii) Medium
	(iii) Chemical spills	(iii) Medium
	(iv) Operational noise	(iv) Medium
	(v) Noise from pre-construction seismic surveys	(v) Medium
	(vi) EMF	(vi) Low
	(vii) Habitat/community composition alteration	(vii) Medium
	(viii) Loss of access to grounds during construction and operation (fixed gear and recreational)	(viii) High
	(ix) Changes in species distribution	(ix) Low
	(x) Damaged/lost gear	(x) High
Avian species	(i) Collision with rotating turbine blades	(i) Medium
	(ii) Pressure gradients around rotor	(ii) Medium
	(iii) Leakage of lubricants/fluids, release of maintenance chemicals	(iii) Medium
	(iv) Large chemical spills	(iv) High
Marine mammals and sea turtles	(i) Entanglement with mooring lines or cables	(i) Medium
	(ii) Strikes with installation or support vessels	(ii) High
	(iii) Operational noise	(iii) Medium

*Denotes that higher priority may be given to this component due to national/regional/local regulatory objectives and obligation.

4.1. Potential Impacts and Monitoring Plan. The Impact decision tree identified this installation as an i2 Impact scenario (Table 4). We recommend that monitoring plans for the four impacts listed as potentially major and negative (Loss of access to grounds for commercial mobile-gear fishermen during construction and operation, displacement or attraction to a device for avian species, seabed scour and/or deposition, and noise from pile driving for marine mammals) be required by federal permitting organizations. An additional 24 impacts were identified as potentially moderate and negative; a subset of these should be considered as part of the permitting requirements but could also serve to inform additional monitoring that might be conducted by other federal or state agencies to address local environmental or stakeholder concerns.

By working through the Component decision trees, we identified nineteen monitoring objectives/protocols that are applicable to this development (Table 14), demonstrating that protocols can be developed to track single and multiple impacts. For example, a sampling protocol for benthic community analysis can also be used to collect information about sediment grain size. Based on the magnitudes of impacts and the local concerns for this wind farm, we identified a subset of eight monitoring objectives/protocols that should be implemented by developers, federal agencies, or both (Table 14). These include monitoring for seabed scour and/or deposition; ventless trap surveys for lobster and trawl surveys for demersal fish; an examination of the spatial use of fishing activity; aerial surveys using both high-definition video and still photography for avian monitoring; and visual surveys, passive acoustic monitoring, and marine mammal observers to track impacts to marine mammals and sea turtles. At a larger (regional) scale, or in an area where perhaps less is known about the local biological resources, a monitoring plan could begin with all of the recommended objectives/protocols and gradually decrease this effort through time as protocols fail to be relevant or detect ecosystem change.

Table 8: A description of the potential impacts resulting from projects harnessing wave energy. See text, Section 3.3, for a narrative summary of this development scenario. Ecosystem components are ranked by their proportion of the major impacts. Moderate impacts are listed in the order they appear in the renewable energy impact matrix.

(i6) Wave energy projects		
Priority	Major impacts	Certainty
(1) Benthic habitat and resources	(i) Changes in hydrodynamics (ii) Scour and/or deposition	(i) Medium (ii) High
(2) Fish species and fishing activity*	Loss of access to grounds during construction and operation (mobile gear)	High
Component	Moderate impacts	Certainty
Benthic habitat and resources	(i) Resuspension of pollutants in sediments (ii) Chemical spills, discharge (iii) Disturbance from installation of cable (iv) Changes to current/wave regime	(i) Low (ii) Medium (iii) Medium (iv) Medium
Fish species and fishing activity	(i) Chemical spills (ii) Operational noise (iii) Noise from pre-construction seismic surveys (iv) EMF (v) Habitat/community composition alteration (vi) Decreased catchability during construction/operation (vii) Loss of access to grounds during construction and operation (fixed gear and recreational) (viii) Changes in species distribution (ix) Damaged/lost gear	(i) Medium (ii) Medium (iii) Medium (iv) Low (v) Medium (vi) Medium (vii) High (viii) Medium (ix) High
Avian species	(i) Displacement/attraction to structure above water surface (ii) Leakage of lubricants/fluids, release of maintenance chemicals (iii) Large chemical spills	(i) Medium (ii) Medium (iii) High
Marine mammals and sea turtles	(i) Entanglement with mooring lines or cables (ii) Strikes with installation or support vessels (iii) Operational noise	(i) Medium (ii) High (iii) Medium

*Denotes that higher priority may be given to this component due to national/regional/local regulatory objectives and obligation.

4.2. Example Monitoring Protocol. Finally, we present an example protocol to address seabed scour and/or deposition (Table 15). Similar protocols for each impact should be developed to implement a consistent and robust monitoring plan. Protocols such as this are intended to provide guidance to regulators and developers on the most suitable methods for detecting the indicators of impacts but, like the overall framework, are designed to be adaptive to regulatory needs and site-specific concerns. In our example, we provided estimates of cost for two different monitoring strategies so that monitoring activities might be prioritized based on ecological and financial factors. We recommend that similar protocols be developed based on best practices identified in the literature and do not aim to be definitive or to provide comprehensive lists of all available methodologies.

5. Discussion

This paper presents a system for selecting both the priority impacts of ORED to be monitored and the appropriate monitoring protocols to address these impacts for a given project. One of the lessons learned from this effort was the importance of a monitoring program that is adaptive to both regulatory needs and local concerns (e.g., [19]). In drafting a set of monitoring objectives we attempted to account for variability in regions, target species, and so forth, but decisions about the most appropriate ways to monitor ORED will still have to be made on a case-by-case basis. Drivers, impacts, indicators, and technologies available to use in a monitoring program are all expected to be site specific. Our framework is flexible enough to address these concerns and to be useful for developing monitoring plans on scales ranging from local to national.

5.1. Development of Monitoring Protocols. It would be impractical to monitor every interaction that could potentially result in an effect on an organism or abiotic component of the ecosystem. Protocols should target priority impacts for monitoring given the ecological or societal importance of the resource, activity, or community and the certainty of their magnitude of impact. Monitoring protocols should test a particular regulatory question that is linked to one or more of these potential effects. In this study, we assumed that regulators would want and need to focus on the major

Table 9: Component decision tree for impacts on benthic habitat and resources. The key is followed to obtain a recommended suite of monitoring protocols.

