Renewable and Sustainable Energy Reviews 149 (2021) 111332

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# A systemic view of potential environmental impacts of ocean energy production

M.L. Martínez [a,*], G. Vázquez [a], O. Pérez-Maqueo [a], R. Silva [b], P. Moreno-Casasola [a], G. Mendoza-González [c], J. López-Portillo [a], I. MacGregor-Fors [a,f], G. Heckel [d], J. R. Hernández-Santana [e], J.G. García-Franco [a], G. Castillo-Campos [a], A.L. Lara-Domínguez [a]

[a] Instituto de Ecología, A.C., Antigua Carretera a Coatepec No. 351, Xalapa, Veracruz, 91073, Mexico
[b] Instituto de Ingeniería, UNAM, Ciudad Universitaria, Mexico City, 04510, Mexico
[c] Facultad de Ciencias UMDI-Sisal, Sede Parque Científico y Tecnológico de Yucatán, Km. 5.5 Carr. Sierra Papacal - Chuburna Pto. Tablaje 31257, 97302, Sierra Papacal, Yuc., Mexico
[d] Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Mexico, Carretera Ensenada-Tijuana No. 3918, Zona Playitas, 22860, Ensenada, Baja California, Mexico
[e] Instituto de Geografía, UNAM, Ciudad Universitaria, Mexico City, 04510, Mexico
[f] Current Address: University of Helsinki, Faculty of Biological and Environmental Sciences, Ecosystems and Environment Research Programme, Niemenkatu 73, 15140, Lahti, Finland

ARTICLE INFO

*Keywords:*
Environmental impact
Ocean energy
Environmental effect
Environmental receptors
Systemic analysis
Mitigation strategies

ABSTRACT

Renewable ocean energy is an alternative that will help reduce carbon emissions into the atmosphere. However, there is uncertainty about potential environmental impacts of the technologies involved, because these are new and untested, and methods for the evaluation and monitoring of environmental impacts are scarce. We performed a systematic literature review (well-structured and organized, always looking for the same terms), followed by a systemic analysis in which we considered the interactions between environmental stressors, effects, receptors, and their responses. We found that most studies are theoretical revisions and modelling exercises, although field and laboratory experiments and observations are beginning to accumulate. **Environmental stressors** are features in the environment (energy-harvesting devices) that modify the natural dynamics of the system. The **effects** are the changes in the environment induced by the stressors; the most frequently acknowledged and measured are noise, collision, habitat change, hydro-sedimentary dynamics and wave modifications. The **receptors** of these changes are marine fauna, such as mammals, fish, sea birds, and benthic communities, as well as the shoreline. Their corresponding **responses** include behaviour, injuries/death, biodiversity loss, alterations in food webs and shoreline change. Once the different components of the environmental impacts are identified, it is important to develop monitoring and mitigation strategies to prevent, or minimize, environmental damage. Ocean energy is a promising option to reduce $CO_2$ emissions into the atmosphere, but the implementation of adequate monitoring and mitigation technologies requires multidisciplinary efforts to obtain effectively clean, renewable energy and to maintain healthy and functional ecosystems.

## 1. Introduction

Global demand for energy is continually increasing and thus, various alternatives are being explored to satisfy these needs [1,2]. As fossil-fuels become scarcer, and to reduce CO2 emissions into the atmosphere to mitigate climate change, renewable energy production has become increasingly relevant. World total renewable energy capacity is currently 2,532,899 MW [1], but this is not produced equally among countries or continents. Nearly 60% of the present renewable energy production capacity is concentrated in Asia and Europe [1].

* Corresponding author.
*E-mail addresses:* marisa.martinez@inecol.mx (M.L. Martínez), gabriela.vazquez@inecol.mx (G. Vázquez), octavio.maqueo@inecol.mx (O. Pérez-Maqueo), RSilvaC@iingen.unam.mx (R. Silva), patricia.moreno@inecol.mx (P. Moreno-Casasola), jorge.lopez.portillo@inecol.mx (J. López-Portillo), macgregor@helsinki.fi (I. MacGregor-Fors), gheckel@cicese.mx (G. Heckel), santana@igg.unam.mx (J.R. Hernández-Santana), jose.garcia.franco@inecol.mx (J.G. García-Franco), gonzalo.castillo@inecol.mx (G. Castillo-Campos), ana.lara@inecol.mx (A.L. Lara-Domínguez).

https://doi.org/10.1016/j.rser.2021.111332
Received 19 June 2020; Received in revised form 15 May 2021; Accepted 7 June 2021
Available online 23 June 2021
1364-0321/

Marine energy production follows the same trends: tidal and OTEC are mostly found in Europe and Asia; wave energy in Europe, South Africa, central and South America; salinity gradient in Europe [3].

Hydrokinetic energy generated in the oceans (Marine Renewable Energy – MRE), such as that harvested from tides, currents, waves, thermal and salinity gradients, has great potential for the generation of electric power [4]. In particular, tidal and stream energy production are projected to increase noticeably in the coming decades [3]. This is especially relevant given that half of the global population living in cities with over 100,000 inhabitants are within 100 km from the coast [5]. So, the potential population that could benefit from MRE is substantial. Many different MRE technologies are being developed and trialled: some are floating devices, others are submerged or anchored to the seabed. Electricity can be harvested from the movement of water through waves, currents, and tides, as well as differences in temperature and salinity (see detailed explanations of their functioning in Refs. [3, 6, 7].

Compared with other ocean energy-related devices, there has been more progress in the deployment of offshore wind-farms in recent years (see Thethys database https://tethys.pnnl.gov/). Studies on electricity production from wind energy account for a total of 3,730, and of these, 1,736 focus on offshore deployments. In turn, there are 2,484 ocean energy studies, mostly dealing with tidal (904) and wave (695). The differences between wind and ocean energy deployments probably stem from the economic investments in each [3], as well as inland experience with wind energy.

Indeed, the technology of ocean energy harvesting has yet to be fully developed. There are a vast number of devices (wave, tidal, currents, thermal), as well as locations (remote, metropolitan, offshore, near-shore), under consideration. Thus, it is likely that in the near future, there will be a substantial increase in the number of devices in a growing number of countries [8]. While this occurs, the environmental impacts should be monitored, mitigated, and kept at a minimum, so that risk-related uncertainties are reduced [9,10]. In other words, although promising, the development of these new technologies comes with environmental concern [11–13]. In a similar vein, wind energy production is also a clean energy alternative; however, it causes death and injury to birds and bats through collision with the turbine blades, while human well-being may be affected by noise and shadow flicker [14].

It is thus necessary to understand the environmental baseline (including physical, geomorphological, chemical and biological features) at the project sites, while addressing the relationships between the natural environment and the energy-producing devices [15]. This knowledge will assist in establishing monitoring methodologies and mitigation strategies that are required to minimize the environmental impacts of the new technologies. It is critical to determine how much energy can be generated from the oceans and to choose locations and conditions in which the functionality of marine and coastal ecosystems will not be drastically affected by the new technology. This is of the utmost importance as coastal ecosystems are fundamental in the protection of our coasts in the face of climate change.

Because this technology is new, potential environmental impacts are largely unknown and have not been explored in detail. This is particularly complex because: a) the physical-geographical environment, the presence of human settlements and the location of suitable sites vary greatly; b) habitats, ecosystems, species and food webs that can be potentially affected are very diverse, and include marine as well as coastal and terrestrial habitats; c) the oceans and coasts are very dynamic and spatially heterogeneous and therefore, the impacts and mitigation strategies may be site-specific; and d) as there are many new technologies, their interactions with the environment (hydrodynamic, geomorphologic, chemical, biotic, ecological and socioeconomic) are also multiple [6].

In addition, the theoretical background and methodological strategies to assess the environmental impacts of MRE and determine monitoring timeframes and mitigation actions are also still incipient [16]. Boehlert and Gill [17] and McMurry [18] developed a theoretical framework to evaluate the environmental effects of ocean energy, which includes the potential impacts across different temporal and spatial scales and considers stressors and receptors.

While the theoretical framework of Boehlert and Gill [11] is an excellent starting point, much remains to be done to effectively assess, and consequently mitigate, the potential environmental impacts of new ocean energy devices. Unanticipated side-effects may arise if cause and effect are considered linearly and with a limited set of variables. In complex systems, such as ocean energy harvesting and environmental impact, causes and effects are often indirect, and vary over time and space. Hence, a systems-thinking approach may be useful to consider multiple interactions and feedbacks. In its simplest form, this approach would consider four interacting elements: climate change mitigation, ocean energy production, environmental impacts (direct) and side effects (unexpected or indirect) (Fig. 1). In this case, ocean energy production reduces the emission of $CO_2$ into atmosphere and thus, helps mitigate climate change. In addition, ocean energy production may affect the environment with negative (i.e. habitat degradation and loss of species) or positive (protection of locations with MRE devices) side effects. If the environmental conditions are improved, then MRE deployment may also be beneficial for climate change mitigation and thus, ocean energy production could be promoted. In brief, a systems-thinking approach is useful because: a) the focus is integrating information from different sources and types; b) it examines the linkages and interactions between the components that comprise the defined system; and c) it is a cognitive process for studying and understanding systems of any kind [19].

Based on the above, in this study, we performed an extensive and systematic (well-structured, always looking for the same trends) literature review, looking for the potential environmental impacts of ocean energy harvesting. Our findings were later analysed with a systemic approach, in which the interactions between the different elements were explored (Fig. 2): stressors, effects, receptors and responses.

