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A framework to evaluate the environmental impact of OCEAN energy devices

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ABSTRACT

Ocean energy technologies are still at an early stage of development; only a handful of concepts are being invented and tested worldwide. The environmental impact of these devices is not always taken into account, mainly because of the prevailing uncertainty regarding its assessment. It is vital that attention is paid to the mitigation of potential negative impacts on physical and biotic marine systems. In this study, the direct and indirect effects of ocean energy projects on biophysical systems, and their interactions, are identified from an analysis of current literature on the subject. A tool that could be applied to any ocean energy project at any stage of an EIA is then proposed from a framework designed to evaluate the widely varying impacts of devices. This framework uses a categorisation of the environmental impacts of MRE devices (biophysical, chemical and socio-economic), based on the technology used and the device location. It is hoped that this tool will facilitate the identification of the potential environmental impacts of MRE devices and thus serve as a guide to quantitatively assess these impacts.

1. Introduction

Converting energy from ocean sources is considered one of the main strategies to reduce carbon emissions [1,2]. One of the most ambitious goals of developing ocean energy technology is the mitigation of global warming, contributing to a 2 °C reduction by 2100 (REN 2017). Converting ocean energy involves the spatial use of marine ecosystems, which are recognised as being of the lesser known ecosystems worldwide, meaning that the potential environmental impacts and negative consequences in the provision of ecosystem services are difficult to predict [3].

Even so, the huge amount of available energy from the oceans is motivating research into the design, construction, and installation of wave energy conversion devices, even in difficult and extreme conditions [4]. The technological means as well as the advances in these concepts vary and, around the world, only a handful of full-scale prototypes have been tested [5,6]. Most operational ocean energy projects use tidal currents; 90% of the installed tidal installations worldwide, are in Sihwa, South Korea and La Rance, France, [5]; REN21 2017). Other ocean energy sources (saline gradient and ocean thermal energy conversion) are still at a very early stage of technological readiness, and most of the developments are still only at the stage of laboratory testing. Countries such as Canada, China, Chile, the United States, the United Kingdom and Mexico have become involved in the development of these technologies and have pilot projects adapted to local conditions [5]; REN21 2017; [7]. In all, there are over 100 conceptual designs for energy conversion from waves, ocean currents, thermal gradient and saline gradient today (REN21 2017).

The importance of the ecosystem services provided by coastal-marine systems and the potential impacts (physical, ecological and socioeconomic) of human activities on them have been increasingly acknowledged [8–10]; Frase el al. 2018). However, impact assessment on marine areas is a complex task, as it depends on understanding marine ecosystem functioning, its resistance and resilience and its responses to anthropogenic pressures [11,12]. In consequence, one of the challenges facing ocean energy generation is the evaluation of the possible impacts that each kind of device can generate in its surrounding environment, specifically in the hydrodynamics,

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geomorphology, the chemical properties of the seawater and sediments, biotic interactions and socioeconomic aspects [7,8,12,13]. The range, or heterogeneity, of ocean energy technologies further increases the complexity of any environmental impact assessment. The occurrence and magnitude of direct, indirect and cumulative impacts on the ecosystems in which the ocean energy devices are installed depend on the local features of the ecosystems and differ for each device, its operation and the dimensions of project [1,8,12–16].

Recently, Willsteed [17] recognised that the cumulative environmental effects of renewable ocean energy projects remain highly uncertain and are problematic in light of the ambitious renewable energy targets and the desire to use our seas sustainably. Efforts to reduce uncertainties to acceptable levels are complicated, first and foremost, by the numerous gaps in the knowledge concerning the cause-effect relationships between devices, or groups of devices, and ecosystem components. In this sense, the focus of the present work is threefold. First, expected environmental impacts were characterized according to ocean energy project type, based on a review of the literature. Secondly, the interactions between the devices and the environment, and the gaps in knowledge were both analysed, in order to build a framework to identify the main environmental impacts of ocean renewable energy devices. Finally, this framework was applied to two case studies.

2. Methods

2.1. The literature review

Peer-reviewed articles, published between 1986 and 2018, were examined. Articles were extracted from the digital database Scopus, searching the terms “renewable energy”, “ocean”, “coastal” and “impact”. Only papers concerning a project already installed, and in which at least one environmental impact had been assessed, were considered. Information was extracted from the studies, including the geographic region, device type, location within the water column and the type of impacts assessed.

2.2. Development of the device classification framework

In this paper, a novel framework is proposed which can serve as the means to distinguish between related environmental impacts depending on the type of ocean energy source, the device to be deployed and its biophysical interactions. This framework gathers research findings from the literature review and classification of devices, to unify the widely varying criteria used to assess impacts, as the basis for developing a tool that could be applied to any ocean energy project. The framework was applied to two case studies.

3. Results

3.1. Literature review of environmental impacts identified worldwide

3.1.1. General trends

335 articles, written since 1986, were found (see Fig. 1). Of these, only 22 describe an energy project that has been implemented and include information about the environmental impact assessment. The remaining articles only had information about the functioning of the device, possible effects and/or numerical simulations. In the last four years, there has been a considerable increase in the number of studies undertaken (193, compared to 164 in the previous 27 years).

Although a general increase can be seen in Fig. 1, some local variability is also evident. Arguably, the peaks and troughs may be a response to the evolution of the development of technologies as this behaviour follows the evolution of patents in ocean energy technologies reported by the International Renewable Energy Agency (IRENA [18], with a time lag of one or two years.

Energy conversion devices were deployed in Asia (mainly China, Japan, India, Russia, Turkey, Malaysia, Iran); Europe (UK, France, Italy, Spain, Sweden, Portugal, Ireland, the Netherlands, Denmark, Norway, Germany, among others) and in the Americas (USA, Canada, Mexico, Peru, Colombia, Brazil, Barbados and the Bahamas). Most ocean energy projects have taken place in Europe, followed by the Americas, Asia, and Oceania (Fig. 2). In contrast, impact assessment cases were only available for deployments in the UK, USA, Canada, Sweden, Portugal, Japan, Denmark, and Germany. It is also interesting to note the long time lapse between the first study on ocean energy and the first impact assessment work found; 8 years, with the USA the first country found to have published an Environmental Impact Assessment (EIA).

The vast majority of environmental studies found in the literature review have focused on tidal turbines (45.45%) and wave energy converters (WECs) (36.4%), with a smaller number focusing on ocean current and river turbines (9.09%), OTECs (4.56%) and marine wind farms (4.5%). Most of the studies analysed the impacts during the operational phase of the project, while only three evaluated possible impacts before installation and only one evaluated the impacts of before and during installation. In Table 1 it can be seen that, in the majority of the cases, the impacts evaluated were environmental, while socioeconomic and negative chemical effects were rarely addressed (two and one articles, respectively).