Determine which impacts to the benthic environment need to be monitored:	
The energy resource is	
Wind	Go to A
Waves	Go to B
Tidal	Go to C
(A) The wind turbine foundation is	
Monopile OR tripod OR lattice	Go to A1
Gravity	Go to A2
Floating mooring	Go to A3
(A1) The stage of the monopile, tripod, or lattice wind turbine project is	
Construction	Z1, Z2
Operation	Z1, Z2, Z3
Decommissioning	Z1, Z2
(A2) The stage of the gravity wind turbine project is	
Construction	Z1, Z2, Z3
Operation	Z1, Z2, Z3
Decommissioning	Z1, Z2, Z3
(A3) The stage of the floating mooring wind project is	
Construction	Z1, Z2
Operation	Z1, Z2
Decommissioning	Z1, Z2
(B) The tidal turbine type is	
Open OR shrouded bottom mounted	Go to B1
Open OR shrouded floating mooring	Go to B2
(B1) The stage of the bottom-mounted tidal turbine project is	
Construction	Z1, Z2
Operation	Z1, Z2, Z3, Z4
Decommissioning	Z1, Z2
(B2) The stage of the floating mooring tidal turbine project is	
Construction	Z1, Z2
Operation	Z1, Z2, Z4
Decommissioning	Z1, Z2
(C) The wave device type is	
Point absorber OR wave attenuator OR oscillating water column	Go to C1
Oscillating wave surge converter	Go to C2
Overtopping	Go to C3
(C1) The stage of the point absorber OR wave attenuator OR oscillating water column project is	
Construction	Z1, Z2
Operation	Z2, Z4
Decommissioning	Z1, Z2
(C2) The oscillating wave surge converter project scale is	
Construction	Z1, Z2
Operation	Z1, Z2, Z3, Z4
Decommissioning	Z1, Z2
(C3) The overtopping device project scale is	
Construction	Z1, Z2
Operation	Z1, Z2, Z4
Decommissioning	Z1, Z2

Recommended protocols:
Z1: seabed scour and/or deposition.
Z2: changes in benthic community composition.
Z3: increase in hard bottom habitat.
Z4: changes in hydrodynamics.

Table 10: Component decision tree for impacts on fish species and fisheries. The key is followed to obtain a recommended suite of monitoring protocols.

Determine which impacts to fisheries resources and fishing activity need to be monitored:	
The energy resource is	
Wind	Go to A
Tidal	Go to B
Waves	Go to C
(A) The wind turbine foundation is	
Monopile OR tripod OR lattice OR gravity	Go to A1
Floating mooring	Go to A3
(A1) The stage of the monopile, tripod, lattice, or gravity wind turbine project is	
Construction	X1, X2, X5
Operation	X1, X2, X3, X5
Decommissioning	X1, X2
(A2) The stage of the floating mooring wind project is	
Construction	X1, X2, X5
Operation	X3, X4, X5
Decommissioning	X1, X2
(B) The tidal turbine type is	
Open OR shrouded bottom mounted	Go to B1
Open OR shrouded floating mooring	Go to B2
(B1) The stage of the bottommounted tidal turbine project is	
Construction	X1, X2, X5
Operation	X1, X2, X3, X4, X5
Decommissioning	X1, X2
(B2) The stage of the floating mooring tidal turbine project is	
Construction	X1, X2, X5
Operation	X1, X2 X3, X4, X5
Decommissioning	X1, X2
(C) The wave device type is	
Point absorber OR wave attenuator OR oscillating water column OR overtopping	Go to C1
Oscillating wave surge converter	Go to C2
(C1) The stage of the point absorber OR wave attenuator OR oscillating water column OR overtopping project is	
Construction	X1, X2, X5
Operation	X1, X2, X5
Decommissioning	X1, X2
(C2) The oscillating wave surge converter project scale is	
Construction	X1, X2, X5
Operation	X1, X2, X3, X5
Decommissioning	X1, X2

Recommended protocols:
X1: mesoscale changes to abundance and distribution (disturbance).
X1a: the species of concern are finfish.
X1b: the species of concern are crustaceans or rock fish.
X2: habitat alteration/community composition: microscale changes to abundance and distribution—finfish.
X3: reef effects.
X4: blade strikes.
X5: spatial use of fishing activity.

negative potential impacts of ORED. However, we identified a number of potential positive impacts that are also worthy of research and monitoring. The positive impacts, such as reef effects, should be considered in any impact assessment for the potential value they may provide to the wider marine environment [2].

Protocols may need to be developed with the assumption that there are no or insufficient existing data on the relevant species to establish reference levels prior to monitoring. In some cases, the data may exist but not at a scale appropriate for integration into monitoring efforts. In other circumstances, baseline data will exist that can and should be

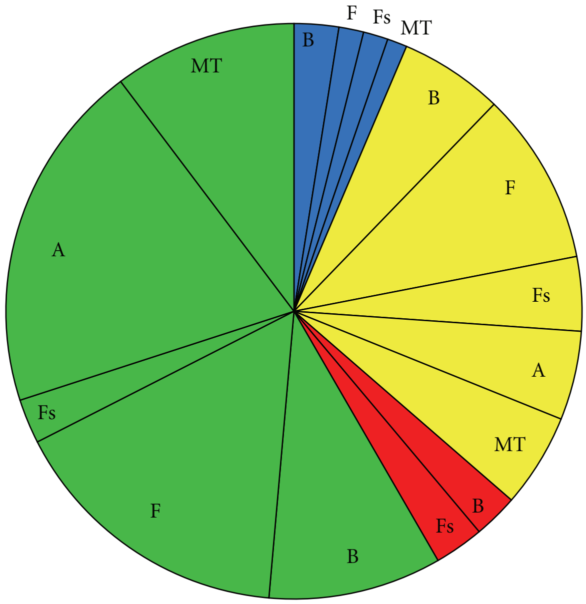


Figure 6: Pie chart representing the proportion of impacts for each ecosystem component for Impact scenario i5, floating mooring tidal turbine projects, categorized by whether the effect is positive (blue), minor negative (green), moderate negative (yellow), or major negative (red). B = Benthic habitat and resources; F = Fish; Fs = Fisheries; A = Avian species; MT = Marine mammals and sea turtles.