- **Environmental stressors** are features in the environment that modify the natural dynamics of the system. This refers to energy-harvesting devices (installation, operation and decommission).
- **Effects** refers to changes in the environment that occur with the implementation of renewable energy techniques during construction, installation, operation and decommission. The intensity, frequency, spatial arrangement and density of the energy-producing devices are highly relevant, since in extreme conditions their impacts may become catastrophic. Examples of impacts are noise and obstacles with which the fauna collides. In turn, changes in the environment may alter the functioning of the energy-producing devices.

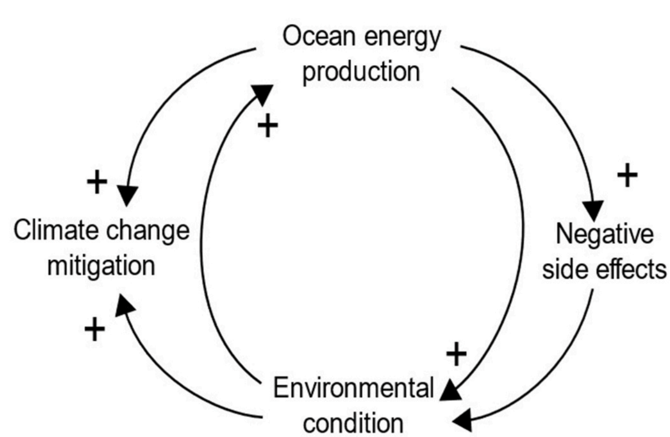


**Fig. 1.** Scheme showing the feedback between potential environmental impacts of ocean energy harvesting.

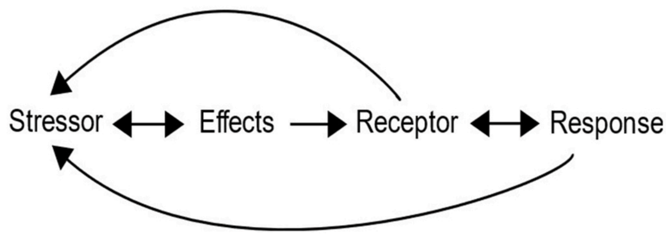


**Fig. 2.** Systemic interactions between the four elements that interact in the assessment of potential environmental impacts of ocean energy extraction.

- **Environmental receptors** are elements from the ecosystems that respond to, and are affected by, the effects generated by the stressors. Receptors include different levels of biological organization (individuals, populations, communities, and ecosystems), and include biotic processes, such as species interactions and food webs. Receptors also comprise the abiotic elements of the environment, such as the shoreline, water column, and ocean floor. The receptors could potentially affect the functioning of the energy producing devices.
- Finally, the **responses** refer to how these receptors change. These responses vary according to different timescales of the stressors (short or long-term, single or multiple events), and can be cumulative. Examples of responses are injuries and death. If injuries and deaths are considered significant, then it may be necessary to alter the devices to minimize this risk.

The interactions between the four elements are multiple and complex. The stressors (energy-harvesting devices) modify the environment (effect) in such a way that different receptors are affected and thus respond according to the new conditions. In turn, changes in the environment (effects) and the receptors may modify the functioning of the stressors (for instance, collisions of the fauna with the devices). Similarly, the responses of the receptors (i.e., biofouling on the new substrates) may also affect the functioning of the stressors. Given this complexity, a systems-thinking approach is useful to find the direct and indirect environmental effects as well as side-effects that were unanticipated.

The amount of scientific literature which focuses on the potential impacts of ocean energy production has gradually increased over recent years, since its first mention almost 20 years ago (see, for example, revision in Refs. [11,20–22], and the Tethys database https://tethys.pnnl.gov/). In this paper we analysed the evidence, gathered so far, which focuses on the potential environmental impacts of ocean energy harvesting. We explored different types of evidence: literature reviews, laboratory experiments, numerical and physical modelling, workshops, field observations, theoretical analyses, interviews and new methods (such as monitoring strategies or spatially explicit analyses). We considered the possible interactions between the stressors and their effects, with the receptors and their corresponding responses. In addition, we also explored possible mitigation strategies and conditions that can be implemented to minimize environmental impacts. The article is structured as follows: Section 2 introduces the reader to the literature review, which was based on the database Web of Science. A synthesis of these findings is presented in this section. Then, Section 3 shows the data analyses of the findings, using multivariate methods as well as a Sankey diagram. Finally, Section 4 discusses these findings, by comparing the results from this study with those from previous studies. This last section identifies information gaps, describes and analyses the caveats of the study, showing how these can be approached in the future.

## 2. Methods

### 2.1. Predicted impacts and supporting evidence

This study is based on a literature search performed in Web of Science (covering 1990 to December 2020, consulted in March 2021), selecting peer-reviewed literature. The following search string and conditions were used: TS=(("ocean energy" OR "wave energy" OR "tide energy" OR "ocean thermal energy conversion" OR "salinity gradient") AND ("environment* impact" OR habitat OR ecolog* OR biodiversity)), and the indexes consulted were: SCI-EXPANDED (Science Expanded), SSCI (Social Sciences), A&HCI (arts and humanities), CPCI–S (Conference Proceedings Citation Index- Science), CPCI-SSH (Social Science & Humanities), BKCI–S (Book citation index), BKCI-SSH (Book citation index. Social sciences & humanities) Timespan = All years (1990–2020).

### 2.2. Data analyses

The literature that we found was downloaded in *.bib format and then analysed with R-library Bibliometrix [23]. With this, we explored the most frequent words mentioned in the literature, the countries where these studies were carried out, and the journals in which they were published.

We then performed a more detailed revision and looked for the scientific publications that directly addressed the environmental impacts of MRE devices, finding a total of 196. After reading and reviewing these articles, we created a new database with the information from each study: energy type, environmental stressors, environmental effects, environmental receptors, and their corresponding responses, following our systemic approach. With this, we generated Sankey diagrams [24], which are flow diagrams in which the width of the arrows is proportional to the flow rate. This was useful to analyse the flows between environmental stressors, their effect, receptors and their responses. Sankey diagrams also helped to identify the most important contributions to a flow; in our case, they helped find the variables most frequently studied when assessing the environmental impacts of MRE devices.

Finally, we performed a multivariate analysis (Principal Component Analysis-PCA) [25], which is useful to find statistical patterns and trends in large correlated multivariate databases. PCA are used in exploratory data analysis and are useful in making predictive models. In our case, such analyses were performed to determine the variables that are mentioned in the literature as frequently interacting. We used the relative frequency (the relative frequency that each term was mentioned in the literature), and the PCA used centred and standardized data, and an orthogonal rotation to maintain the perpendicularity between the ordination axes.

## 3. Results

### 3.1. Literature review

We found a total of 16,432 references that mentioned at least one of the alternatives for marine renewable energy production, using the following search string: TS=(("ocean energy" OR "wave energy" OR "tide energy" OR "ocean thermal energy conversion" OR "salinity gradient"); 561 publications used "Marine Renewable Energy", and 752 "Ocean energy". This highlights the current interest in the topic. Despite its importance, studies on the potential environmental impacts of MRE devices are generally lacking, and only a small percentage of the literature mentioned the environment (Table 1). Furthermore, we observed a time lag of 10–23 years between studies dealing on how to transform ocean energy into electric power, and those focused on potential environmental impacts (Table 1). Most of the studies come from only a handful of countries; USA, China, Japan, Spain, Ireland and England. Ireland and Scotland also have noteworthy contributions to the study of

**Table 1**
Findings of the literature review performed to explore the studies aimed at determining the environmental impact of ocean hydrokinetic energy. The dates in brackets indicate the year in which the earliest study was found. The percentage of environmental studies refers to those that explore environmental impacts, for each type of energy. The three countries with the largest number of studies are shown. More than three countries are mentioned when they share the same number of publications.

| Type of Energy | Total number of references | Environmental impact studies | Environmental studies (%) |
|---|---|---|---|
| Ocean | 752 (1980) | 96 (1998) | 12 |
| Top 3 | USA, China, Spain | USA, China, Ireland | |
| Wave | 871 (1983) | 49 (2006) | 6 |
| Top 3 | USA, China, Japan | USA, Italy, China | |
| Tidal | 1450 (1980) | 209 (1990) | 14 |
| Top 3 | USA, England, China | USA, England, Scotland | |
| OTEC | 401 (1980) | 31 (1995) | 8 |
| Top 3 | USA, Japan, China | USA, Japan, France-China | |
| Salinity | 12 (1987) | 2 (2009) | 17 |
| Top 3 | China, USA, England | Germany, China | |

the environmental impact of MRE (specifically, tidal).

Diverse methods were used to explore the potential environmental impacts of MRE (Table 2). Most of the studies are literature reviews and modelling exercises (40 and 26% respectively). In these, the potential environmental impacts are determined based on previous findings on how natural coastal and ocean ecosystems respond to different types and levels of disturbances (natural and human-related). Because the databases are often incomplete, modelling exercises are a valuable, commonly used tool that helps fill the gaps when empirical data are not available. Assessments using field observations are becoming increasingly frequent, and these studies will probably render relevant information under field conditions. Other significant methods are workshops, interviews and spatial analyses. In combination, they will help determine more precisely the potential environmental impacts from different points of view. Studies with an environmental approach have been performed in 30 countries, but mostly in Scotland, UK and USA (Table 2). Nevertheless, it is very important to promote site-specific studies, because local environmental conditions determine the type of energy that can be used, as well as the receptors that will potentially be affected. Indeed, a robust biological and physicochemical baseline dataset is needed to fully understand pre- and post-conditions of the functioning MRE devices already operating [15]. Furthermore, these databases should capture daily, seasonal and annual variations of the natural environmental conditions.