Among the main impacts identified are the physical damage caused to marine and coastal habitats and the possible effects of noise on marine mammals. The importance of monitoring these impacts during installation and operational phases is often highlighted, even if the study case itself did not evaluate those phases.

3.1.2. Type of devices and possible impacts

Fifteen kinds of devices were found, including vertical and horizontal axes turbines, floating devices with vertical movement such as attenuators and point absorbers; systems that use wave surges, such as overtopping devices and oscillating wave surge converters; cross-flow turbines or barriers and oscillating water column converters.

The possible environmental impacts of the devices will depend on characteristics such as the energy source, the construction materials and the operation principle of the device. However, regarding their particular characteristics, all could be classified according to their position in the water column (Fig. 3).

3.1.3. Environmental impacts

Twenty possible impacts were found in the literature review. However, the indicators needed to evaluate all of these impacts were not found. Furthermore, none of the projects which included EIA refer to a comprehensive set of indicators for physical, biological, and social impacts in any of the project phases.

The most common environmental impacts addressed were the loss of habitat integrity and connectivity; changes in nutrient availability and ecological interactions; modification of coastline dynamics and water column physicochemical properties; an increase of noise and vibrations; loss of recreational activities, fishing opportunities, scenic value and mental health issues arising from conflicts with local communities. From the data found, the possible impacts can be categorised as a) hydrodynamic modification; b) physical or geomorphological alteration; c) chemical effects; d) biotic interference and, e) potential socio-economic losses.

3.1.4. Relationship between the type of device and the expected impacts

Depending on the type of device and the local environmental conditions, the interactions between them will be more or less important. Surface and floating devices are commonly related to biotic (aerial and marine habitats) and socioeconomic (exclusion zones) impacts, while geomorphological and chemical interactions were seen as being less important (Table 2).

Interactions between submerged devices and socio-economic aspects were frequently mentioned in the literature review [31]; Bonar

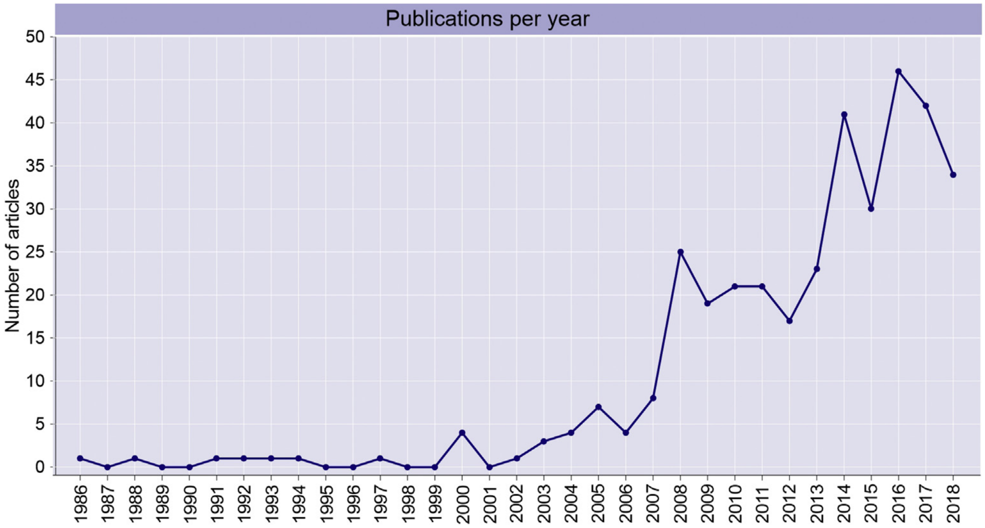


Fig. 1. Relevant publications per year, 1986 to August 2018.

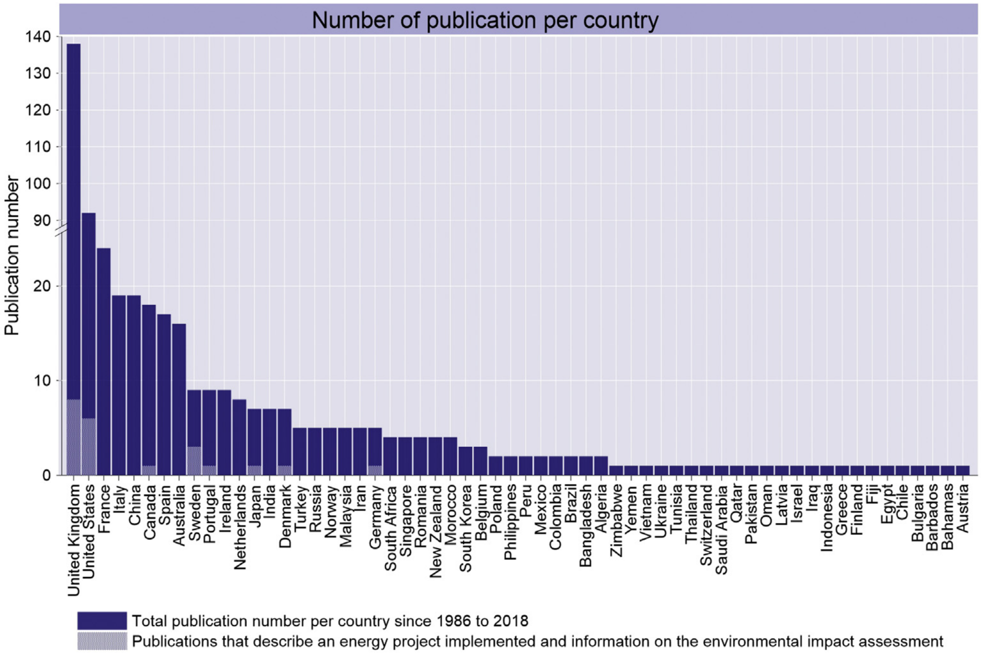


Fig. 2. Relevant publications between 1986 and 2018 by country.