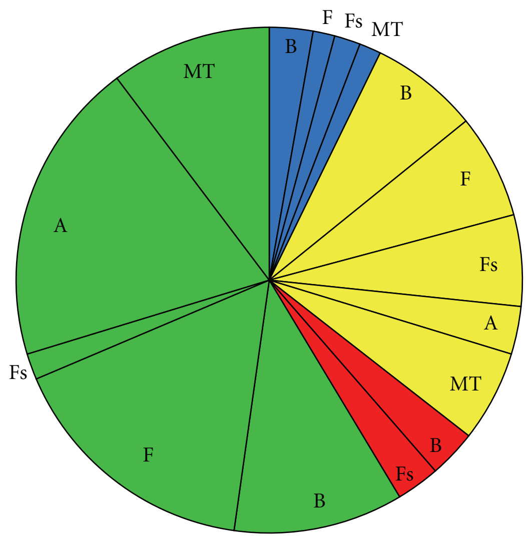


Figure 7: Pie chart representing the proportion of impacts for each ecosystem component for Impact scenario i6, wave energy project, categorized by whether the effect is positive (blue), minor negative (green), moderate negative (yellow), or major negative (red). B = Benthic habitat and resources; F = Fish; Fs = Fisheries; A = Avian species; MT = Marine mammals and sea turtles.

incorporated into monitoring efforts. As described above, we assign reference directions to indicators when we have insufficient data to establish a quantitative threshold. Protocols should therefore be flexible to incorporate new and existing data for better estimates of particular reference points. Where there is an ongoing environmental monitoring program in the project area, and if the methods in use are sufficient to detect a change due to development, data collection should continue using the same methodology for comparable data. Examples of existing monitoring programs with appropriate data for incorporating into ORED studies may include species monitored under the Endangered Species or Marine Mammal Protection Acts for which monitoring may be occurring as part of a stock assessment program. Monitoring data collected for threatened, endangered, or other protected species could be compared directly to existing reference levels. For these species in particular it will be important to know if negative impacts are caused by ORED of any kind because such impacts will trigger immediate federal regulatory response/mitigation measures. In many cases, site-specific monitoring will still be desirable to analyze change related directly to the ORED.

Table 11: Component decision tree for impacts on avian species. The key is followed to obtain a recommended suite of monitoring protocols.

Determine which impacts to avian species need to be monitored:	
The energy resource is	
Wind	Go to A
Waves	Go to B
Tidal	Go to C
(A) The stage of the wind energy project is	
Construction	Go to D
Operation	Go to D, Go to E, V11
Decommissioning	Go to D
(B) The stage of the tidal project is	
Construction	Go to D
Operation	Go to D, V12
Decommissioning	Go to D
(C) The stage of the wave energy project is	
Construction	Go to D
Operation	Go to D
Decommissioning	Go to D
(D) The target species are	
Easily disturbed, cryptic	V3, V4
Easily disturbed, noncryptic	V2, V3, V4
Not easily disturbed, cryptic	V1, V3, V4
Not easily disturbed, noncryptic	V1, V2, V3, V4
(E) The target species are	
Diurnal	V5, V6
Nocturnal	V5, V7

Recommended protocols:
V1: ship-based visual surveys.
V2: aerial surveys using human observers.
V3: aerial surveys using high-definition videography.
V4: aerial surveys using digital still photography.
V5: radar surveys.
V6: visual surveys.
V7: flight call surveys.
V11: remote detection system.
V12: sonar and video technology.

Table 12: Component decision tree for impacts on marine mammals. The key is followed to obtain a recommended suite of monitoring protocols.

Determine which impacts to marine mammals need to be monitored:	
The energy resource is	
Wind	Go to A
Tidal	Go to B
Waves	Go to C
(A) The stage of the wind energy project is	
Construction	W1, W2, W3, W4, W5
Operation	W1, W2, W3, W4, W5
Decommissioning	W1, W2, W3, W4, W5
(B) The stage of the tidal energy project is	
Construction	W1, W2, W3, W4, W5
Operation	W1, W2, W3, W4, W5
Decommissioning	W1, W2, W3, W4, W5
(C) The stage of the wave energy project is	
Construction	W1, W2, W3, W4, W5
Operation	W1, W2, W3, W4, W5
Decommissioning	W1, W2, W3, W4, W5

Recommended protocols:
W1: visual surveys.
W2: passive acoustic monitoring.
W3: marine mammal observers.
W4: stranding response networks.
W5: tagging.
W6/7: underwater photography.
W8: SCUBA surveys.
W9: ROV surveys.

The time scales of monitoring protocols should be long enough to observe short-term or immediate impacts caused by an ORED, include enough data to limit some of the effects of natural variability on the analysis, and last long enough to observe whether conditions return to a preconstruction state. Developer-led monitoring will probably not be conducted on time scales of a length sufficient to observe very long-term effects from ORED (i.e., decades). Supplementary monitoring should be conducted for a decade or more in order to understand long-term effects. For example, five years of monitoring may be enough time to observe effects on some species but may not be sufficient to identify stock- or population-level effects, particularly on slow-growing or long-lived species such as elasmobranchs. Additionally, some have speculated that if offshore renewable energy devices result in reef effects, this could create secondary effects such as larval spillover if spawning is occurring around the devices. These sorts of secondary effects may not be observable during the time scales of developer-led monitoring. Thus we recommend that, where feasible, monitoring and supplementary studies take place well beyond the minimum time frames required by federal permitting agencies.

5.2. Demonstration-Scale Projects as Opportunities. Demonstration-scale projects provide an opportunity for research to reduce some of the existing uncertainty around the potential environmental effects of offshore renewable energy projects, assisting regulators in prioritizing monitoring needs and making better decisions. Due to their size, individual demonstration-scale projects should be considered separately from commercial-scale projects in the extent to which monitoring should be required. Demonstration-scale projects are not expected to result in environmental impacts of the same magnitudes as commercial projects for any of the renewable energy device types. These projects, or those testing new technologies, should however be subject to more extensive monitoring relative to the scale of the potential impact, at least in the early phases of these technologies, due to the high levels of uncertainty surrounding impacts. Greater monitoring effort at these early stages may later reduce monitoring requirements at commercial-scale facilities, as impacts are better understood. We recommend that the monitoring requirements for demonstration-scale projects be adaptive; more studies that respond to the major and moderate impacts of a commercial-scale project should also be conducted initially as these projects are deployed, particularly at a stage where there are few or no commercial-scale facilities available for monitoring. As impacts are better characterized and methodologies are made more efficient, individual monitoring activities could be phased down in order to maximize the suite of activities at each development. Overall, we recommend that as many monitoring protocols be implemented as is feasible for the early stages of ORED development in the U.S.

5.3. Multiple Projects and Cumulative Impacts. Without a more complete understanding of the direct impacts of ORED on the various environment components discussed here, it is infeasible to develop a monitoring framework to address multiple projects or cumulative impacts. While the likelihood of an effect at the stock or population scale may increase with multiple ORED projects in a given area, not enough conclusive evidence exists at this point to indicate whether those effects are additive or increase in a nonlinear fashion. At the stage in which there are multiple projects in an area, monitoring may need to occur on a regional scale to understand the magnitude of an impact and may need to occur over a longer time series, and data collected from separate projects may need to be analyzed together to more completely understand what is happening. Meta-type analyses could be considered to attempt to maximize the utility of data collected from multiple projects.

As monitoring data are collected at single projects and analyzed, the potential effects at the individual project level will become better understood, and some of these impacts

Table 13: Component decision tree for impacts on sea turtles. The key is followed to obtain a recommended suite of monitoring protocols.