### 3.2. *System approach (environmental stressors, effects, receptors and responses)*

The generation of electric power from devices located in the ocean relies on the dynamic features of the abiotic environment, which, in turn, is paralleled by the dynamic and diverse nature of the biotic environment. Thus, it is essential to guarantee that their interactions will be maintained with the construction of new infrastructure. To achieve this, it is necessary to have information on the presence and absence of species, and to have a baseline for the natural variations in the biological components (abundance, distribution and interactions), at different stages of the project (before, during development, piloting and operation). These environmental concerns can be explored considering the environmental stressors and their effects on the receptors and their

**Table 2**
Percentage of studies that explore the environmental impact of ocean energy, performed with different approaches and in different countries. Total refers to total relative contribution of studies performed in different countries, from the total number of studies we found. UK and Scotland, which belong to the United Kingdom, are displayed separately because that is how they are reported in the literature. New method refers to articles in which a new method (mostly involved with spatially explicit assessments) was developed. Countries with the highest percentages are highlighted in bold.

| Country | Review | Lab exp | Modelling | Workshop | Field obs | Field/Modelling | Theoretical | New method | Interviews | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Arab Emirates | | | 0.01 | | | | | | | 0.01 |
| Australia | 0.01 | | | | | | | | | 0.01 |
| Brazil | | | 0.01 | | | | | | | 0.01 |
| Canada | | | 0.03 | | 0.01 | 0.01 | | | | 0.05 |
| China | 0.01 | | 0.02 | | | | | | | 0.03 |
| Colombia | | | 0.01 | | | | | | | 0.01 |
| Denmark | | | | | | | 0.01 | 0.01 | | 0.01 |
| Europe | 0.01 | | 0.01 | | 0.01 | | 0.01 | | | 0.02 |
| France | | | | | | | 0.01 | | | 0.01 |
| Germany | | | 0.01 | | | | | | | 0.01 |
| Greece | | | 0.01 | | | | | | 0.01 | 0.01 |
| India | | | 0.01 | | | | | | | 0.01 |
| Iran | 0.01 | | 0.01 | | | | | | | 0.01 |
| Ireland | | | 0.03 | | 0.02 | 0.01 | | | 0.01 | 0.06 |
| Italy | 0.01 | 0.01 | 0.03 | | | | 0.01 | | | 0.05 |
| Japan | 0.01 | | 0.01 | | | | | | | 0.02 |
| Malaysia | 0.01 | | 0.01 | | | | 0.01 | | | 0.02 |
| Mexico | 0.01 | | | | | | | 0.01 | | 0.01 |
| New Zealand | | | | | | | | | 0.01 | 0.01 |
| Norway | | | 0.01 | | | | 0.01 | | | 0.01 |
| Portugal | | | 0.01 | | 0.01 | 0.01 | | 0.01 | | 0.02 |
| Romania | | | 0.01 | | | | | | | 0.01 |
| Russia | | | | | | | 0.01 | | | 0.01 |
| **Scotland** | 0.02 | | 0.06 | 0.01 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 | 0.17 |
| South Korea | 0.01 | | 0.01 | | | | | | | 0.01 |
| Spain | | 0.01 | 0.03 | | | | | | | 0.04 |
| Spain/Mexico | | | 0.01 | | | | | | | 0.01 |
| Spain/UK | 0.01 | | | | | | | | | 0.01 |
| Sweden | 0.01 | | | | 0.03 | | 0.01 | | | 0.04 |
| **UK** | 0.02 | | 0.06 | | 0.02 | 0.01 | 0.02 | 0.01 | | 0.13 |
| **USA** | 0.06 | 0.01 | 0.06 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.18 |
| Global | 0.01 | | | | | | | | | 0.01 |
| **Total** | 0.18 | 0.02 | 0.44 | 0.01 | 0.13 | 0.06 | 0.09 | 0.04 | 0.03 | 1.00 |

resulting responses.

We grouped the predictions of the potential environmental impacts of different ocean energy devices according to their potential effects, receptors and responses (Fig. 2). The relative frequency of each environmental effect and the receptors varies according to the type of device (Fig. 3). Noise and collisions are the effects most frequently mentioned in the literature, regardless of the device. Altered hydro-sedimentary dynamics, habitat change, pollution (especially from the paint used to inhibit marine growth and biofouling), and electromagnetic fields are also of concern. Studies on the potential environmental impact of wave and tidal devices are much more frequent than of OTEC (Ocean Thermal Energy Conversion) and salinity gradients.

Like environmental effects, environmental receptors also differ, depending on the type of device (Fig. 4). Benthic communities, fish, marine mammals, and birds are frequently mentioned (for all devices). When energy is harvested from waves and tides, the relevant receptors are physical changes in the shoreline, and marine fauna, turtles, plankton and invertebrates [26]. Most of the studies which focus on the responses of receptors such as fish, cetaceans and birds are still theoretical and preliminary, and rely mostly on revisions of how ocean ecosystems and species might respond to changes in the environment. Nevertheless, empirical evidence through field observations and laboratory experiments is beginning to appear [27–36].

### *3.3. Systemic analysis of the interactions between stressors, effects, receptors, and their responses*

The multivariate analyses were performed considering the effects of different energy devices and the receptors most frequently mentioned in the literature (Fig. 5). The analysis which focused on the potential effects of ocean energy devices explained a substantial percentage of the variance, mostly in axis 1 (81.3%), showing that wave and tidal energy devices are very likely to induce noise, collision, wave or tidal alterations, and habitat changes. In turn, for salinity, the effects most frequently mentioned are water quality and, for OTEC, entrapment and entrainment (Fig. 5a).

Multivariate analysis was performed considering the keywords most frequently mentioned in the literature, which varied according to the type of energy. Again, the system responses were organized according to the wave energy devices. Environmental receptors receive the impact of the alterations or modifications generated by the above-mentioned environmental stressors (Fig. 5a). Like the analysis for effects, the first principal component accounted for a large percentage of the variance (95.2%) (Fig. 5b). The receptors most frequently mentioned in the literature search were similar for wave and tidal energies: benthic communities, marine fauna, marine mammals, birds, shoreline, wave or tidal attributes and invertebrates. Regarding OTEC, the effect on fish and plankton is that most frequently mentioned in the literature. In our literature review we did not find clear receptors for salinity gradient devices.

Finally, a systemic analysis was performed according to the stressors, effects, receptors and responses (Fig. 6). We subdivided environmental stressors into three broad categories: the functioning device, the physical presence of a device, and mooring. As expected, most of the studies focus on the impacts of functioning devices, because this is the most long-lasting stressor. The most frequently mentioned effects of functioning devices are noise, collision, habitat change, hydro-sedimentary alterations, wave/tidal modifications and decreased water quality.

Noise mostly affects marine fauna, marine mammals and fish, resulting in altered behaviour, injuries and even death [37–41]. Nevertheless, noise also acts as orientation cues for the pelagic larvae of reef fishes and crustaceans [42]. Similarly, collision is likely to affect the same animals as noise, but here, seabirds are also mentioned as potential receptors, because of their diving behaviour in order to catch fish [8]. In both cases, modifications in the food web are expected [43,44]. Habitat changes and altered hydro-sedimentary dynamics induced by the functioning devices affect the biota (marine fauna, marine mammals, and fish), including turtles, invertebrates, and benthic communities. The results include alterations or loss of biodiversity, the arrival of invasive species, and the potential loss of coastal ecosystems such as coral reefs, and seagrass beds [45–48]. Altered hydro-sedimentary dynamics may also induce shoreline changes through erosion and sediment accumulation, resulting in beach erosion and loss of coastal dunes [49,50]. Similarly, modifications in wave-tidal dynamics may also affect shoreline dynamics and coastal ecosystems [51,52] or existing infrastructure [53]. Finally, reduced water quality may affect marine ecosystems and plankton, resulting in altered primary productivity and changed food webs [28,43].

The physical presence of the devices may also impact the biota through collision and habitat changes, affecting species mentioned earlier for noise, with similar responses. In addition, the physical presence of the devices creates artificial reefs and alters the sea floor. These affect the benthic communities (benthos, coral reefs, seagrass beds), which might induce a secondary succession process and promote the