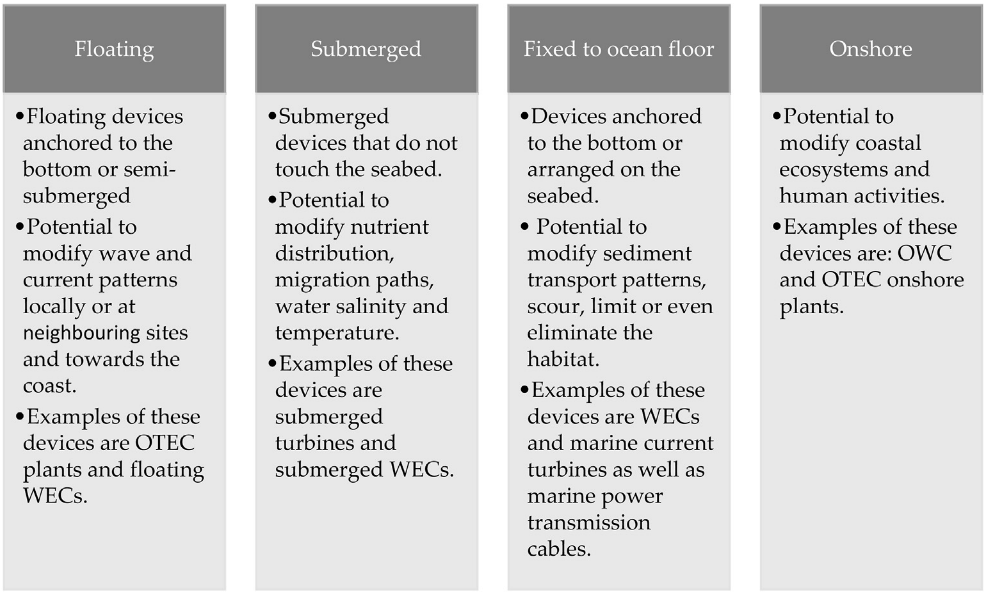
et al.; [32], with the changes in water column stratification (hydrodynamic interactions) identified as the main effect of these devices. In consequence, possible effects on the halocline, pycnocline, and thermocline (chemical interaction) gradients were observed. In turn, bottom devices were strongly associated with changes in seabed morphology (geomorphological interactions), vertical mixing in the water column (hydrodynamic interaction) and marine habitat perturbation (biotic interactions) [6]. Among the category "onshore", tidal barrages were perceived to have a high impact on biotic and social interactions (coastal habitat and recreational opportunities, respectively and socio-economic interactions) [33]. Bottom device impacts were also seen as having a high impact on sediment dynamics (geomorphological interactions), but changes induced in the coastline were more frequently mentioned than possible effects on seabed morphology (geomorphological interactions) [24]. Fig. 4 shows the interactions and the intensity found between devices and their surrounding environments.

Ecological interactions include aspects related to habitat integrity and connectivity, as well as nutrient availability and ecological interactions. These refer mainly to the presence of devices where previously they did not exist. Ocean energy devices can generate changes in the environment, acting as an artificial barrier and interrupting the connectivity to small organisms; they can also produce a constant collision risk to bigger organisms such as cetaceans, fish and aquatic birds [2,12]. These devices can also impact biodiversity by functioning as an artificial reef. Even though they do not have this primary function; they will inevitably be colonized by organisms. Artificial reefs can house different communities to those in natural reefs and have the potential to change or modify the biodiversity in nearby areas, therefore generating changes in food webs [23]. During the construction and maintenance stages of the devices, changes in the water chemistry and nutrient availability may be induced, mainly when deep water is brought to the surface. Some pollutants may be present through the life of the device including heavy metals, carbon dioxide and high concentrations of nutrients [2].

It is known that the greatest noise disturbance is produced during the construction period, due to typical building noises. Once the devices

Table 1
Environmental impacts assessed in the peer-reviewed literature.

Region (country)	Ocean energy technology	Device	Impacts	Reference
USA and Canada	Tidal power plant	Submerged horizontal axis turbine	Biological: Physical damage to marine fauna	[19]
Germany	Underwater trans. cables	Marine cables anchored or arranged on the bottom	Biological: Exposure to a static magnetic field	[20]
Denmark	Offshore wind park	Wind turbines	Biological: Physical injury to seabirds	[21]
Sweden	Wave energy	Linear generator attached to a foundation on the seabed, and buoy at the surface	Biological: Creation of new habitats	[22]
Sweden	Wave energy	Generator attached to a foundation on the seabed, and buoy at the surface	Biological: Colonisation of foundations by invertebrates and fish (new habitat)	[23]
Sweden	Wave energy	Generator attached to a foundation on the seabed, and buoy at the surface	Biological: Changes in microfaunal biomass, abundance and biodiversity	[24]
Portugal	Wave energy	Generator attached to a foundation on the seabed, and buoy at the surface	Physical: changes in wave energy	[25]
United Kingdom	Tidal energy	Devices anchored to the bottom with submerged turbines	Socio-economic: Social perception of devices, construction and operation	Devine-Wright [32]
United States	Wave energy	Submerged wave energy devices	Biological: Potential noise impacts of WEC installation and operation	Haxel et al.[43]
United Kingdom	Tidal energy	Devices anchored to the bottom with submerged turbines	Biological: Changes in megafauna occupation patterns, distributions and behaviour	[26]
United Kingdom	Offshore wave, and tidal installations	Construction phase	Biological: Changes in the anti-depredator response	[27]
UK/US	Tidal energy	Device anchored to the bottom with submerged turbines	Biological: Changes in pelagic nekton biological characteristics	[28]
Ireland, Spain, Sweden, Portugal, France, and the UK	Wave power generator	Submerged wave energy devices and devices anchored to the bottom	Biological: Changes in biodiversity, Socio-economic: Local landscape, Geo: Changes in physical factors, Hydro (hydrodynamics), and Chemical (water quality)	[6]
Japan	Current turbines	Submerged device anchored to the bottom	Biological: Changes in marine fauna behaviour around turbines	[29]
United States	Tidal energy	Devices anchored to the bottom with submerged turbines	Socio-economic: Perception of tidal energy	[13]
United Kingdom	Tidal energy	Devices anchored to the bottom with submerged turbines	Biological: Changes in seabird, fish and marine mammal behaviour, and collision risks	[7]
United States	Tidal energy	Device anchored to the bottom with submerged turbines	Biological: Changes in fish behaviour	[8]
United States	Tidal energy	Device anchored to the bottom with submerged turbines	Biological: Changes in fish distribution due to noise	Schramm et al., 2017
United Kingdom	Tidal energy	Device anchored to the bottom with submerged turbines	Biological: Changes in rates of fish schools	[14]
United Kingdom	Tidal energy	Device anchored to the bottom with submerged turbines	Biological: Changes in fish migration behaviour	[15]
Ireland	Tidal energy	Device anchored to the bottom with submerged turbines	Biological: Change in marine mammals behaviour	[30]



Floating

- Floating devices anchored to the bottom or semi-submerged
- Potential to modify wave and current patterns locally or at neighbouring sites and towards the coast.
- Examples of these devices are OTEC plants and floating WECs.