Determine which impacts to sea turtles need to be monitored:	
The energy resource is	
Wind	Go to A
Tidal	Go to B
Waves	Go to C
(A) The wind turbine foundation is	
Monopile OR tripod OR floating mooring	Go to A1
Lattice OR gravity	Go to A2
(A1) The stage of the monopile or tripod or floating mooring wind turbine project is	
Construction	W1, W3, W4, W5, W8
Operation	W1, W3, W4, W5
Decommissioning	W1, W3, W4, W5, W8
(A2) The stage of the lattice structure or gravity foundation wind project is	
Construction	W1, W3, W4, W5, W8
Operation	W1, W3, W4, W5
Decommissioning	W1, W3, W4, W5, W6, W7, W8
(B) The tidal turbine type is	
Open OR shrouded bottom-mounted	Go to B1
Open OR shrouded floating mooring	Go to B2
(B1) The stage of the bottommounted tidal turbine project is	
Construction	W1, W3, W4, W5, W8
Operation	W1, W3, W4, W5
Decommissioning	W1, W3, W4, W5, W6, W7, W8
(B2) The stage of the floating mooring tidal turbine project is	
Construction	W1, W3, W4, W5, W8
Operation	W1, W3, W4, W5
Decommissioning	W1, W3 W4, W5, W8
(C) The stage of the wave energy device is	
Construction	W1, W3, W4, W5, W8
Operation	W1, W3, W4, W5
Decommissioning	W1, W3, W4, W5, W8

Recommended protocols:
W1: visual surveys.
W2: passive acoustic monitoring.
W3: marine mammal observers.
W4: stranding response networks.
W5: tagging.
W6: underwater photography.
W7: SCUBA surveys.
W8: ROV surveys.

may be found to be negligible. However, in some cases an impact could be negligible when there is a single project but more severe when combined from multiple projects. It is not known *a priori* which situation is applicable to a particular project-species interaction.

5.4. Effects and Indicators. Currently there is a great deal of uncertainty surrounding the environmental effects of offshore renewable energy technologies. Through implementing a comprehensive monitoring program at each new ORED and by comparing and aggregating data, much of this uncertainty will be reduced and negative impacts will be better understood. Additional studies, including both *in situ* and laboratory-based research, are needed to better understand ORED drivers of ecosystem change and impacts. In many cases this is beyond the scope of what can be determined by a straightforward monitoring study and may be unreasonable to require of a developer. Regardless, it would be best if studies on these unknowns are ongoing and occur alongside other monitoring efforts. Paradoxically, without a better understanding of these impacts, it may not be feasible to design a protocol to be applied on a widespread scale.

Our work has provided a starting point for identifying these types of research priorities. Those effects

Table 14: Monitoring protocols relevant to addressing the potential impacts identified from the Impact decision tree and component decision trees for the case study of a scale 2 (∼200 devices) jacketed wind turbine farm involving pile driving. Protocols in bold face represent those that uniquely address the Impact scenario and local concerns and should thus be prioritized for implementation.

benthic habitat and resources:
(Z1) Seabed scour and/or deposition
(Z2) Changes in benthic community composition
(Z3) Increase in hard bottom habitat
Fish and fisheries resources
(X1a) Trawl surveys
(X1b) Ventless trap surveys
(X2) Habitat alteration/community composition: micro-scale changes to abundance and distribution—finfish
(X3) Reef effects
(X5) Spatial use of fishing activity
Avian species
(V3) Aerial surveys using high-definition videography
(V4) Aerial surveys using digital still photography
(V5) Radar surveys
(V6) Visual surveys of flight ecology
(V11) Remote detection system
Marine mammals/sea turtles
(W1) Visual surveys
(W2) Passive acoustic monitoring
(W3) Marine mammal observers
(W4) Stranding response networks
(W5) Tagging
(W8) ROV surveys

found to have a low level of certainty are those for which additional research should be conducted. We recommend research funding and effort be directed toward understanding the level of risk of the following potential effects.

Benthic habitat and resources:

(i) changes to currents or wave regimes,

(ii) increase in sediment temperature around cable,

(iii) reef effects on marine hydrokinetic (MHK) devices,

(iv) noise effects from construction, operation, and decommissioning,

(v) EMF effects from the power cables.

Fish species and fisheries:

(i) effect of pressure and velocity gradients around a rotor, and rotor wake, for tidal devices,

(ii) effects resulting from chemical discharge, including leaking, spills, or flaking of marine coating,

(iii) noise effects, including preconstruction noise from seismic surveying, construction noise, vessel noise, and operational noise,

(iv) EMF effects from the power cables,

(v) changes to community composition from reef effects or disturbance,

(vi) changes in species distribution.

Avian species:

(i) collision with rotating turbine blades from tidal devices,

(ii) pressure and velocity gradients around a rotor for both tidal and wind turbines,

(iii) EMF effects from the power cables,

(iv) changes to foraging due to changes in turbulent dissipation/boundary layers for MHK devices,

(v) changes to foraging due to changes in the wave energy regime, for all device types.

Marine mammals and sea turtles:

(i) reef effects from devices,

(ii) entanglement with mooring lines or cables,

(iii) potential for effects from diffusion or flaking of marine coating,

(iv) effects of operational noise, especially from tidal and wave energy devices,

(v) EMF effects from the power cables.

The potential for effects from EMF on all species has emerged as a particular issue of concern; there is considerable uncertainty around what the effects of EMF might be on each of the topic areas considered in this paper. When possible, we recommend site-based EMF studies be conducted alongside other monitoring projects.

6. Conclusions

The tools developed for this project represent an important first step in standardizing monitoring for offshore renewable energy projects in the United States. The data collected through a standardized monitoring program will provide a means for refining our understanding of the potential effects of offshore renewable energy projects and will feed back into better siting decisions. It is our hope that these results will prove useful to scientists, developers, managers, and regulators in understanding environmental changes resulting from offshore renewable energy development.

Table 15: An example monitoring protocol from the benthic habitat and resources category for seabed scour and/or deposition at a commercial-scale installation.