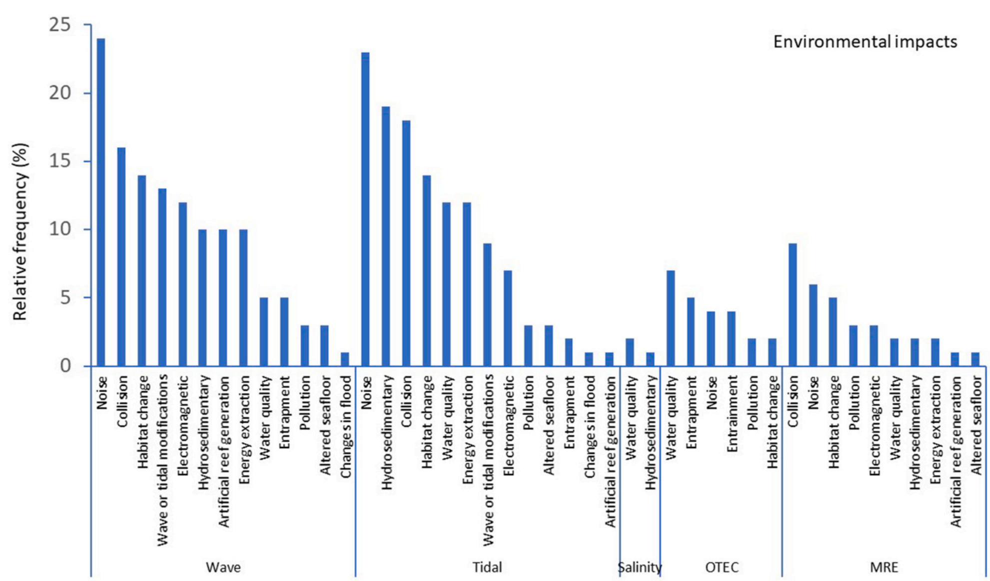


**Fig. 3.** Potential environmental impacts of ocean energy devices, based on the literature review (N = 190 studies).

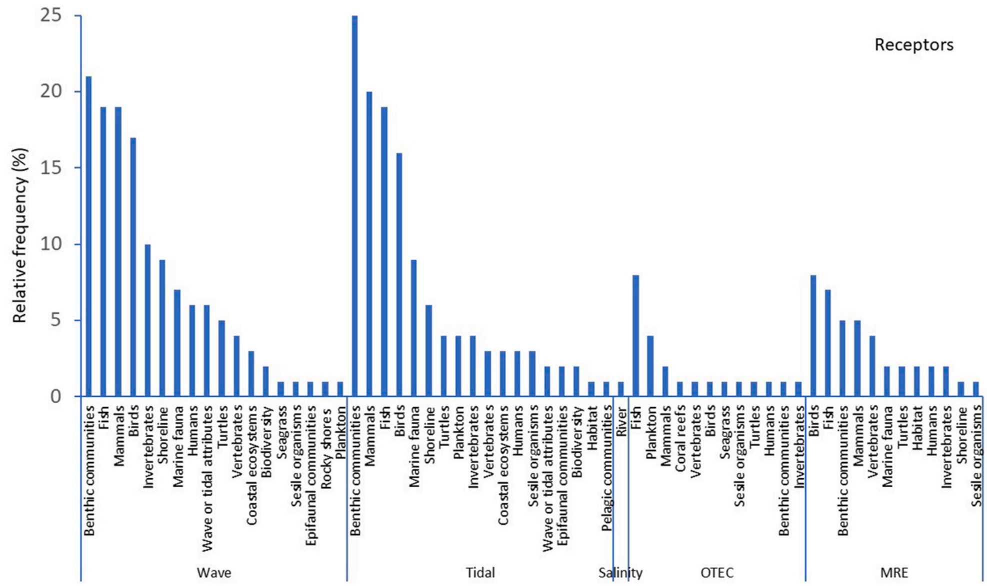


**Fig. 4.** Potential environmental receptors of the impacts induced by ocean energy devices, based on the literature review (N = 190 studies).

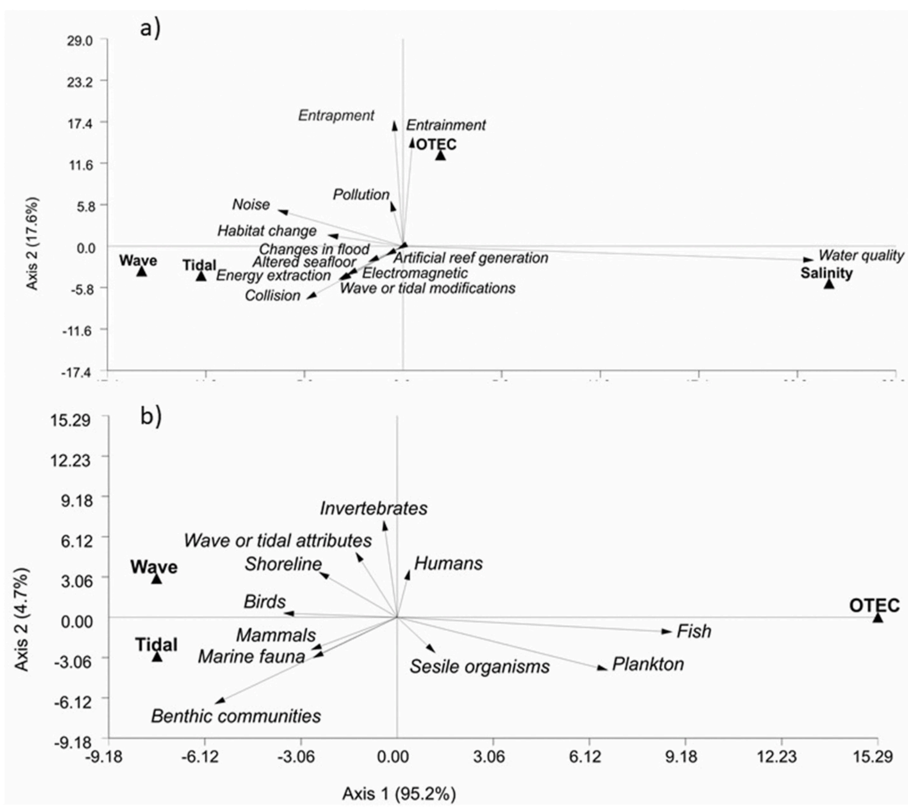


**Fig. 5.** Multivariate analysis (PCA) exploring the relative frequency of the effects of environmental stressors (a) amd environmental receptors (b) likely to be affected by the operation of different ocean energy devices (tidal, wave, ocean thermal energy conversion, OTEC, and salinity gradient), according to the scientific literature reviewed.

arrival of invasive species and result in altered, or loss of, biodiversity [54–56]. The above changes contribute to an increasing risk of extinction for seagrass species [57].

Mooring is the stressor least frequently mentioned in the literature (Fig. 6). Like the physical presence of devices, it is expected to induce habitat changes, modify hydro-sedimentary dynamics and induce changes in the sea floor. The receptors and their corresponding responses are similar to those described above.

In the literature review few feedbacks were found on how the functionality of the devices may be affected by, for example, the receptors or their responses. The only explicit mention concerns the potential effect of biofouling (arrival of biota to the new substrates) on the functionality and structural integrity of the devices (the weight may be more than 33 kg per square metre) [58]. Various projects are underway to face this problem without affecting the environment, through the use of biocides, for instance Ref. [59].

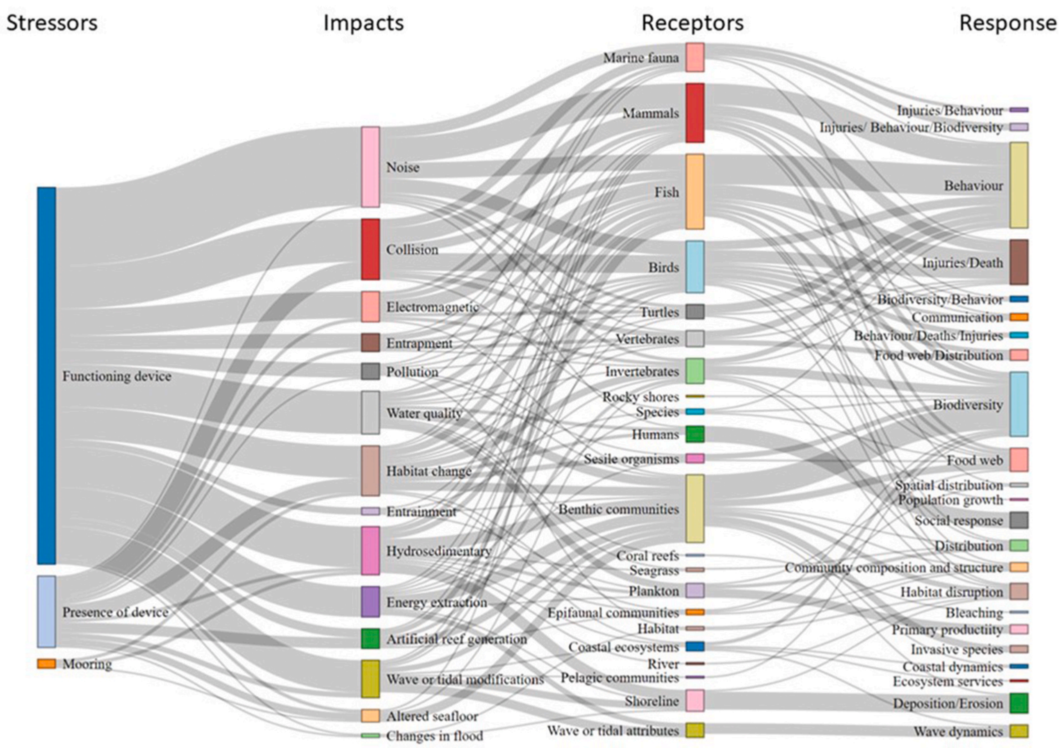


**Fig. 6.** Sankey diagram showing the interaction between environmental stressors and their effects on environmental receptors and their responses, based on the literature review (N = 190 refereed articles).

## 4. Discussion

Ocean energy harvesting and resultant environmental impacts are complex systems in which causes and effects are often indirect, and variable over space and time. Assessing the ecological implications is therefore very important while these new technologies are being developed [60,61]. Unanticipated side-effects are likely to occur, and a systems-thinking approach can be useful in preparing for unexpected events. This approach integrates information from various sources and different types, and examines the links and interactions between the components that comprise the system defined by the MRE devices and their potential impacts on the environment [19]. The aim of the literature review performed in this study was to analyse the evidence available up to now on the potential environmental impacts of ocean energy harvesting. Using a systematic approach four interacting elements were considered: stressors, effects, receptors and responses. With a systemic analysis, we can integrate the four elements (stressor, effect, receptor and response) that comprise environmental impact, identify information gaps and suggest mitigation strategies.