Submerged

- Submerged devices that do not touch the seabed.
- Potential to modify nutrient distribution, migration paths, water salinity and temperature.
- Examples of these devices are submerged turbines and submerged WECs.

Fixed to ocean floor

- Devices anchored to the bottom or arranged on the seabed.
- Potential to modify sediment transport patterns, scour, limit or even eliminate the habitat.
- Examples of these devices are WECs and marine current turbines as well as marine power transmission cables.

Onshore

- Potential to modify coastal ecosystems and human activities.
- Examples of these devices are: OWC and OTEC onshore plants.

Fig. 3. Type of devices according to their position in the water column.

are installed and running, those with moving parts, such as turbines, will be the noisiest. Some studies suggest that marine mammals respond to the presence of extra noise, by moving away from the noise source and that, once the noise disappears, they return to the area. However, the response of marine biota to a permanent sound source is still unknown [34].

The electricity generated by the ocean devices is usually carried by marine cables. These can produce electromagnetic fields, the intensity of which depends on the amount of electricity running through each cable. It is known that a large number of aquatic species are sensitive to electromagnetic fields, mainly those that take part in large-scale migrations. However, there is still a lack of evidence on the electromagnetic effects on the receptors and possible biological importance [33,34].

Geomorphological interactions refer to aspects related to the coastline, seabed, water column, sediments, sounds and vibrations, water temperature, wave direction, current direction, and electromagnetism. The presence of any obstacle, such as wave energy converters, can result in localized changes in wave energy, water turbulence, modifications in water circulation, and marine currents, as well as alterations in tidal ranges [1,2,33]; [11,12].

Socioeconomic interactions are those related to the possible effects on recreational activities, fishing opportunities, scenic beauty and mental health. Support for renewable energy is often derived from environmental concerns and ethical obligations to displace fossil fuels and reduce greenhouse gas emissions which in turn; are supported by the resulting social benefits [31,35]. According to Bedard [31] and Bonar et al. [35]; some of the benefits that ocean energy offer society

Table 2
Classification of ocean energy conversion devices according to their environmental interactions.

Classification according to environmental interactions	Interactions	Description
	Hydrodynamic	*Free water surface:* Floating devices, attached to the sea bottom or semi-submerged structures. Potential to disturb wave patterns. i.e. OTEC plants, WECs near the surface or floating, devices of large dimensions near or above the free surface.
		Water column: Devices affecting the vertical water column. Vertically large enough to produce changes in water column velocities. i.e. submerged turbines, OTEC plants, and WECs anchored or deployed at sea.
	Geomorphologic	*Sea bottom:* Can modify sediment transport patterns, scour or limit/destroy associated habitats. i.e. WECs or turbines anchored or deployed at the sea bottom and marine cables for electricity transmission.
		Coastline: Devices capable of attenuating or concentrating energy from waves and currents. Sediment accumulation or removal of material from nearby beaches. i.e. semi-submerged WECs, low-depth turbines, plants that discharge near the coastline.
	Chemical	*Salinity:* Devices producing chemical interactions (natural conditions of salinity stratification). i.e. reverse electrodialysis (RED) and pressure retarded osmosis (PRO) salinity gradient plants and OTEC plants.
		Temperature: Devices affecting temperature often disturb the thermal stratification. i.e. RED and PRO salinity gradient plants and OTEC plants.
		Other discharges and emissions: Devices discharging or emitting harmful fluids or substances to the marine environment as a main or secondary product.
	Biotic	*Aerial habitat:* Devices which change reproductive and migratory habits of coastal birds, as well as risk of collision.
		Marine habitat: Any device which can alter reproductive and migratory habits; food availability and nutrient distribution; and may cause collision risk. The impact is a function of the dimensions.
		Coastal terrestrial habitat: Any device that can generate collision risk, interrupt ecosystem connectivity, block migration pathways or destroy areas for nesting or raising, as well as changes in food availability and nutrient distribution.
	Socio-economic	*Fisheries:* Devices that reduce the area available for fishing, or the reproduction of species for human consumption; they may result in the creation of areas where fishing is not allowed for safety reasons.
		Recreational areas: Devices deployed near the coast may interfere with recreational or sporting activities.
		Marine and terrestrial landscape: Large or highly visible devices could interrupt landscape continuity.

Interactions	Floating	Submerged	Bottom	Onshore
Far field sediment transport and properties	🟧	🟨	🟩	⬜
Local sediment transport and properties	⬜	🟨	🟥	🟥
Current direction	🟩	🟧	🟩	⬜
Wave energy distribution	🟥	🟩	⬜	🟥
Wave turbulence	🟩	🟨	🟥	⬜
Habitat	🟥	🟧	🟥	🟥
Ecological interactions	🟨	🟧	🟧	🟧
Electromagnetism	🟧	🟧	🟨	⬜
Noise and vibration	🟨	🟨	🟨	🟥
Nutrients	🟩	🟨	🟨	🟨
Water quality	⬜	🟨	🟨	🟨
Fishing	🟥	🟥	🟨	🟩
Recreation	⬜	⬜	⬜	🟥
Scenic value and mental health	🟩	⬜	⬜	🟥

Degree of negative impact	⬜	🟩	🟨	🟧	🟥
	No impact	Very low	Low	Medium	High

Fig. 4. Classification framework. Interactions between the type of device and the surrounding environment, with the expected adverse impact intensity. (No impact means none reported to authors' knowledge.)

are: reduced the dependence on imported energy supplies, reduction in the volatility of fossil fuel prices, reducing greenhouse gas emissions and stimulating the creation of employment and development at a local level. On the other hand, the noise disturbance induced by the installation and operation of ocean energy converters can have negative impacts on the local fishing, navigation safety, recreation activities, tourism, property value and quality of life [36,37].

In terms of quality of life Meireles et al. [38] carried out a study in Ceará, Brazil. They found that the wind farm construction affected the population; producing insomnia and constant discomfort mainly due to noise. Other studies report similar results concerning the continuous noise generated by rotors in North Carolina and Massachusetts, United States [39]. The destruction of public water supply sources, water and soil quality loss and negative impacts on archaeological sites have also been reported [40,41]. Studies in the Netherlands, England and Wales concluded that the presence of power plants causes a fall in property prices of up to 2–6% [42]. Gibbons [42] also suggested that, in places like Denmark and the United States, residents are willing to pay more to avoid seeing energy parks near their property. et al. [35]; concluded that communication, education, exchange of information, improvement in public participation practices, as well as avoiding exaggerated economic projections could produce greater acceptance of renewable energy projects and gain the trust of local communities.