	High cost	Low cost
Indicator(s) of the impact	Scour: increase in median grain size, decrease in organic content, decrease in seabed volume Deposition: decrease in median grain size, increase in organic content, increase in seabed volume	
Methodology or technique to collect data	Particle size analysis, multibeam/interferometric bathymetry	
Description of methodology or technique(s) for collecting data	Seasonal surveys, 5 years Grain size: *5-sample transect at 3 devices out to 200 m Bathymetry: overlapping transects for 100% coverage (at least 0.5 m pixels) 1 km radius at 3 devices	Annual surveys, 3 years Grain size: *3-sample transect at 3 devices out to 200 m Bathymetry: overlapping transects for 100% coverage (at least 0.5 m pixels) 500 m radius 3 devices
Methodology for analyzing data	ANOVA on median grain size, volume change estimate using mosaicked bathymetry models	
Frequency and duration	1 preconstruction survey, seasonal operation, 1 postconstruction survey	1 preconstruction survey, annual operation, 1 postconstruction survey
Spatial scale	200 m–1 km radius around 3 devices	500 m radius around 3 devices
How well does this methodology account for environmental variability?	Seasonal and interannual variability	Interannual variability
Cost	$25 k/year, 5 years	$15 k/year, 3 years
Other considerations (e.g., advantages or disadvantages)	Can be combined with benthic community composition monitoring protocol	

Type of data output required: time series values for median grain size and standard deviations, time series on volume at each turbine and standard deviation.

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Review Article

Artificial Reef Effect in relation to Offshore Renewable Energy Conversion: State of the Art

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The rapid worldwide growth of offshore renewable energy production will provide marine organisms with new hard substrate for colonization, thus acting as artificial reefs. The artificial reef effect is important when constructing, for example, scour protections since it can generate an enhanced habitat. Specifically, artificial structures can create increased heterogeneity in the area important for species diversity and density. Offshore energy installations also have the positive side effect as they are a sanctuary area for trawled organisms. Higher survival of fish and bigger fish is an expected outcome that can contribute to a spillover to outer areas. One negative side effect is that invasive species can find new habitats in artificial reefs and thus influence the native habitats and their associated environment negatively. Different scour protections in offshore wind farms can create new habitats compensating for habitat loss by offshore energy installations. These created habitats differ from the lost habitat in species composition substantially. A positive reef effect is dependent on the nature and the location of the reef and the characteristics of the native populations. An increase in surface area of scour protections by using specially designed material can also support the reef effect and its productivity.

1. Introduction

A changing climate due to fossil fuel emissions and increasing energy demands leads to a new focus on renewable energy sources. Therefore, diverse countries in Western Europe have plans to build and commercialise offshore renewable energy resources along their coastlines and this industry is going to grow significantly. Offshore wind, for example, has a much higher potential to produce energy than terrestrial farms and may contribute with about 140 GW in the year 2030 and would thus produce more than 10% of Europe's electricity [1]. Moreover, offshore wave power is developing fast, gaining increased attention [2], and with the first units in operation [3, 4]. All in all, offshore renewable energy production is a fast growing industry and typically spread out over large areas on the seafloor. Cables, concrete or steel piles, and foundations will be the typical hard bottom structures in an offshore renewable energy park. Still, there is a gap of knowledge in general and local effects of large scale offshore development on these already stressed marine environments. Today's research on offshore energy conversion is focused on fish [5], marine mammals [6], effects of electromagnetic fields [7], noise [8], hydrodynamic changes, and benthic communities [9, 10]. Concerning sea cables, impact studies showed that there were no general negative impacts on species abundance, composition and biomass of infauna, and species specific reactions in some elasmobranch fish [11–13].

Still, research on offshore renewable industry is in the beginning phase. Both long-term studies and large scale effects are topics of high scientific value that need to be prioritised. Furthermore, there is a lack of both replication and baseline studies that are very essential for reliable results that can be used for more general decision makings. So far, the impacts during the construction phase of offshore installations seem to be at its highest during this phase, including a lot of noise, boat traffic, cable laying, and seabed disruptions. During maintenance, the noise generation of the turbines/generators, vibrations from the installations, and their physical presence may be some of the critical impact factors [4, 7]. The marine environment may on the other hand benefit from the installation of offshore renewable energy, since trawling will be excluded and new hard substrate will be introduced. In this paper I will discuss the opportunities of offshore renewable energy as a habitat enhancement. Specifically for threatened or commercially interesting species, such as for example, juvenile whiting, cod and lobsters this may lead to a great benefit for nature conservation. There is a high plausibility that offshore energy installations act as artificial reefs [5, 14–16] which in its way can support both environmental and commercial interests.

2. Colonisation of Offshore Structures

Artificial offshore constructions will inevitably be colonized by a number of organisms. This should be considered when constructing for example scour protections with their potential to enhance the reef effect for higher biodiversity or commercial interesting species. Artificial reefs generally hold greater densities and biomass of fish and decapods, and provide higher catch rates, compared to surrounding soft bottom areas, and in several cases also in relation to adjacent natural reefs [17–24]. There are, however, some studies that show no significant impacts of artificial reefs on fish assemblages [25]. The proposed reasons for higher abundance and diversity of fish on and around artificial reefs differ among organisms. The most important seems to be the provision of shelter from both predation and water movements, and enhanced feeding grounds. Fish also seem to use the structures as reference points for spatial orientation [18, 19, 26].

Coming at the base of wind power farms, scouring protections may have a potential in terms of altering the nature of the seabed in the vicinity of wind farms. In that way different shapes and sizes may create different habitats and thus dictate what kind of organisms colonize for living and feeding. Wind farms are usually constructed on soft bottom substrate for technical reasons, and this contributes to higher complexity in three-dimensional scale. Therefore, scour protections have the potential to turn exposed, biodiversity-poor soft bottoms into species rich ecosystems. When the conditions are ideal, wind park foundations will become heavily colonized by organisms abundant in the water mass or nearby hard-bottom habitats. The colonisation is highly dependent on sufficient number of larvae and suitable environmental conditions [27]. On the other hand habitat mitigation can occur depending on the location of the renewable energy installations. Therefore, adequate location decision is important to prevent negative impacts in areas where red-listed or key-species exist.

Recruitment of marine organisms primarily occurs in two different ways when new constructions such as scour protections are set in place: by migration from the surrounding substrate or by settling of larvae. The recruitment will be governed by the local hydrodynamic regime [28] carrying the larvae to the wind farm, and then it will depend on its material and textures [29], and on the location of the scour protection in respect of water depth [30], salinity and temperature [31–33], and so forth. An initial macromolecule film, bacteria, microalgae, and fungi colonising the surface of scour protections may either favour or deter the settlement of larvae [34]. The colonisation will often have a characteristic succession, starting with diatoms and filamentous algae, followed by barnacles, and thereafter by a more diverse community [35]. There will be differences in the composition of fouling communities at particular depths on the scour protections. However, there is a high probability that scour protections will create increased heterogeneity in the area that is of great importance for species diversity and density. The size, diversity, and density of organisms on and in an artificial reef are conditional on the number and size of niches and not necessarily the presence of food. The conditions for the supply of nutrients are well established since offshore energy installations in shallow waters (<30 m) are built in areas with higher water turbulence efficiently transporting food, oxygen, and carbon dioxide. The extent to which scour protections may attract marine organisms and the species attracted will largely be dictated by the design of the components of the installation, with structural complexity of exposed surfaces being an important factor [36, 37].