### *4.1. Information gaps*

Although an increasing amount of scientific evidence on ocean energy harvesting is being published, there are still many information gaps to be filled concerning the potential environmental consequences. The limited number of studies available are mostly literature reviews showing how natural ecosystems work, without the energy-harvesting devices, which then infer potential and expected changes. Laboratory studies usually focus on single, scaled turbines [30,33,35], while field observations are only just emerging, focusing on fish [62]; seabirds [63]; fish and seabirds [64,65]; benthic and epibenthic communities [29,66]; and marine mammals [37,67]. There is still a considerable lack of information on how ocean-harvesting devices will modify the environment, the potential receptors, and how these will respond. Indeed, it is necessary to ascertain whether there is a conflict between the conservation of ecosystems and species, and the development of marine renewable energy [68].

The methods used to determine the impact of ocean energy harvesting vary, although reviews and modelling exercises are the most frequently used. Laboratory experiments and field observations are more prevalent now, as new devices are developed and tested, each accounting for approximately half the total number of studies. It is worth noting that, except for the USA, there are few studies focused on environmental impacts of ocean energy harvesting in countries within the hurricane belt, only in China [69], Japan [70] and Mexico [55]. The conditions produced during these events (wave energy and height, storm surge, winds, sediment removal) should be considered when defining sites for ocean energy harvesting in hurricane-prone areas. Strategies and costs for deploying equipment will differ considerably and so will maintenance. The costs of structural design and calculation of infrastructural over-resistance in sites of notable recurrence of natural events such as hurricanes, earthquakes, and tsunamis, or of changing geotechnical conditions, such as sedimentary consolidation, should also be taken into consideration.

The environmental impacts of each energy device vary according to how they function [6]. The environmental effects, receptors and their responses depend on the device and the environmental conditions where they are deployed. This highlights the need for local, site specific, studies rather than generalized assessments. For example, the depth of the continental shelf should be considered because it affects both the establishment and distribution of coastal ecosystems, as well as hydro-sedimentary dynamics. Thus, if ocean energy devices were installed in shallow waters, vulnerable coastal ecosystems such as seagrass beds and coral reefs [46,47,71] would be at risk.

The literature shows several environmental receptors, such as nurseries for fish and aquatic invertebrates, coral reefs, and seagrass beds, as well as coastal ecosystems (beach, coastal dunes, mangroves, and coastal lagoons) that are particularly sensitive to environmental changes. While most coastal ecosystems are considered in the literature, we did not find studies on mangroves and coastal lagoons, which are

**Table 3**
Summary of the potential impacts of different ocean energy devices, considering environmental effects, receptors and recommendations for mitigation (information from Refs. [31,84] and the literature review carried out).

| Effects / Receptors | Wave | Tidal | OTEC | Recommendation |
|---|---|---|---|---|
| **Effects** | | | | |
| Noise | | | | Monitoring the behaviour of animals in response to noise pollution is necessary to determine the optimum location of the devices, and decibels and frequency, so that mitigation strategies can be implemented, based on scientific knowledge. |
| Collision | | | | Device location should avoid migratory routes and nesting locations. The spatial arrangement of devices needs to consider migratory routes. |
| Habitat change | | | | Avoid areas of high biodiversity. Monitor the arrival of invasive species |
| Wave or tidal modifications | | | | Establish a baseline of nutrients, sediments, and water flow, and the morphodynamic trends of the coast and associated geoforms, for several kilometres landward and seaward of the potential site. |
| Electromagnetic | | | | The location of devices should avoid migratory routes and nesting locations. The spatial arrangement of devices needs to consider migratory routes. |
| Hydro sedimentary | | | | Establish a baseline of nutrients, sediments, and water flow, and the morphodynamic trends of the coast and associated geoforms, for several kilometres landward and seaward of the potential site. |
| Artificial reef generation | | | | Avoid areas of high biodiversity. Monitor the arrival of invasive species |
| Energy extraction | | | | Care is needed when selecting the sites where ocean energy devices will be installed, so that changes in shoreline and ocean currents do not affect coral reefs and coastal ecosystems. A 5 km buffer-zone, at least, is recommended. |
| Water quality | | | | Refrain from employing OTEC plants in sensitive areas such as fishing grounds, reef habitats, seagrass beds and spawning sites; avoid toxic coatings such as biocides and ammonia or chlorine; small, individual energy-producing devices are likely to have less impact in the environment than large, multiple devices |

| Effects / Receptors | Wave | Tidal | OTEC | Recommendation |
|---|---|---|---|---|
| Entrapment/entrainment | | | | The location of devices should avoid migratory routes and nesting locations. The spatial arrangement of devices needs to consider migratory routes. |
| Pollution | | | | Refrain from employing OTEC plants in sensitive areas such as fishing grounds, reef habitats, seagrass beds and spawning sites; avoid toxic coatings such as biocides and ammonia or chlorine; small, individual energy-producing are likely to have less impact in the environment than large, multiple devices |
| Altered seafloor | | | | Avoid areas of high biodiversity. Monitor the arrival of invasive species |
| Changes in flood | | | | Establish a baseline of nutrients and water flow, and the morphodynamic trends of the coast and associated geoforms, for several kilometres landward and seaward of the potential site. |
| **Receptors** | | | | |
| Benthic communities | | | | Areas with fragile coral reefs or seagrass meadows, which have an essential role in coastal protection, should be avoided. |
| Fish | | | | Monitor frequency and follow up injured organisms. Consider the spatial distribution and size of devices to minimize collisions. |
| Epifaunal communities | | | | Monitor relative abundance and species composition. Avoid areas with fragile coral reefs. |
| Marine mammals | | | | Monitor frequency and follow-up injured organisms. Consider the spatial distribution and size of devices to minimize collisions |
| Seabirds | | | | Monitor frequency and follow-up injured organisms. Consider the spatial distribution and size of devices to minimize collisions |
| Invertebrates | | | | Develop techniques to prevent entrapment of invertebrates, the base of food-webs |
| Shoreline | | | | Locate ocean energy devices where hydro-sedimentary dynamics will not be drastically altered, to prevent coastal erosion. |
| Marine fauna | | | | Monitor frequency and follow-up injured organisms. Consider the spatial distribution and size of devices to minimize collisions |
| Humans | | | | Avoid affecting fisheries and tourist areas |
| Wave or tidal attributes | | | | The natural hydrodynamics should be maintained to preserve natural ecosystems. |

| Effects / Receptors | Wave | Tidal | OTEC | Recommendation |
|---|---|---|---|---|
| Turtles | | | | Monitor frequency and follow-up injured organisms. Consider the spatial distribution and size of devices to minimize collisions |
| Marine Vertebrates | | | | Monitor frequency and follow-up injured organisms. Consider the spatial distribution and size of devices to minimize collisions |
| Coastal ecosystems | | | | The natural hydrodynamics should be maintained to preserve natural ecosystems. |
| Biodiversity | | | | Avoid the installation of devices in highly diverse locations (5 km buffer zone) |
| Seagrass | | | | Avoid installation of devices near seagrass beds (5 km buffer zone) |
| Sessile organisms | | | | Areas with coral reefs or seagrass meadows, which have an essential role in coastal protection, should be avoided. |
| Epifaunal communities | | | | Monitor epifaunal communities. |
| Plankton | | | | Develop techniques to prevent entrapment of phyto and zooplankton, the base of food-webs |
| Pelagic communities | | | | Baseline studies are necessary, with adequate control sites and replicates, to predict the impact of new structures placed in the ocean |
| Coral reefs | | | | Avoid installation of devices near coral reefs (5 km buffer zone). This applies to rocky reefs as well. |
| Habitat | | | | Avoid the installation of devices near habitats with high diversity (5 km buffer zone) |

likely to be affected.

In addition, the population size of large keystone and charismatic vertebrates, such as marine mammals, sea turtles, birds, are likely to be reduced [64,67,72], affecting ecosystem functionality. The interactions between coastal ecosystems occur through hydro-sedimentary and biological fluxes [73,74], so if one of these is modified, a cascade effect is likely to occur. Therefore, the potential impacts of ocean energy devices must be assessed taking into consideration that marine and coastal environments are complex and dynamic systems.

Using a systemic approach, it is also relevant to consider how the biota will affect the operational effectiveness of ocean-energy devices. The biological colonization of infrastructure placed in the ocean, such as oil platforms and energy devices, can become very productive ecosystems [75]. On the other hand, the biofouling process that occurs on the devices can rapidly become a problem. We found studies that assessed the biofouling processes [48,76] as well as the hydrodynamic consequences of biofouling on marine renewable energy infrastructure [28, 77]. While anti-fouling paints are commonly used to reduce such adverse effects, these have been found to have toxic environmental consequences [78,79]. Finding alternatives to these paints is thus increasingly sought after to reduce the environmental impact of ocean energy devices (see for example [59,80]).

Finally, information gaps in the ocean energy sector may find that know how from the sectors that are more advanced, such as offshore wind energy, can be applied for shared elements such as mooring and seabed foundations. The environmental impact of offshore wind energy has been thoroughly studied by 44 and could therefore provide useful information for ocean energy production.

### 4.2. Mitigation measures and monitoring

The first consideration when choosing mitigation measures is the location of the ocean energy devices: these should offer optimal conditions for ocean energy harvesting, but also be where the environmental impact is minimal. Once the devices are installed, it is necessary to measure the environmental impacts (e.g., alterations in the hydro-sedimentary conditions) and receptors (e.g., marine fauna), allowing new strategies to be designed that control and minimize the impacts [81].