4. Proposed classification of devices to facilitate EIA

A simple classification of environmental impacts related to ocean energy conversion devices is proposed in terms of their potential impact on the marine hydrodynamic, geomorphologic, chemical, biotic and socio-economic fields (Table 2).

The device classification shown in Table 2, combined with the flux diagram of Fig. 5 clarifies the application of the proposed framework. Section 5 gives some examples of this process.

5. Classification examples

The proposed framework was applied to two different types of prototypes (onshore and offshore); it can be seen that once the device classification is set (device position and interactions) the identification of specific impacts is facilitated. Hence, the scoping phase of EIA can be fulfilled in a more intuitive and certain way.

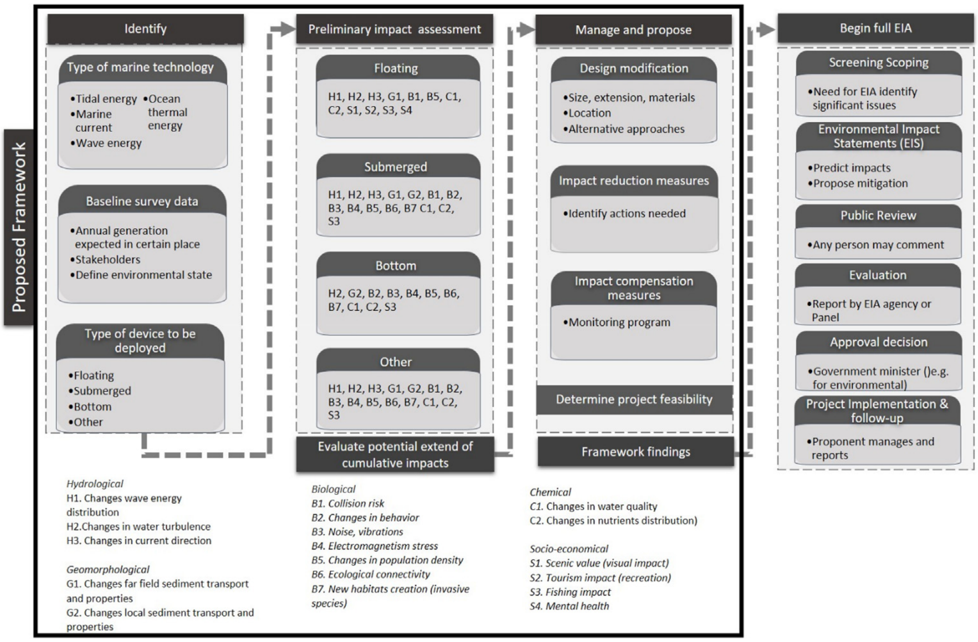


Fig. 5. Flux diagram for the proposed framework.

5.1. SeaGen-S, submerged tidal turbine

SeaGen-S is a 2 MW tidal stream generator with a horizontal axis turbine, located in Strangford Narrows, Northern Ireland. SeaGen-S is considered the most advanced, field-proven tidal generation system available. The SeaGen-S tidal turbine incorporated twin horizontal axis rotors and was developed by Marine Current Turbines Ltd.

The turbine technology consists of a pair of two blade horizontal axis rotors mounted on a pile. The diameter of each rotor is 20 m, and both are connected to a gearbox that increases the rotational speed of the shaft to drive a generator. SeaGen-S is suitable for marine environments with a water depth of up to 38 m and has higher efficiency with tidal currents greater than 2.4 m/s. It operates automatically, self-starting when the tide reaches an average speed of about 1 m/s. When operating below rated power, the pitch angle and rotor speed are self-adjusted to maximise the hydrodynamic efficiency.

The biophysical interactions identified for the EIA of such a device are:

- Hydrodynamic: Changes in water turbulence and water circulation.
- Geomorphologic: Changes in local sediment properties (more than one device).
- Biotic: Induces collision risk, changes in behaviour, noise, vibrations, and electromagnetism stress as well as new habitat creation, changes in population density, and ecological connectivity (only with more than one device).
- Chemical: Changes in gas distribution
- Socio-economic: Impact on fishing.

5.2. Mutriku oscillating water column

Mutriku harbour, in the Bay of Biscay is regularly hit by heavy storms that often cause damage to the piers, so a 440 m-long, detached rubble mound breakwater was built, in 2005. In 2011 a wave energy plant was installed on the breakwater, without affecting the primary functions of the structure. Several technologies were examined and the Voith Siemens Hydro oscillating water column (OWC) technology was chosen because of its simple and non-disruptive design. The Mutriku wave energy plant generates 30 kW, to power 250 households.

The plant includes a hollow, trapezium shaped structure, with a front opening, which is submerged, and an opening at the top. The front opening is 3.20 m high and 4 m wide. The hollow structure contains 16 air chambers housing 16 turbines. Each turbine weighs 1200 kg and is 2.83 m high and 1.25 m wide. They do not have a gearbox, hydraulics or pitching blades and are connected to a turbogenerator with a capacity of 18.5 kW. The turbogenerator has a butterfly valve at the bottom to isolate it, if necessary. The plant also has control and power conditioning equipment, a transformer centre and a power take-off line.

The biophysical interactions identified for the EIA of this device are:

- Hydrodynamic: Changes in wave energy distribution; changes in water circulation.
- Geomorphologic: Changes in erosion/accretion patterns; changes in sediment properties.
- Chemical: Changes in gas and nutrient distribution.
- Biotic: Changes in behaviour; changes in population density and ecological connectivity; new habitat creation.
- Socio-economic: Landscape interruption, tourism impact and fishing impact.

6. Discussion

The use of marine areas for electricity plants can severely impact nearby ecosystems. Although some of these impacts may be considered positive, and although the overall benefits are undeniable, in terms of increasing energy availability and reducing greenhouse gases emissions, a proper analysis of the possible impacts together with the identification of strategies for their minimisation and mitigation should be mandatory. Even though this is widely known and accepted, many developers and institutions still find it difficult to assess impacts, partly because of the lack of a comprehensive framework. It is hoped that the classification and impact identification facilitator presented here may help in developing more effective EIA for ocean energy conversion projects.

6.1. Main findings

In this review, a list of 15 devices and 20 possible environmental and social impacts were compiled. All the case studies found emphasised the importance of the spatial and temporal extension of the individual project. Arguably, the main difficulties presented in the available literature are the lack of consensus about EIA and envisaging the possible impacts with no long-term monitoring of marine ecosystems.