Structural complexity appears to be a condition for many productive and intricate environments such as coral reefs, mangroves, and sea grass meadows. These environments are productive, not only because they act as a substrate that have a great turnover, but also because they offer a high degree of substrate complexity and an extensive spectrum of niche sizes, which are advantageous for young and juvenile organisms. One topic that is usually discussed when establishing artificial reefs is whether the reefs actually produce new biomass, or if it only aggregates or redistributes biomass. This depends mainly on the species and its limitation by food, refuge, territory, and/or behavioural requirements [18, 38]. For other species and in other regions> with different environmental conditions, artificial reefs do only redistribute or aggregate biomass [18]. However, studies on the production/aggregation theory are lacking, mostly because they are relatively short term and scarce in appropriate control sites or replications [39].

3. No-Trawling Areas/Sanctuary Areas

The deployment of artificial reefs in regions where there are no rocky bottoms may be important for specific hard substrate species [40]. Bottom trawling and dredging on soft sediments has been conducted over most of the world's continental shelves for decades and includes heavy fishing gear that is towed over the seafloor. These types of fishing stir up bottom sediments and loading suspended solids into the water column and have an immense and chronic impact on the marine environment [41, 42]. As a result of these processes, vulnerable species will be reduced, as well as biodiversity, production, and biomass in general [43–45]. Furthermore, ecological changes towards more opportunistic organisms due to removal of biomass are expected [46], and possible domino effects on the ecological relationships and food webs may be caused by the selective removal of some benthic species [47]. Additionally, about 70% of the marine fish stocks are overexploited or depleted due to trawling [48]. The primary dispute over trawling concerns the magnitude and duration of these impacts. An earlier meta-analysis showed that the large-scale effects of trawling are complex and depend on many factors including habitat, benthic composition, trawl intensity, and trawl gear types [49].

Over the last few decades the needs of protected areas where all fisheries and other forms of extraction of organisms are excluded have become a major focus in marine ecology, fisheries management, and conservation biology [50, 51]. There has been a growing interest for establishing no-trawling zones (NTZ), since they have been proposed to be efficient and inexpensive ways of maintaining and managing fisheries, while simultaneously conserving biodiversity and meeting other conservation objectives as well as human needs [50, 51]. NTZs established around the world range in size from a fraction of 1 km^2 to 10 km^2 or more. Around 0.04% of the world's oceans are currently designated as NTZ, in which all fishing is banned and can enable the ecosystem within the area to recover (at least partially) from the effects of fishing. Thus, NTZs can be defined as Marine Protected Areas in which the extraction of living and nonliving resources is permanently prohibited, except that they are necessary for monitoring or research to evaluate effectiveness.

Establishing offshore energy parks will make it impossible to trawl close by the devices since there is always in a certain safety zone preventing entanglement of fishing gear. Trawling will be prohibited or limited in these safety zones that cover some km^2, and accordingly, these offshore parks may act as NTZs, mitigating habitat losses and degradation. In these areas juvenile fish will have a higher chance to survive, and even older, bigger fish will improve survival rates, and in this way contributing to a spillover effect. One risk might be higher fishing pressure outside those parks where no safety zone exists since there might be a higher productivity within offshore parks leading to a spill over effect.

4. Invasive/Nonindigenous Species

One mitigating effect of offshore renewable energy on the local biodiversity may occur due to colonization by invasive species. Ever since international shipping started, marine organisms have been distributed all over the world by ballast water or as fouling on boat hulls. This introduction of alien species has dramatic ecological effects, since it can be a threat to global biodiversity [52, 53] and lead to local extinctions and fishery collapses [53]. Artificial hard substrates offer habitats for a large number of invasive species normally attached to rocky reefs [54]. In general, artificial structures do not host exactly the same species as a natural hard substrate [55, 56]. The installation of offshore renewable energy parks may not only introduce hard substrata in otherwise sandy-dominated bottoms, but can also provide new habitats for invasive species. Different hydrodynamics, such as more shelter due to new structures may lead to colonization of organisms very different to those on nearby hard substrates and thereby establish and spread nonindigenous species [57]. On wind turbine constructions in the North Sea and in the Baltic Sea the presence of alien species has been recorded [58–60] and may provide stepping-stones for spread, which could facilitate the establishment of the new taxa in the recipient region.

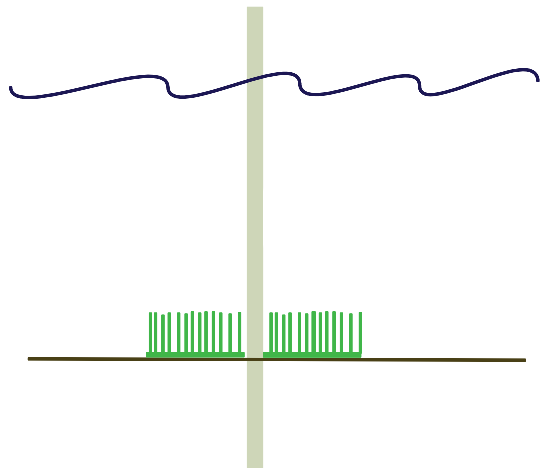


Figure 1: Illustration of polypropylene fronds designed as scour protection around monopile offshore wind turbines.

5. Scour Protections in Offshore Wind Farms

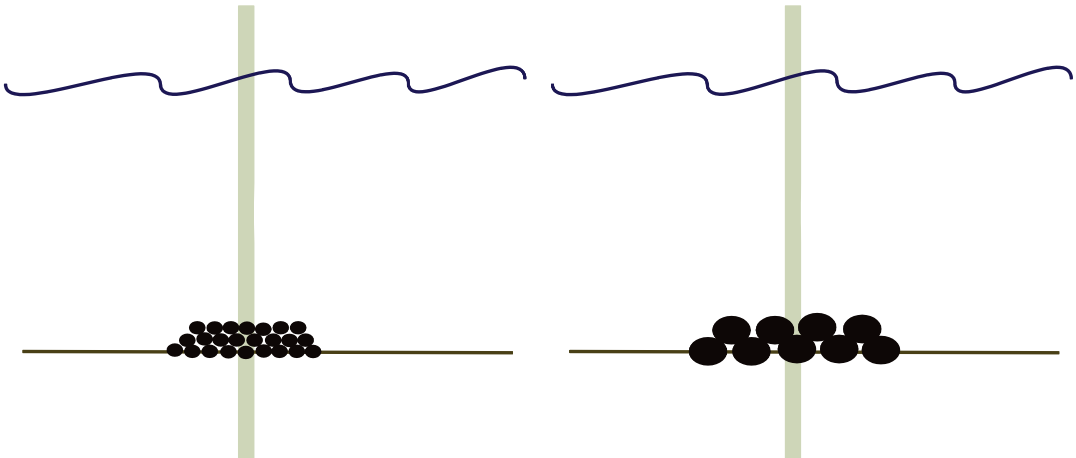
Scour or erosion is the removal of granular seabed material around coastal structures by hydrodynamic forces. Scour around wind turbines is a major industrial and engineering problem and can result in serious (up to 10 m deep) sediment reduction around the foundations [61]. So far, there are some common procedures to prevent scouring [62].