Mitigation measures should be accompanied by long-term monitoring of environmental conditions prior, during and after the installation of ocean-energy devices. Nevertheless, there are very few project sites [37,40,82] with a long-term dataset from continuous monitoring of the environmental (physical-chemical conditions) and the biological (plants and animals) attributes, including variations in abundance, distribution, and behaviour at different temporal (daily, seasonal, annual or supra-annual) and spatial (local, regional) scales. While the available information is limited, it is still useful, even though it leaves significant gaps in the understanding of how the biotic and abiotic elements function and interact [15] and will respond to ocean energy devices.

A major impact of MRE devices on the marine environment is that they provide a new substrate and biophysical conditions for the establishment and propagation of biofouling benthic non-native species. These benthic assemblages create a new habitat for the colonization of epibenthic species and fish seeking food and/or protection [83].

In Table 3, we show a summary of potential environmental effects and receptors and recommend mitigation and control strategies for each potential impact. The determination of these environmental effects and receptors depends on knowledge of how disturbed coastal ecosystems function, in comparison with those that are undisturbed.

As with any revision analysis, certain caveats should be considered. First, given that the technology is new, and is still being developed, all studies regarding potential impacts in the environment necessarily focus on prototypes and demonstration devices. Probably, the impact of commercial energy farms will be greater and different from the findings currently available on single (or a few), smaller scale devices. Thus, as technology develops and ocean energy farms are deployed, the opportunity to fully understand the environmental impacts and how to mitigate them will be more realistic; the earlier work on prototypes may offer a head start. Initially there was a time lag between the onset of studies regarding ocean energy harvesting technology and the potential impacts this has on the environment, but these are now being studied in tandem, fortunately. Undoubtedly, works determining the environmental impacts of MRE devices are few, but they are gradually growing in number [6]. As the new technologies develop, it will be of upmost significance to identify the real impacts of ocean energy farms, deployed at real scale and with a large number of devices, and to determine if the area of influence, and the impacts on populations are biologically significant. Mitigation measures and their effectiveness need also to be fully explored beyond prototypes and models [85].

Second, although we may be able learn from other renewable energy technologies that are more fully developed than MRE (such as offshore wind energy), it is important to be aware of the peculiarities of all coastal zones in terms of their dynamics, and environmental heterogeneity, making the collection of local data essential [90]. Transferring information from one location (and energy device) to another may lead to errors in the assessment of environmental impacts and may trigger irreversible damage. An accurate diagnosis (from initial setting to dismantling) for each locality and energy device is necessary to fully understand potential environmental impacts.

Third, the magnitude of the effects and responses were not outlined and analysed in this study. In fact, the magnitude of the environmental impacts is seldom mentioned in most of the studies we analysed, as these were mainly performed through literature revisions or numerical modelling exercises, which do not explore the magnitude of the impact. In contrast, field observations and laboratory experiments do offer information on the magnitude of the impacts, however they only account for 13% of the studies. Of course, it is not possible to make general statements regarding the magnitude of the effects, because this will depend on the location, energy device deployed, size, arrangement, and number of devices. Thus, we only focused on the consequences, not on the magnitude of these. When MRE devices are deployed in their specific locations, local studies and monitoring of environmental impacts will be useful to facilitate mitigation actions to decrease such impacts.

Fourth, equating the frequency of occurrence of an effect mentioned in the literature should not be linked with the relevance of the effect as such. The literature may be skewed towards studying some effects over others, disregarding the relative impacts of each. For instance, the fact that noise was most frequently mentioned in wave and tidal energy does not mean that OTEC systems are unlikely to induce noise. Other factors such as funding sources, or the specific interests of the researchers may be driving the frequency with which environmental impacts are studied.

## 5. Conclusions

Ocean energy is a promising alternative to reduce the emissions of $CO_2$ into the atmosphere, but care must be taken so that its environmental impacts are as low as possible. Currently, many devices are being deployed and tested around the world and it is expected that their number will increase in the coming years. In this study, we reviewed published journal and conference papers that cover environmental impact assessments of ocean energy converters. Undoubtedly, there are uncertainties around the effects that those devices may produce in the environment, and while the number of projects aiming to assess this issue is relatively low, the number of marine energy converters that are being developed and tested is rising. The lack of prototypes operating in real-sea conditions is also a hindrance to conclusions based on practical evidence. Therefore, this article will be of interest to a wide variety of readers from different sectors, including scientists interested in the issue (biologists, oceanographers, engineers); those developing energy converters, who could adjust their prototype designs to meet forthcoming EIA requirements; the public sector and regulators who will make decisions regarding marine spatial planning. Because of its relevance, it is necessary to create an inventory of potential impacts, considering effects, receptors and responses. Environmental considerations related to ocean energy devices should be of concern to government agencies, enterprises, project developers and the public in general.

The implementation of environmental monitoring and mitigation technologies requires multidisciplinary efforts to obtain clean and renewable energy effectively, and to maintain healthy and functional ecosystems. Prior to, or alongside the deployment of such devices, environmental impacts must be considered.

Field and laboratory experiments are necessary to design prototypes, and to establish robust baselines to determine and mitigate potential environmental impacts of the different ocean-energy production devices. This would allow evaluation, both quantitative and qualitative, of the changes in environmental parameters and the structure and functioning of ecosystems, including biodiversity. At the same time, the cost-benefit relation of these technological innovations for ocean energy exploitation should be taken into consideration.

Finally, only through the interaction of empirical/experimental evaluation with quantitative modelling will we be able to define the limits of environmental stressors, beyond which natural ecosystems lose resilience, and their integrity and functioning collapse. As well as the potential impacts of ocean energy devices, coastal and marine ecosystems are also being affected by other stressors (overexploitation, sediment and nutrient runoff, invasive species, disease, overgrazing, algal blooms, and the superimposed impacts of global warming, ocean acidification, introduced species, and emerging diseases) [86,87]. Current management practices should be able to rely on a systemic understanding of how ecosystems respond to, and recover from, increasing human impacts [88,89]. To achieve this, the establishment of a baseline of optimal ecosystem conditions is necessary. It is also important to determine the cost/benefit ratios of multifunctional devices (used for shoreline protection, fisheries, restoration) and compare them with traditional technologies. More work is required to identify the full range of environmental stressors and receptors to be considered and integrated into the governmental decision process. However, we should be aware that there are no zero-risk renewable energy devices; they do not exist and never will [90]. So, we should not mislead ourselves and others into believing in a zero-risk strategy. Instead, we should accept residual risks, and work towards minimizing them as much as possible, based on growing information and knowledge, as well as the needs of society.

**Credit author statement**

Martínez, M.L.: Conceptualization, Investigation, Data curation, Writing – original draft preparation. Vázquez, G.: Conceptualization, Investigation, Data curation, Data Formal analysis, Reviewing. Pérez-Maqueo, O.: Conceptualization, Investigation, Data curation, Data Formal analysis, Reviewing. Silva, R.: Writing- Reviewing and Editing, Funding acquisition. Moreno-Casasola, P.: Writing, Reviewing and editing. Mendoza-González, G.: Writing, Reviewing and editing. López-Portillo, J: Writing, Reviewing and editing. MacGregor, I.: Reviewing and editing. Heckel, G.: Reviewing and editing. Hernández-Santana, J. R.: Reviewing and editing. García-Franco, J.G.: Reviewing and editing. Castillo-Campos, G.: Reviewing and editing. Lara-Domínguez, A.L.: Reviewing and editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

Financial support for this contribution was provided by CEMIE-Océano (CONACYT-Secretaría de Energía -Ministry of Energy). We are very grateful to Jill Taylor for proof-reading the manuscript and for checking English, grammar and syntax. MLM dedicates this article in loving memory of her father, Antonio Martinez, who was a firm believer in the advances of technology in combination with the protection of nature. This research was funded by CONACYT-SENER Sustentabilidad Energética project: FSE- 2014-06-249795. Centro Mexicano de Innovación en Energía del Océano (CEMIE-Océano).