6.2. Hydrodynamic

Free water surface: Free water surface impacts are mostly related to floating or semi-submerged devices that are anchored to the sea bottom. According to the numerical models of Leeney et al. [11]; floating or semi-submerged wave energy converters will extract between 3 and 15% of the wave incident energy; this can cause localized changes in the wave and current distribution and water turbulence patterns. These impacts increase with the size of the device, or array of devices.

Water column: Water column impacts are related to submerged devices. Palha et al. [25] and Greaves et al. [6] demonstrated that changes in wave energy, generated by the presence of semi-submerged or submerged devices, can modify the hydrodynamic interactions, which in turn can alter the sediment transport patterns and modify the availability and distribution of nutrients. In the case of arrays of devices, special attention should be paid to the overall circulation damping, not only within the energy plant but also nearby.

6.3. Geomorphologic

Sea-bottom: The sedimentary and seabed characteristics could be modified by the presence of devices. It has been reported [24] that the presence of devices resulted in changes to local sediment size; this, together with scour and other effects, may degrade the benthic habitat.

Coastline: Palha et al. [25] found that wave energy damping due to the presence of devices may produce erosion and sedimentation in places where there this did not occur previously. These severe, rapid environmental changes should be avoided if sustainability is the goal. When the plant uses an array of devices, the wave energy damping can be estimated via numerical procedures, but the possible beach response is harder to forecast and requires the use of various tools for reliable results.

6.4. Chemical

Alterations to wave energy patterns and current circulation can cause changes in gas transport and distribution, as well as in nutrient distribution and availability. When such impacts are unavoidable, mitigation and compensation measures must be taken, and the size of the affected area should be determined as precisely as possible.

6.5. Biotic

6.5.1. Aerial habitat

Boehlert and Gil [34]; stated that devices with parts above the sea surface could be a collision risk for seabirds and migratory birds. The same issue was addressed by Larsen and Guillemette [21]; who found that coastal birds avoid flying near, or within, wind farms because of the movement and noise they generate. Other impacts that need to be assessed include food availability for birds and, in the case of non-movable parts, the provision of space for colonisation by birds.

6.5.2. Marine habitat

Bevelhimer et al. [8] detected a decrease in fish abundance, to approximately half of the population, after the construction of a tidal energy turbine. In the fish that remained, changes in behaviour were found (to avoid their collision with the turbines, such as adjustments in swimming direction and speed). No evidence was found of fish colliding with the rotating blades. Similar results were obtained by Zhang et al. [29] in a laboratory experiment based on a scaled test of the turbine rotation speed and a maximum swim speed of marine animals; a 100% survival rate was reported after 48 h. These authors point out that the area occupied by the fish, and the rotation of the turbines produce significant effects on the movement of the fish, although there is no direct interaction between the two parameters. Likewise, in a more recent study, Piper et al. [15]; found that most eels and adult fish avoided a turbine by modifying their migration routes. It is unknown if such changes in behaviour will have any significant consequences on normal fish movement patterns, bioenergetics, seasonal migrations and predator exposure. As for marine mammals, Sparling et al. [30]; conducted a study with seals, of the species *Phoca vitulina*, and found that the presence of the turbine did not produce a 'barrier' effect, in that it did not alter the transit of the seals through the channel. However, when the turbine was operating, the seal behaviour did change. The findings therefore, suggest that collision risk is less important than the changes in the behaviour of marine fauna; it has yet to be investigated if these changes affect their survival rates.

Another impact which has not been sufficiently documented are changes in the marine electromagnetic fields. Bochert and Zettler [20]; conducted laboratory experiments with crustaceans and showed that externally applied magnetic fields could interact with their biological systems, producing detectable changes in their reproductive behaviour.

Everley et al. [27] conducted an experiment in three ports in the United Kingdom, concluding that the noise of pile construction can negatively affect the anti-predator behaviour of fish, which would increase the probability of individuals being killed by predators.

6.5.3. Coastal habitat

Work on the use of infrastructure by marine fauna as an artificial habitat, include Langhamer and Wilhelmsson [22]; and Langhamer et al. [23]. Both of these studies examined the function of structural foundations, in Lysekil, Sweden, as an artificial reef. The main findings were that three months after completion of the construction of a power plant, the density of mobile organisms was significantly lower, while the abundance of fish and crabs in the foundations of the plant was higher than in the surrounding soft bottoms. Similarly, Want et al. [16] and Fraser et al. [14] found more fish schools around structures associated with a project on the coasts of Orkney, United Kingdom. In addition to the alteration of the habitats, colonisation of the infrastructure brings the risk of biofouling.

6.6. Socio-economic (fisheries, recreational areas, and landscape)

Fisheries. One of the main socio-economic problems produced by the presence of ocean energy plants could be direct damage to the marine macrofauna. For example, Dadswell and Rulifson [19] found a large number of injured or dead fish in the area of influence of the plant located in the Bay of Fundy, USA, concluding that the plant can significantly affect the fish population and also, therefore, nearby fisheries.

Other possible impacts are fish avoiding and evading the site occupied by the devices and its area of influence. Boehlert and Gill [34]; Bevelhimer et al. [8] and Haxel et al. [43] showed that fish responded to the noise of the device by moving as far as possible away from the noise source.

6.7. The novel framework

The wide variety of interactions, devices and possible impacts found in the review conducted, shows the need for a classification framework. The framework helps not only to identify the impacts to be evaluated but also helps in disregarding impacts which are not associated with specific technologies, locations or interactions. The usefulness of impact disaggregation is evident in the two examples provided, where obvious impacts were detected, together with other, less obvious impacts. In both cases, non-relevant impacts were left aside.

The classification proposed has the advantage of being simple and intuitive, but sufficiently comprehensive for use by private institutions, investors and stake holders. The main idea is to offer an initial approach to EIA, which is still quite complex and uncertain regarding ocean energy exploitation.

6.8. The problem of including cumulative effects

The better understanding of the impacts of ocean energy devices relies on acknowledgment of the effects of existing devices and how they interact with other effects of human activities in that same environment. Cumulative environmental evaluation effects may be considered from different viewpoints [17,44]:

- Temporal accumulation: refers to the changes caused by accumulative disturbances over time. This is one of the least studied fields, mainly due to the lack of data.
- Spatial scale: refers to the effects that overlap the physical space with any scale.
- Endogenous and exogenous disturbances: refers to the multiple pressures from endogenous sources, that is, those created within the system; and exogenous those that come from outside the system, or that operate beyond the scale of the system.

In light of recent, ambitious renewable energy goals for the seas, Willsteed [17] recognised that the cumulative environmental effects of renewable ocean energy developments remain highly uncertain and problematic. Efforts to reduce these uncertainties are hindered by the numerous gaps in the knowledge regarding the cause-effect relationships between devices or groups of devices and ecosystem components.