5.1. Synthetic Fronds. Polypropylene fronds that resemble seaweed beds can be used as scour control. They are fixed in concrete and anchors on the seafloor and form mattresses (Figure 1). The fronds slow down the local current and cause suspended particulate matter to settle. This matter accumulates over time to build up a sand or sediment bank, effectively reinstating the seabed. This fibre-reinforced bank will then resist further erosion. An installation in larger depths will make fewer problems with fouling organisms and debris. Around the wind power pilings the mats are building up a cohesive underwater sandbank and thus prevent scouring [63].

Synthetic fronds can mimic a seagrass environment, and thus may be used by several different species as habitat, feeding ground, shelter from predation, and nursery ground [64, 65]. A three-dimensional design of the new environment and sediment stabilization will support a rich and diverse invertebrate and fish fauna. Synthetic sea fronds may have a positive artificial reef effect since they create new habitat and thus increase the carrying capacity of an area and its ecological functioning. In contrast to sparse areas of the seabed (where offshore wind farms generally are placed), carrying capacity of more complex habitats will be higher [66]. Considering net habitat gain and losses the synthetic fronds will establish a reduced habitat availability because

Table 1: Net habitat loss and gain through the installation of different types of scour protections around an offshore wind turbine and calculated biomass of expected motile organisms. The expected carrying capacities have been calculated based on reef ball observations. Adapted from [13].

	Habitat loss (m^2)	Habitat created (m^2)	Net loss/gain (m^2)	Biomass per year (kg)
Gravel protection	452	1102	650	19 806
Boulder protection	452	1129	677	20 291
Synthetic fronds	452	439,5	−12,5	7 899
Reef ball	452	3616,6	3164,6	65 000
SeaCult	452	5464	5012	98 203



(a) (b)

Figure 2: Illustrations of gravel (a) and boulder (b) protections around a monopile offshore wind power foundation.

their surfaces give less space for colonization compared to the area they cover (Table 1) [16]. Still they will contribute to an increased ecological functioning since they create new habitat and thus heterogeneity.

5.2. Gravel/Boulder Protections. Another inexpensive method of scour protection is to cover the base of wind turbines with bigger boulders and/or gravel (Figure 2). Here, one or more layers are aggregated around the turbine base to shape a circular reef of 10–15 m radius with the foundation at the centre. At the Danish Horns Rev this method is applied for protecting wind turbines.

These kinds of scour protections are hard substrate environments that may be colonized by first barnacles, tube worms, and sea squirts. Later on, motile organisms such as lobsters, crabs as well as reef fish (wrasse, conger eel) can occur. Hard substrate generally have a higher biodiversity and species abundance than surrounding soft bottoms [67]. In comparison to boulders, gravel protections will result in low diversity and abundance of organisms due to a more unstable environment. Out of nature conservation perspectives that alternative is the least desired and low colonisation of hydrodynamically resistant species such as polychaetes, bivalves, echinoderms, and crustaceans (*Liocarcinus* spp., *Pagurus* spp.) is expected. In the case of low currents, hydroids, sea anemones, and bryozoans may occur.

5.2.1. Case Study: Danish Horns Rev. The established offshore wind farm covers approximately 14 500 m^2 including scour protection. The whole offshore wind farm covers a total area of 27.5 km^2. That gives an impact on the altered habitats in the range of 0.5% of the area of the offshore wind farm and the total loss of habitat would affect less than 0.1% of the bottom fauna within the site [68]. Colonisation processes at Horns Rev include fouling by algae and invertebrates [60]. Introduction of epifouling communities have increased the general biodiversity in the wind farm area and a succession in the benthic community and biodiversity has been observed. Evidence that the hard bottom substrates provide habitat as nursery grounds for larger and more mobile species has been shown for the edible crab *Cancer pagurus* [60].

A very high variation and differences in faunal assemblages on the scour protection between different sampling sites were shown. Still, some similarities between different zones mainly reflecting different type of substrate were demonstrated [60]. At the scour protection, sea anemones and the soft coral *Alcyonium digitatum* contributed with high percentages to the total biomass. Loss of infauna habitats has been replaced by hard bottom habitats providing an estimated 60 times increase in the availability of food for fish and other organisms in the wind farm area compared to the native infauna biomass.

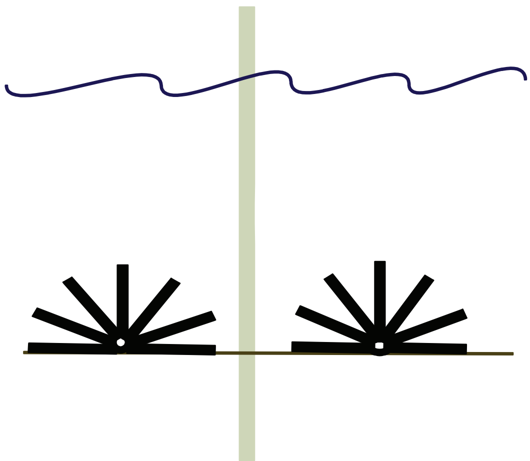


Figure 3: An illustration of the design of the reef system scouring protection around a monopile wind turbine.

Seasonal variations in fish fauna diversity were found in schools of cod often observed at the scour protections as well as individuals of benthic fish species [60]. Number of fish was higher in September than in March probably due to feeding on crustaceans that aggregated on scour protections.

Two designated species have been found in the Horns Rev area, the bristle worm *Sabellaria* presumably the ross worm *S. spinulosa* and the white weed *Sertularia cupressina*, which both are regarded as threatened or red listed in the Wadden Sea area [60].

Looking at benthic communities, the Danish monitoring studies observed that the introduction of the turbine foundations and scour protections onto seabed that previously consisted of relatively uniform sand have increased habitat heterogeneity [60]. Local changes to benthic communities have occurred, affecting typical fauna communities, with most aquatic animals living in the seabed, to hard bottom communities with increased abundance and biomass. There was a massive colonisation by common mussels, and a cover of algae was found shifting from an initial colonisation of filamentous green algae to a more diverse and permanent vegetation of green, brown, and red algae (Leonard and Pedersen, 2005). The Horns Reef wind farm will act as no-take zone since a cable protection zone of 200 m is going to be established around the wind farm and the cable where anchoring and fishing will not be allowed.