## References

[1] IRENA. Renewable. Energy statistics 2016 statistiques D ' énergie renouvelable 2016 estadísticas de Energía. 2016.
[2] IEA. World energy balances (database). 2020. https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics.
[3] IRENA. Innovation Outlook. Ocean energy technologies. Abu Dhabi: International Renewable Energy Agency; 2020.
[4] Borthwick AGL. Marine Renewable Energy Seascape. Engineering 2016;2:69–78. https://doi.org/10.1016/J.ENG.2016.01.011.
[5] Barragán JM, de Andrés María. Analysis and trends of the world's coastal cities and agglomerations. Ocean Coast Manag 2015;114:11–20. https://doi.org/10.1016/j.ocecoaman.2015.06.004.
[6] Mendoza E, Lithgow D, Flores P, Felix A, Simas T, Silva R. A framework to evaluate the environmental impact of OCEAN energy devices. Renew Sustain Energy Rev 2019;112:440–9. https://doi.org/10.1016/j.rser.2019.05.060.
[7] Martínez ML, Silva R, García J. How can we use ocean energy to generate electricity? Frontiers (Boulder) n.d.;in press.
[8] Waggitt JJ, Scott BE. Using a spatial overlap approach to estimate the risk of collisions between deep diving seabirds and tidal stream turbines: a review of potential methods and approaches. Mar Pol 2014;44:90–7. https://doi.org/10.1016/j.marpol.2013.07.007.
[9] Hammar L, Eggertsen L, Andersson S, Ehnberg J, Arvidsson R, Gullström M, et al. A probabilistic model for hydrokinetic turbine collision risks: exploring impacts on fish. PloS One 2015;10:e0117756. https://doi.org/10.1371/journal.pone.0117756.
[10] Hammar L, Gullstrom M, Dahlgren TG, Asplund ME, Braga Goncalves I, Molander S. Introducing ocean energy industries to a busy marine environment. Renew Sustain Energy Rev 2017;74:178–85. https://doi.org/10.1016/j.rser.2017.01.092.
[11] Boehlert G, Gill A. Environmental and ecological effects of ocean renewable energy development: a current synthesis. Oceanography 2010;23:68–81. https://doi.org/10.5670/oceanog.2010.46.
[12] Inger R, Attrill MJ, Bearhop S, Broderick AC, Grecian WJ, Hodgson DJ, et al. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. J Appl Ecol 2009. https://doi.org/10.1111/j.1365-2664.2009.01697.x.
[13] Panwar NL, Kaushik SC, Kothari S. Role of renewable energy sources in environmental protection: a review. Renew Sustain Energy Rev 2011;15:1513–24. https://doi.org/10.1016/j.rser.2010.11.037.
[14] Saidur R, Rahim NA, Islam MR, Solangi KH. Environmental impact of wind energy. Renew Sustain Energy Rev 2011;15:2423–30.
[15] McClure R, Acker T, Dawson J. Environmental assessment and monitoring of ocean energy sites - a rapid, proven, and economical approach. IEEE: Ocean. 2010 MTS/IEEE Seattle; 2010. p. 1–5. https://doi.org/10.1109/oceans.2010.5664110.
[16] Patricio S, Moura A, Simas T. Wave energy and underwater noise: state of art and uncertainties. IEEE: Ocean. 2009 - Eur.; 2009. p. 1–5. https://doi.org/10.1109/oceanse.2009.5278302.
[17] Boehlert Gill GWAB. Environmental and ecological effects of ocean renewable energy development. Oceanography 2010;23:68–81.
[18] McMurry GR. Wave energy ecological effects workshop: ecological assessment briefing paper. Ecological effects of wave energy development in the Pacific Northwest 2008.
[19] Sterman JD. Business dynamics. USA: McGraw-Hill; 2000.
[20] Pelc R, Fujita RM. Renewable energy from the ocean. Mar POLICY 2002;26:471–9. https://doi.org/10.1016/S0308-597X(02)00045-3.
[21] Lim YS, Koh SL. Analytical assessments on the potential of harnessing tidal currents for electricity generation in Malaysia. Renew Energy 2010;35:1024–32. https://doi.org/10.1016/j.renene.2009.10.016.
[22] Shields MA, Dillon LJ, Woolf DK, Ford AT. Strategic priorities for assessing ecological impacts of marine renewable energy devices in the Pentland Firth (Scotland, {UK}). Mar Pol 2009;33:635–42. https://doi.org/10.1016/j.marpol.2008.12.013.
[23] Aria M, Cuccurullo C. bibliometrix : an R-tool for comprehensive science mapping analysis. J Informetr 2017;11:959–75. https://doi.org/10.1016/j.joi.2017.08.007.
[24] Schmidt M. The Sankey diagram in energy and material flow management. J Ind Ecol 2008;12:173–85. https://doi.org/10.1111/j.1530-9290.2008.00015.x.
[25] Mvsp. Multivariate statistical package. 2000.
[26] Neill SP, Jordan JR, Couch SJ. Impact of tidal energy converter ({TEC}) arrays on the dynamics of headland sand banks. Renew Energy 2012;37:387–97. https://doi.org/10.1016/j.renene.2011.07.003.
[27] Lovall C, Seitz R, Knick K. Direct and indirect impacts of shoreline development on shallow-water benthic communities in a depauperate estuarine system. Bull Mar Sci 2017;93:715–41. https://doi.org/10.5343/bms.2016.1076.
[28] Want A, Crawford R, Kakkonen J, Kiddie G, Miller S, Harris RE, et al. Biodiversity characterisation and hydrodynamic consequences of marine fouling communities on marine renewable energy infrastructure in the Orkney Islands Archipelago, Scotland, {UK}. Biofouling 2017;33:567–79. https://doi.org/10.1080/08927014.2017.1336229.
[29] Sheehan EV, Gall SC, Cousens SL, Attrill MJ. Epibenthic assessment of a renewable tidal energy site. Sci World J 2013;2013:1–8. https://doi.org/10.1155/2013/906180.
[30] 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;22:219–30. https://doi.org/10.1007/s00773-016-0405-y.
[31] Grecian WJ, Inger R, Attrill MJ, Bearhop S, Godley BJ, Witt MJ, et al. Potential impacts of wave-powered marine renewable energy installations on marine birds. IBIS Int J Avian Sci 2010;152:683–97. https://doi.org/10.1111/j.1474-919X.2010.01048.x.
[32] Westerberg H, Lagenfelt I. Sub-sea power cables and the migration behaviour of the European eel. Fish Manag Ecol 2008;15:369–75. https://doi.org/10.1111/j.1365-2400.2008.00630.x.
[33] Schramm MP, Bevelhimer M, Scherelis C. Effects of hydrokinetic turbine sound on the behavior of four species of fish within an experimental mesocosm. Fish Res 2017;190:1–14. https://doi.org/10.1016/j.fishres.2017.01.012.
[34] Viehman HA, Zydlewski GB. Fish interactions with a commercial-scale tidal energy device in the natural environment. Estuar Coast 2015;38:241–52. https://doi.org/10.1007/s12237-014-9767-8.
[35] Turnpenny A, Clough S, Hanson K, Ramsay R, McEwan D. Risk assessment for fish passage through small, low-head turbines. London, UK: ETDEWEB; 2000.
[36] Castro-Santos T, Haro A. Survival and behavioral effects of exposure to a hydrokinetic turbine on juvenile atlantic salmon and adult American shad. Estuar Coast 2013;38:203–14. https://doi.org/10.1007/s12237-013-9680-6.
[37] Kolar HR, McKeown EP, Purcell ME, Gaughan PJ, Westbrook AG, Barry MG, et al. The design and deployment of a real-time wide spectrum acoustic monitoring system for the ocean energy industry. MTS/IEEE Ocean. - Bergen; 2013. p. 1–4. 2013.
[38] Pine MK, Schmitt P, Culloch RM, Lieber L, Kregting LT. Providing ecological context to anthropogenic subsea noise: assessing listening space reductions of marine mammals from tidal energy devices. Renew Sustain Energy Rev 2019;103:49–57. https://doi.org/10.1016/j.rser.2018.12.024.
[39] Walsh J, Bashir I, Thies PR, Johanning L, Blondel P. Acoustic emission health monitoring of marine renewables: illustration with a wave energy converter in Falmouth Bay ({UK}). Ocean. 2015 - Genova, IEEE; 2015. p. 1–7. https://doi.org/10.1109/oceans-genova.2015.7271455.
[40] 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. J Ocean Eng 2017;42:948–65. https://doi.org/10.1109/joe.2016.2637179.
[41] Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten Cate C, Popper AN. A noisy spring: the impact of globally rising underwater sound levels on fish. Trends Ecol Evol 2010;25:419–27. https://doi.org/10.1016/j.tree.2010.04.005.
[42] Montgomery JC, Jeffs A, Simpson SD, Meekan M, Tindle C. Sound as an orientation cue for the pelagic larvae of reef fishes and decapod Crustaceans. Adv Mar Biol 2006;51:143–96. https://doi.org/10.1016/S0065-2881(06)51003-X.
[43] Broadhurst M, Orme CDL. Spatial and temporal benthic species assemblage responses with a deployed marine tidal energy device: a small scaled study. Mar Environ Res 2014;99:76–84. https://doi.org/10.1016/j.marenvres.2014.03.012.
[44] Ward J, Schultz I, Woodruff D, Roesijadi G, Copping A. Assessing the effects of marine and hydrokinetic energy development on marine and estuarine resources. Ocean 2010:1–7. 345 E 47TH ST, NEW YORK, NY 10017 USA: IEEE; 2010.
[45] Fujita R, Markham AC, Diaz JED, Garcia JRM, Scarborough C, Greenfield P, et al. Revisiting ocean thermal energy conversion. Mar Pol 2012;36:463–5. https://doi.org/10.1016/j.marpol.2011.05.008.
[46] Etemadi A, Emdadi A, AsefAfshar O, Emami Y. Electricity generation by the ocean thermal energy. In: Huang Q, Kang J, editors. Proc. Int. Conf. Smart grid clean energy technol, vol. 12. Icsgce; 2011. p. 936–43. https://doi.org/10.1016/j.egypro.2011.10.123. 2011.
[47] Stevens AW, Lacy JR. The influence of wave energy and sediment transport on seagrass distribution. Estuar Coast 2012;35:92–108. https://doi.org/10.1007/s12237-011-9435-1.
[48] Nall CR, Schläppy M-L, Guerin AJ. Characterisation of the biofouling community on a floating wave energy device. Biofouling 2017;33:379–96. https://doi.org/10.1080/08927014.2017.1317755.
[49] Laws ND, Epps BP. Hydrokinetic energy conversion: technology, research, and outlook. Renew Sustain Energy Rev 2016;57:1245–59. https://doi.org/10.1016/j.rser.2015.12.189.