The classification and identification proposed here may help to evaluate cumulative impacts a priori, or even during the operation stage of energy plants, and can be applied recurrently (e.g. yearly). A recurrent application of the classification may even identify unforeseen interactions and impacts and, as has been said, open a pathway to compensation and mitigation measures.

6.9. Data gap

Most environmental studies have focused on tidal turbines and wave energy converters, and there has been little emphasis on ocean current and river turbines [45]. This lack of coherent, generalised information, strategies and the lack of monitoring and mitigation plans have been an obstacle to ocean energy development around the world [6,46].

A simple approach, such as that proposed here, is valuable in the case of data scarcity, as it eliminates unnecessary data and allows the main impacts of specific technologies in specific locations to be seen.

6.10. Positive effects

In general, in all the studies analysed it is said that more research is needed in the field of EIA for the pre-construction stages, during construction and in the operation and maintenance stages. They also point out the need for a consensus on the objectives and forms of measurement and monitoring frequency. On the other hand, the socio-economic implications of renewable energy projects may have for the community involved, that is the appreciation that society has, or will have, towards the installation of energy plants and its possible economic effects, is also important and is lacking.

Devine-Wright [32] found that most of the inhabitants of Strangford Lough, Northern Ireland, accepted and supported the construction of ocean energy extraction plants. The survey results indicate that the location of the tide project improved the esteem of residents for the area, as well as their emotional responses of hope and curiosity and, to a lesser extent, pride and enthusiasm. The positive reactions were strongly associated with the belief that tidal energy could play a positive role in combating climate change and meeting national energy objectives. The author also pointed out that one of the main reasons for supporting the development of the project was that the infrastructure altered only minimally the visual continuity of the landscape. Both studies emphasised the importance of adequate communication between the inhabitants of the areas surrounding the construction, technology developers, decision-makers and scientists as a way to facilitate a reasonable exchange of information and public participation. Similarly, Dreyer et al. [13] evaluated the attitudes and the perceived benefits and risks of tidal energy of inhabitants in Washington, USA. The study revealed that, in general, there is a positive feeling regarding tidal energy, as indicated by the high levels of acceptability and support as well as the perceived positive effect of such energies in the fight against climate change. However, community support decreased once the project was moved from the laboratory to the sea.

7. Conclusions

The results of environmental impact assessment of ocean energy conversion devices, plants and processes depend to a large extent on their operational mode and where they are located. This site-specificity has led to EIAs being project specific and still uncertain for other places or devices due to the scarcity of installations and of monitored projects. Nevertheless, the industry is growing rapidly, and with it the pressure exerted for technological and environmental approval. It is unacceptable to allow environmental impacts to be identified as they occur, as happened with previous energy developments, i.e. fossil fuels. In this scenario this paper provides the basis for a simple and comprehensive approach to environmental impact identification, focused on the biophysical interactions of specific MRE devices. The location, submergence, operation and emissions of the device were taken into account, making it easier to focus on the possible negative impacts and set apart impacts that are not related to a given process, plant or device, e.g. for floating devices, no attention should be paid to local seabed impacts but far field alterations to sediment transport patterns may be relevant. Due to its simplicity, the classification of interactions proposed here can be applied recurrently for a specific project in order to detect unforeseen impacts and mitigate their possible consequences.

Two examples were presented in which the suggestions offered by the proposed approach were shown. Depending on the device interactions, the phenomena which require most analysis were illustrated. For the results to be all embracing, two well-known devices were selected as examples. It is expected that some less evident results may be obtained for new WEC concepts.

There is still much research needed to achieve a universal methodology for the EIA of ocean energy projects but, if comprehensive tools are provided to institutions, investors and stakeholders, the likelihood of making environmental mistakes because of a lack of knowledge can be reduced.

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References

[1] Gill AB. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. J Appl Ecol 2005;42(4):605–15.
[2] Huckerby J, Jeffrey H, Jay B, Executive O. An international vision for ocean energy. The Ocean Energy Systems Implementing Agreement (OES); 2011.
[3] Papathanasopoulou E, Beaumont N, Hooper T, Nunes J, Queirós AM. Energy systems and their impacts on marine ecosystem services. Renew Sustain Energy Rev 2015;52:917–26.
[4] Aderinto T, Li H. Ocean wave energy converters: status and challenges. Energies 2018;11(5):1–26.
[5] Copping A, Battey H, Brown-Saracino J, Massaua M, Smith C. An international assessment of the environmental effects of marine energy development. Ocean Coast Manag 2014;99:3–13.
[6] Greaves D, Conley D, Magagna D, Aires E, Leitão JC, Witt M, Embling CB, Godley BJ, Bicknell AWJ, Saulnier JB, Simas T, O'Hagan AM, O'Callaghan J, Holmes B, Sundberg J, Torre-Enciso, Marina D. Environmental Impact Assessment: gathering experiences from wave energy test centres in Europe. Int. J. Mar. Energy 2016;14:68–79.
[7] Williamson BJ, Fraser S, Blondel P, Bell PS, Waggitt JJ, Scott BE. Multisensor Acoustic Tracking of fish and seabird behavior around tidal turbine structures in Scotland. IEEE *J Ocean Eng* 2017;42(4):948–65.
[8] Bevelhimer M, Scherelis C, Colby J, Adonizio MA. Hydroacoustic assessment of behavioral responses by fish passing near an operating tidal turbine in the east river, New York. Trans Am Fish Soc 2017;146(5):1028–42.
[9] Borja A. Grand challenges in marine ecosystems ecology. Front. Mar. Sci. 2014;1:1.
[10] Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita R. A global map of human impact on marine ecosystems. Science 2008;319(5865):948–52.
[11] Leeney RH, Greaves D, Conley D, O'Hagan AM. Environmental Impact Assessments for wave energy developments–Learning from existing activities and informing future research priorities. Ocean Coast Manag 2014;99:14–22.
[12] Uihlein A, Magagna D. Wave and tidal current energy–A review of the current state of research beyond technology. Renew Sustain Energy Rev 2016;58:1070–81.
[13] Dreyer SJ, Polis HJ, Jenkins LD. Changing Tides: acceptability, support, and perceptions of tidal energy in the United States. Energy Res. Soc. Sci. 2017;29:72–83.
[14] Fraser S, Williamson BJ, Nikora V, Scott BE. Fish distributions in a tidal channel indicate the behavioural impact of a marine renewable energy installation. Energy Rep 2018;4:65–9.
[15] Piper AT, Rosewarne PJ, Wright RM, Kemp PS. The impact of an Archimedes screw hydropower turbine on fish migration in a lowland river. Ecol Eng 2018;118:31–42.
[16] Want A, Crawford R, Kakkonen J, Kiddie G, Miller S, Harris RE, Porter JS. Biodiversity characterisation and hydrodynamic consequences of marine fouling communities on marine renewable energy infrastructure in the Orkney Islands Archipelago, UK. Biofouling 2017;33(7):567–79.
[17] Willsteed E, Gill AB, Birchenough SN, Jude S. Assessing the cumulative environmental effects of marine renewable energy developments: establishing common ground. Sci Total Environ 2017;577:19–32.
[18] International Renewable Energy Agency-IRENA. Patents evolution of renewable energy technologies. Net additions, worldwide, ocean energy. 2019 Last accessed 04/22/2019 http://resourceirena.irena.org/gateway/dashboard/index.html?topic=1019&subTopic=1058.
[19] Dadswell MJ, Rulifson RA. Macrotidal estuaries: a region of collision between migratory marine animals and tidal power development. Biol J Linn Soc 1994;51(1-2):93–113.
[20] Bochert R, Zettler ML. Long-term exposure of several marine benthic animals to static magnetic fields. Bioelectromagnetics 2004;25(7):498–502.
[21] Larsen JK, Guillemette M. Effects of wind turbines on flight behaviour of wintering common eiders: implications for habitat use and collision risk. J Appl Ecol 2007;44(3):516–22.
[22] Langhamer O, Wilhelmsson D. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes–a field experiment. Mar Environ Res 2009;68(4):151–7.
[23] Langhamer O, Wilhelmsson D, Engström J. Artificial reef effect and fouling impacts on offshore wave power foundations and buoys–a pilot study. Estuar Coast Shelf Sci 2009;82(3):426–32.
[24] Langhamer O. Effects of wave energy converters on the surrounding soft-bottom macrofauna (west coast of Sweden). Mar Environ Res 2010;69(5):374–81.
[25] Palha A, Mendes L, Fortes CJ, Brito-Melo A, Sarmento A. The impact of wave energy farms in the shoreline wave climate: Portuguese pilot zone case study using Pelamis energy wave devices. Renew Energy 2010;35(1):62–77.
[26] Benjamins S, Dale AC, Hastie G, Waggitt JJ, Lea MA, Scott B, Wilson B. Confusion reigns? A review of marine megafauna interactions with tidal-stream environments. Oceanogr Mar Biol 2015;53:1–54.
[27] Everley KA, Radford AN, Simpson SD. Pile-driving noise impairs antipredator behavior of the european sea bass Dicentrarchus labrax. In the effects of noise on aquatic life II. Advances in experimental medicine and biology vol. 875. New York,