5.3. Alternative Designs to Enhance Biomass and Diversity. There are several designs of scour protection that have been suggested to function both as scour protection and effective artificial reef around wind power foundations. The SeaCult Reef System consists of a circular, perforated concrete cylinder with plastic pipes inserted radially into the perforations (Figure 3) and has a diameter of 6.4 m. The reef may be applied standing, but will be more stable if applied lying down on the seabed in Grip Reef mode. In this mode, parts of the pipes are removed to provide a stable footing. The reefs are used to stimulate marine growth and to control erosion of the seabed. Possible fields of applications are cultivation projects for establishing fishing grounds as artificial habitats and erosion projects in coastal areas and around offshore installations. Field observations during several years (2002–2006) showed high densities of fish and sessile organisms using the structures as habitat, establishing high diverse hard substrate communities [69]. However, low sample size ($n = 2$) just gave an indication and no statistically significant conclusions concerning biodiversity and abundance could be drawn.

Reef Balls are a specially designed artificial reef used to restore ailing coral reefs and to create new fishing and scuba diving sites [70, 71]. Reef Balls have been applied for beach protection, freshwater, mitigation, and many other uses too. These reefs are about 1.83 m wide and contain around 25–40 holes and a hollow centre. They have been successful within habitat creation both in tropical and temperate waters. The estimated carrying capacity of a reef ball is about 385 kg fish during a year and there will be needed 169 reef balls to cover a scour area [16]. The yearly fish biomass around the base of one wind turbine has been calculated to be 65 000 kg. That shows how efficient that area may become when reef balls are installed compared to control areas. The same case will be expected with the deployment of several SeaCult Reef Systems (Table 1). Even though the expected carrying capacity might be greater than for gravel or boulder protections, negative aspects may be higher expected costs due to specific designs and production processes.

6. Aquaculture and Offshore Energy Installations

The rearing of marine organisms under controlled conditions can be combined locally with offshore energy installations [50, 72]. Thus, it would be within the footprint of the energy installations and should also be applied under environmentally friendly conditions, since sustainability is one of the worries for managers and regulators within the field of renewable energy production. Fishery management is one of the major topics and requires a deeper understanding of ecosystem functioning with its structure and dynamics. An increase in seafood consumption and a decrease in wild fish stocks raise the importance of a higher support for open ocean aquaculture [73]. Today, the most common finfish species used in marine fish farms is salmon [73]. Mussel (*Mytilus* spp.) production is one of the most economically important aspects of global aquaculture and has increased in both the global production and value [74]. In Europe, the annual production of mussels lies about 50% of total the world's production [75]. In Norway kelp has been commercially harvested during the past 40 years by trawling along the coast and the annual harvest is about 170 000 tons. A multifunctional comanagement may be possible for offshore energy installations and open ocean aquaculture where solid turbine foundations can serve as anchor points. In that way both installations will simultaneously use a certain area and may gain both economically, environmentally, and technically. In a review by Buck et al. (2004) a programme for the combination of offshore wind and marine aquaculture has been suggested [72]. The most important points were that (a) a positive spin-off effect may be approached by using existing fishermen with their (modified) boats for the maintenance of wind turbines and for harvesting from aquaculture facilities, (b) local fishermen with their local knowledge have advantages to establish their own aquaculture business, (c) wind foundations can be used to satisfactorily solve anchoring problems by aquaculture structures, and (d) since both constructions share the same area, it is economically efficient to undertake environmental impact assessments.

Furthermore the whole system does not allow fisheries within the offshore farms which are beneficial for the preservation of existing spawning and breeding grounds. Additional hard substrate introduced by the aquaculture structures will be positive for the productivity and diversity of the ecosystem in terms of artificial reef effect. The carrying capacity will be higher and so will density and biomass of several species.

7. Conclusions

When introduced into the marine environment, turbine towers together with their associated scour protection, constitute an artificial reef, and the surfaces are readily colonised by a typical and broadly predictable assemblage of organisms, reflecting zonation patterns observed in adjacent rocky shore communities. Although the scientific literature mostly agreed that there is likely to be a positive effect on fish and crabs, the extent and nature of the effect, it appears, is heavily dependent on the nature of the reef created, the location, and the characteristics of the native populations at the time of introducing the artificial reef. A greater increase in surface area of scour protections by using specially designed material, such as reef ball or SeaCult offshore protections may in fact enhance the reef effect with biodiversity and species richness around the energy devices. Still, a significant research effort is required to predetermine specifically the eventual advantages when creating new habitats and how they can be positive on commercial interesting species such as fish, lobsters, and crabs. To achieve a positive side effect, it is essential that offshore energy installations will be strategically located and monitored carefully. Unfortunately, many artificial reefs have problems to achieve their intentions to enhance biomass production due to lack of knowledge about involved species and habitat requirements of target species. Long-term monitoring of the different scouring protections, gathering data of occurring species and successions, is of high importance. Detailed ecological studies that test the enhancement potential of different types and dimensions of scour protection are necessary. Before developing options for fisheries around closed zones, studies to clarify key questions about target species and the nature of scour protections are needed. An exclusion of trawling in the areas seems to be convenient for both operation of offshore devices and conservation management. Temporarily, fishermen may be affected negatively by no-take zones in and around offshore energy farms. But in a longer term, a spillover of fish and invertebrates to other areas open for commercial fishing is expected. Studies on these spillover organisms using different tagging methods (electromagnetic, acoustic telemetry and conventional) would provide some more exact data on movements, occurrences, and behavioural patterns. Another interesting approach and useful management tool can be to conduct genetic studies for obtaining information about connectivity and spatial population structure of organisms colonising offshore energy devices.

A multifunctional area that includes mussel farming or seaweed cultivation appears to be one of the most straightforward economic opportunities within existing offshore parks. Still, much research needs to be done to design culture techniques that resist harsh climates in these high energy environments and to combine them with offshore energy installations.

Habitat loss cannot be mitigated, but compensation can be done either by creating new habitats in the same location or the same habitat somewhere else. There is a good potential for offshore renewable energy installations and their associated scour protection to provide a certain amount of habitat creation. This could have far-reaching benefits for both the local and regional environment, as well as potentially local fisheries using the area. With further work, using more recent data sets and employing modelling techniques, it would also provide a greater argument in the future for the installation of offshore energy installations, strengthening planning applications for future developments.

Finally, different offshore energy parks should cooperate on environmental aspects, based on a BACI design to accelerate application process and to reduce the need to repeat studies. That will help good techniques to reach the market and deliver environmental friendly energy.

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