[50] Posner AJ, O'Sullivan K, Murphy J. Economic and environmental impact appraisal of commercial scale offshore renewable energy installations on the west coast of Ireland. J Coast Res 2013;65:1639–44. https://doi.org/10.2112/si65-277.1.
[51] Eberhards G, Lapinskis J, Saltupe B. Hurricane Erwin 2005 coastal erosion in Latvia. Baltica 2006;10–9.
[52] Stockdon HF, Doran KS, Thompson DM, Sopkin KL, Plant NG, Sallenger AH. National assessment of hurricane-induced coastal erosion hazards–Gulf of Mexico. 2012. https://doi.org/10.3133/ofr20121084.
[53] Silva R, Martínez ML, Hesp PA, Catalan P, Osorio AF, Martell R, et al. Present and future challenges of coastal erosion in Latin America. J Coast Res 2014;71:1–16. https://doi.org/10.2112/SI71-001.1.
[54] Connell S. Urban structures as marine habitats: an experimental comparison of the composition and abundance of subtidal epibiota among pilings, pontoos and rocky reefs. Mar Environ Res 2001;52:115–25.
[55] Felix A, Hernández-Fontes J, Lithgow D, Mendoza E, Posada G, Ring M, et al. Wave energy in tropical regions: deployment challenges, environmental and social perspectives. J Mar Sci Eng 2019;7:219. https://doi.org/10.3390/jmse7070219.
[56] Greene HG. Habitat characterization of a tidal energy site using an ROV: overcoming difficulties in a harsh environment. Continent Shelf Res 2015;106: 85–96. https://doi.org/10.1016/j.csr.2015.06.011.
[57] Short FT, Polidoro B, Livingstone SR, Carpenter KE, Bandeira S, Bujang JS, et al. Extinction risk assessment of the world's seagrass species. Biol Conserv 2011;144: 1961–71. https://doi.org/10.1016/j.biocon.2011.04.010.
[58] Macleod A, Stanley M, Day J, Cook E. Biofouling community composition across a range of environmental conditions and geographical locations suitable for floating marine renewable energy generation. Biofouling 2016;32:261–76.
[59] Nir S, Reches M. Bio-inspired antifouling approaches: the quest towards non-toxic and non-biocidal materials. Curr Opin Biotechnol 2016;39:48–55. https://doi.org/10.1016/j.copbio.2015.12.012.
[60] Abbasi SA, Abbasi N. The likely adverse environmental impacts of renewable energy sources. Appl Energy 2000;65:121–44. https://doi.org/10.1016/S0306-2619(99)00077-X.
[61] Gill AB. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. J Appl Ecol 2005;42:605–15. https://doi.org/10.1111/j.1365-2664.2005.01060.x.
[62] Stokesbury MJW, Logan-Chesney LM, McLean MF, Buhariwalla CF, Redden AM, Beardsall JW, et al. Atlantic sturgeon spatial and temporal distribution in minas passage, nova scotia, Canada, a region of future tidal energy extraction. PloS One 2016;11:e0158387. https://doi.org/10.1371/journal.pone.0158387.
[63] Lees KJ, Guerin AJ, Masden EA. Using kernel density estimation to explore habitat use by seabirds at a marine renewable wave energy test facility. Mar Pol 2016;63: 35–44. https://doi.org/10.1016/j.marpol.2015.09.033.
[64] Henkel SK, Suryan RM, Lagerquist BA. Marine renewable energy and environmental interactions: baseline assessments of seabirds, marine mammals, sea turtles and benthic communities on the Oregon shelf. Mar. Renew. Energy technol. Environ. Interact. Springer Netherlands; 2014. p. 93–110. https://doi.org/10.1007/978-94-017-8002-5_8.
[65] Williamson BJ, Blondel P, Armstrong E, Bell PS, Hall C, Waggitt JJ, Scott BE. A self-contained subsea platform for acoustic monitoring of the environment around marine renewable energy Devices{\textendash}Field deployments at wave and tidal energy sites in orkney, Scotland. J Ocean Eng 2016;41:67–81. https://doi.org/10.1109/joe.2015.2410851.
[66] Langhamer O. Effects of wave energy converters on the surrounding soft-bottom macrofauna (west coast of Sweden). Mar Environ Res 2010;69:374–81. https://doi.org/10.1016/j.marenvres.2010.01.002.
[67] Onoufriou J, Brownlow A, Moss S, Hastie G, Thompson D. Empirical determination of severe trauma in seals from collisions with tidal turbine blades. J Appl Ecol 2019;56:1712–24. https://doi.org/10.1111/1365-2664.13388.
[68] Simmonds MP, Brown VC. Is there a conflict between cetacean conservation and marine renewable-energy developments? Wildl Res 2010;37:688–94. https://doi.org/10.1071/wr10020.
[69] Liu Y, Ma C, Jiang B. Development and the environmental impact analysis of tidal current energy turbines in China. IOP Conf Ser Earth Environ Sci 2018;121:42003. https://doi.org/10.1088/1755-1315/121/4/042003.
[70] Otsuka K, Iio K. Economic and environmental evaluations for multi-purpose utilizations of deep ocean water in Hateruma Island. Japan. 2016 Techno-Ocean, IEEE; 2016. p. 217–20. https://doi.org/10.1109/techno-ocean.2016.7890649.
[71] Azzellino A, Lanfredi C, Riefolo L, De Santis V, Contestabile P, Vicinanza D. Combined exploitation of offshore wind and wave energy in the Italian seas: a spatial planning approach. Front Energy Res 2019;7:42. https://doi.org/10.3389/fenrg.2019.00042.
[72] Jones EL, Sparling CE, McConnell BJ, Morris CD, Smout S. Fine-scale harbour seal usage for informed marine spatial planning. Sci Rep 2017;7:1–11. https://doi.org/10.1038/s41598-017-11174-4.
[73] Waycott M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarnik S, et al. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci Unit States Am 2009;106:12377–81. https://doi.org/10.1073/pnas.0905620106.
[74] Moreno-Casasola P. Servicios ecosistémicos de selvas y bosques costeros de Veracruz. Costa Sustentable no 8. INECOL-ITTO-CONAFOR-INECC; n.d.
[75] Claisse JT, Pondella DJ, Love M, Zahn LA, Williams CM, Williams JP, et al. Oil platforms off California are among the most productive marine fish habitats globally. Proc Natl Acad Sci Unit States Am 2014;111:15462–7. https://doi.org/10.1073/pnas.1411477111.
[76] Tiron R, Mallon F, Dias F, Reynaud EG. The challenging life of wave energy devices at sea: a few points to consider. Renew Sustain Energy Rev 2015;43:1263–72. https://doi.org/10.1016/j.rser.2014.11.105.
[77] Langhamer O, Wilhelmsson D. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes {\textendash} A field experiment. Mar Environ Res 2009;68:151–7. https://doi.org/10.1016/j.marenvres.2009.06.003.
[78] Bao VWW, Leung KMY, Qiu J-W, Lam MHW. Acute toxicities of five commonly used antifouling booster biocides to selected subtropical and cosmopolitan marine species. Mar Pollut Bull 2011;62:1147–51. https://doi.org/10.1016/j.marpolbul.2011.02.041.
[79] Copping A, Hanna L, Van Cleve B, Blake K, Anderson RM. Environmental risk evaluation system - an approach to ranking risk of ocean energy development on coastal and estuarine environments. Estuar Coast 2015;38:287–302. https://doi.org/10.1007/s12237-014-9816-3.
[80] Callow JA, Callow ME. Trends in the development of environmentally friendly fouling-resistant marine coatings. Nat Commun 2011;2:244. https://doi.org/10.1038/ncomms1251.
[81] Dolman S, Simmonds M. Towards best environmental practice for cetacean conservation in developing Scotland's marine renewable energy. Mar Pol 2010;34: 1021–7. https://doi.org/10.1016/j.marpol.2010.02.009.
[82] O'Carroll JPJ, Kennedy RM, Savidge G. Identifying relevant scales of variability for monitoring epifaunal reef communities at a tidal energy extraction site. Ecol Indicat 2017;73:388–97. https://doi.org/10.1016/j.ecolind.2016.10.005.
[83] Loxton J, Macleod AK, Nall CR, McCollin T, Machado I, Simas T, et al. Setting an agenda for biofouling research for the marine renewable energy industry. Int J Mar Energy 2017;19:292–303.
[84] Pelc R, Fujita RM. Renewable energy from the ocean. Mar Pol 2002;26:471–9. https://doi.org/10.1016/S0308-597X(02)00045-3.
[85] Copping AE, Hemery, Lenaïg G, Overhus DM, Garavelli L, Freeman MC, Whiting JM, et al. Potential environmental effects of marine renewable energy development—the state of the science. J Mar Sci Eng 2020;8:1–18. https://doi.org/10.3390/jmse8110879.
[86] Doney SC, Fabry VJ, Feely RA, Kleypas JA. ocean acidification: the other CO2 problem. Ann Rev Mar Sci 2009;1:169–92. https://doi.org/10.1146/annurev.marine.010908.163834.
[87] Orth RJ, Carruthers TIMJB, Dennison WC, Duarte CM, Fourqurean JW, Heck KL, et al. A global crisis for seagrass ecosystems. Bioscience 2006;56:987–96. https://doi.org/10.1641/0006-3568. 2006)56[987:agcfse]2.0.co;2.
[88] Bellwood DR, Hughes TP, Folke C, Nyström M. Confronting the coral reef crisis. Nature 2004;429:827–33. https://doi.org/10.1038/nature02691.
[89] Knowlton N, Jackson JBC. Shifting baselines, local impacts, and global change on coral reefs. PLoS Biol 2008;6:e54. https://doi.org/10.1371/journal.pbio.0060054.
[90] Silva R, Oumeraci H, Martínez ML, Chávez V, Lithgow D, van Tussenbroek BI, et al. Ten commandments for sustainable, safe, and W/healthy sandy coasts facing global change. Front Mar Sci 2021;8:126.