NY: Springer; 2016. p. 273–9.

[28] Wiesebron LE, Horne JK, Scott BE, Williamson BJ. Comparing nekton distributions at two tidal energy sites suggests potential for generic environmental monitoring. Int. J. Mar. Energy 2016;16:235–49.

[29] Zhang J, Kitazawa D, Taya S, Mizukami Y. Impact assessment of marine current turbines on fish behavior using an experimental approach based on the similarity law. J Mar Sci Technol 2017;22(2):219–30.

[30] Sparling C, Lonergan M, McConnell B. Harbour seals (*Phoca vitulina*) around an operational tidal turbine in Strangford Narrows: No barrier effect but small changes in transit behaviour. Aquat Conserv Mar Freshw Ecosyst 2018;28(1):194–204.

[31] Bedard R. Economic and social benefits from wave energy conversion marine technology. Mar Technol Soc J 2007;41(3):44–50.

[32] Devine-Wright P. Enhancing local distinctiveness fosters public acceptance of tidal energy: a UK case study. Energy Policy 2011;39(1):83–93.

[33] Frid C, Andonegi E, Depestele J, Judd A, Rihan D, Rogers SI, Kenchington E. The environmental interactions of tidal and wave energy generation devices. Environ Impact Assess Rev 2012;32(1):133–9.

[34] Boehlert GW, Gill AB. Environmental and ecological effects of ocean renewable energy development: a current synthesis. Oceanography 2010;23(2):68–81.

[35] Bonar PA, Bryden IG, Borthwick AG. Social and ecological impacts of marine energy development. Renew Sustain Energy Rev 2015;47:486–95.

[36] Firestone J, Kempton W. Public opinion about large offshore wind power: underlying factors. Energy Policy 2007;35(3):1584–98.

[37] Warren CR, Lumsden C, O'Dowd S, Birnie RV. ‘Green on green’: public perceptions of wind power in Scotland and Ireland. J Environ Plan Manag 2005;48(6):853–75.

[38] Meireles AJ, Gorayeb A, da Silva DRF, de Lima GS. Socio-environmental impacts of wind farms on the traditional communities of the western coast of Ceará, in the Brazilian Northeast. J Coast Res 2013;65(sp1):81–6.

[39] Ellenbogen JM, Grace S, Heiger-Bernays WJ, Manwell JF, Mills DA, Sullivan KA, Weisskopf MG. Wind turbine health impact study: report of independent expert panel. Prepared for Massachusetts Department of Environmental Protection and Massachusetts Department of Public Health; 2012. p. 340p.

[40] Mahirt-Smith J. Implicaciones ambientales de las tecnologías de energía renovable. Ingenierías USBMed 2011;2(2):10–6.

[41] Regueiro RMF. Las implicaciones ambientales del proceso de implantación de los parques eólicos: la situación en Galicia. Rev Galega Econ 2011;20(1):1–20.

[42] Gibbons S. Gone with the wind: valuing the visual impacts of wind turbines through house prices. J Environ Econ Manag 2015;72:177–96.

[43] Haxel JH, Dziak RP, Matsumoto H. Obtaining baseline measurements of ocean ambient sound at a mobile test berth site for wave energy conversion off the central Oregon coast. OCEANS'11 - MTS/IEEE Kona, Program Book 6107223. IEEE; 2011, September. p. 1–5.

[44] Elliott M. Marine science and management means tackling exogenic unmanaged pressures and endogenic managed pressures–a numbered guide. Mar Pollut Bull 2011;62(4):651–5.

[45] Ocean Energy Systems, OES. ocean energy in the world: GIS map page. 2016 Available at: https://www.oceanenergy-systems.org/ocean-energy-in-the-world/gis-map/.

[46] Copping A, Smith C, Hanna L, Battey H, Whiting J, Reed M, Brown-Sarcino J, Gilman P, Massaua M. Tethys: developing a commons for understanding environmental effects of ocean renewable energy. Int. J. Mar. Energy 2013;3:41–51.