Environmental Assessment tool in DTOcean+: reducing local and global environmental impacts for ocean energy projects

Emma Araignous, Youen Kervella, Nicolas Michelet, Neil Luxcey, Vincenzo Nava, Rui Duarte, Rocio Isorna and Georges Safi

Abstract— **Designing reliable ocean energy devices with reduced costs is crucial for the sector's development. This development of renewable energies should also be implemented in a sustainable manner and not cause additional environmental stress and related damage. In order for the ocean energy sector to consider environmental impacts at the earliest stage of concept creation, the Environmental Assessment (EA) module was developed and included in an integrative suite of design and assessment tools (namely DTOceanPlus) to support technology innovation processes. Several complementary features were developed in the EA module which provides insight into impacts at different levels. At local scale, environmental impacts are assessed in relation to the different design choices that cover various potential pressures induced by the ocean energy array. Moreover, surveys and mitigation measures are provided regarding endangered species potentially present. At global scale, a life cycle assessment is conducted to evaluate the carbon footprint of a project in terms of its contribution to global warming and the cumulative energy demand. The present paper describes the integration of EA into DTOcean+ and two case studies were used to exemplify the use and relevancy of the EA's features to evaluate environmental impacts of a wave and a tidal ocean energy projects. Overall the EA module provides insight and support to the ocean energy sector to achieve sustainable development of marine renewable energies.**

Keywords—**DTOceanPlus, environmental impacts, ocean energy, tools, life cycle assessment, endangered species**

I. Introduction

Greenhouse gases from human activities are the most significant driver of observed climate change since the mid-20th century [1]. There is more and more evidence that the Earth's climate is warming and that this trend is expected to continue in future years, with a projected increase in surface water temperatures of between 1.64 and 3.51°C by the end of the century [2]. In this context, and to tackle climate change and its negative impacts, 196 countries adopted the Paris Agreement in 2015 at the 21st session of the Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change [3]. Countries thereafter adopted action plans known as Nationally Determined Contributions for climate action towards implementing their commitments under the Paris Agreement. In the European Union, the Commission proposed the 2030 climate and energy framework, including wide targets and policy objectives for the period from 2021 to 2030, to move towards a climate-neutral economy by 2050. The 2030 key targets of this framework being at least (i) 40% cuts in greenhouse gas emissions from 1990 levels, (ii) 32% share for renewable energy and (iii) 32.5% improvement in energy efficiency. Among the renewable energies, ocean energy is expected to play an important role in addressing one of the EU's biggest challenges: providing clean, affordable and sustainable energy [4].

The global capacity of ocean energy is high with an installation capacity of 337 GW by 2050. In this market, wave and tidal energy are particularly interesting and 100 GW capacity could be deployed in Europe by 2050 [5].

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Wave and tidal energy have low variability compared to wind, can be accurately forecast, and thus can be complementary to wind and solar energy, smoothing the otherwise peaking nature of renewables in the production mix [6], [7]. However, the ocean energy sector is still facing challenges related to performance, reliability, and survivability which ultimately translate into above grid-parity costs [8]. Also, many of the animal populations that reside in the energy-rich areas of the ocean are already under considerable stress from other human activities including shipping, fishing, waste disposal, and shoreline development [9]. To achieve sustainable development, it is important that the ocean energy industry does not cause additional environmental stress and related damage. Tidal and wave energy devices may pose, for instance, a risk of collision to marine mammals, fish, and seabirds. The collision risk relates to the moving components of devices (blades and rotors), as well as vessel traffic from and to deployed ocean energy sites. One way of helping the ocean energy sector to move forward is to develop forecasting tools that support developers in designing reliable ocean energy arrays with reduced costs ([8], [10]) and tools to (i) predict the arrays' potential environmental impacts and (ii) prove their efficiency in reducing greenhouse gas emission.

Life cycle assessment (LCA) and environmental impact assessment (EIA) are existing procedures applied by developers at different stages of ocean energy development and deployment. LCA is a tool that quantitatively accounts for all the energy, materials, emissions and waste products associated with a given project (e.g. deployment of an ocean energy array), considering all stages from the extraction of raw materials to disposal at the end of use of the technology (ISO 14040) [11]. An LCA allows a decision-maker to study an entire system and to compare the environmental impacts of systems or technologies that have an equivalent function or performance [12]. Although LCA can investigate different impact categories (e.g. Global warming, ocean acidification; ozone depletion; Human toxicity etc.), it is very often applied in the ocean energy sector to assess carbon dioxide emissions (i.e. greenhouse gas emissions) as a proxy for estimating the contribution of the technology to global warming [13]–[18]. EIA is a procedure that follows specific regulatory frameworks requiring that biological resources and ecosystems are protected throughout the siting and permitting (consenting) processes of a project [19], [20]. Different instruments, methods and models are available for the environmental monitoring of ocean energy impacts on ecosystem compartments, including resource assessment and monitoring, collision risk monitoring, etc. [20]. Although the legislative framework and assessment instruments for EIA and LCA exist and are constantly being improved, these procedures are often applied to ocean energy projects that are already well advanced (i.e. the technology design is chosen) and in the process of preparing the siting and permitting processes prior to installation. However, very few tools exist today, as open access tools, to allow the ocean energy sector to forecast potential environmental impacts of their ocean energy projects at an early stage of concept design (i.e. the technology design is not yet established). For instance, a series of logic models exists that describe studies and processes for environmental siting and permitting. Each study and environmental permitting process is assigned a cost derived from existing and proposed marine tidal and wave and riverine hydrokinetic projects. In this way, the contribution of environmental siting and permitting requirements to the cost of ocean energy devices can be estimated ([19], [21], [22]). Also, an open access tool is available for managers, decision makers and industry to assess the suitability of Wave Energy Converter installation projects, in terms of the potential impacts that they can cause to marine ecosystems (https://azti.shinyapps.io/wec-era/). The tool is based on the Ecosystem Risk Assessment of three different Wave Energy Converter technologies during their life-cycle stages (from installation to operation and decommissioning). It provides the assessments for pressures and the sensitivity of ecosystem components to pressures produced by Wave Energy Converters. However, to our knowledge, no open access tools exist today for the assessment of the environmental impacts of both tidal and wave energy devices, at an early stage of ocean energy concept design, considering global level impacts (i.e. global warming impacts) and local level impacts (i.e. EIA applied to a local site for the deployment of an ocean energy array). At an early concept design stage, the choice of the technology and its components is still to be determined. The importance of such a tool lies in the fact that it ensures that the new concept and choices made will meet carbon reduction targets and reduce environmental impacts in order to avoid additional pressure on the marine environment.

In order to support the ocean energy development sector and to address the identified gaps, the Environmental Assessment (EA) module was developed and integrated within DTOceanPlus software. This open-source suite of design tools was developed under the Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment (DTOceanPlus) project [23]. The EA module produces an environmental impact assessment for a chosen technology (either tidal or wave energy) including an evaluation of the environmental impacts related to the deployment of the ocean energy array (i.e. Operations and maintenance at sea, electrical connection to shore, etc.). The environmental assessment conducted by EA is structured into a two levels assessments: local and global. At the local level, a first preliminary assessment targets the identification of the potential presence of endangered species in the area (i.e. species included in the IUCN Red List) where the ocean energy array is to be deployed. Then, a second more comprehensive environmental impact assessment is conducted, based on a series of identified pressures such as underwater noise produced by the array or the collision risk between vessels/devices and marine wildlife. At global level, the assessment focuses on the carbon dioxide footprint of the project in terms of global warming participation or cumulative energy demand. Based on these two assessments, the EA module produces a quantitative estimation of the environmental impact, together with a list of recommendations to guide the user in ways of reducing the impacts and/or to suggest relevant existing methods to be considered for monitoring environmental impacts during the project lifecycle.

The objectives of the present paper are to describe the novel EA module and to test the accuracy and usefulness of its functionalities using two case studies. For this purpose, a brief review of the DTOcean+ tool will be done to understand the integration of EA within this set of tools, followed by a detailed description of the two levels of environmental assessments and the two case studies: reference model 1 (RM1) in Puget Sound, Washington and RM3 in Humboldt County, California [24]. The results and recommendations provided by the module regarding the assessments of the two RMs are outlined in Section 3. The ability of the tool to provide a relevant assessment for the ocean energy sector is discussed in Section 4. The most important outcomes of the work are summarized in Section 5.

II. METHODS

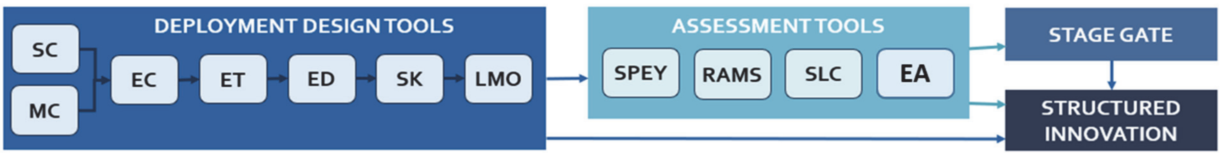
DTOCEANPLUS OVERVIEW

The DTOceanPlus software (DTO+) is an open source suite of design tools for the selection, development, deployment and assessment of ocean energy systems. It was developed and demonstrated through the H2020 DTOceanPlus project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement n° 785921. The goal of the DTO+ project is the acceleration of commercialization within the ocean energy sector (https://gitlab.com/dtoceanplus; it is worth noticing that in the online version, the tool is called Environmental and Social Acceptance "ESA" as it will also include social aspects of ocean energy project in further development).

DTO+ was designed to mitigate the technical and financial risks of the technology to achieve the deployment of cost-competitive wave and tidal arrays. The objective is to underpin a rapid reduction in the Levelized Cost of Energy offered by facilitating improvement of the reliability and survivability performance of ocean energy systems, and analyzing the impact of design on energy yield, operation and maintenance, as well as on the environment, thus making the sector more attractive for private investment. DTO+ aligns innovation and development processes with those used in mature engineering sectors:

- Technology concept selection is facilitated by a Structured Innovation tool [25], [26].
- Technology development is enabled by a Stage-Gate tool [27].
- Technology deployment is supported by a set multidisciplinary design [28]–[34] and assessment tools [35]–[39] that produce metrics used as inputs by the Stage Gate and Structured Innovation tools, as illustrated in Fig.1.

Horizon 2020 uses a scale of Technology Readiness Levels (TRL) to evaluate project eligibility [40]. This baseline has been used within the DTO+ project to define the complexity levels of the tool. In this sense, each module can be used at three levels of complexity that reflect the stage of development of the user project and the level of



SC	**Site Characterisation** – Characterise the site, including metocean, geotechnical, and environmental conditions.
MC	**Machine Characterisation** – Characterise the device prime mover
EC	**Energy Capture** – Calculate and optimise the hydrodynamic capture performance of single devices and arrays
ET	**Energy Transformation** – Design PTO and control solutions
ED	**Energy Delivery** – Design electrical and grid connection solutions to transmit power to shore
SK	**Station Keeping** – Design moorings and foundations solutions
LMO	**Logistics & Marine Operations** – Design logistical solutions and operation plans related to installation, operation, maintenance, and decommissioning operations
SPEY	**System Performance and Energy Yield** – Evaluate projects in terms of energy performance.
RAMS	System **Reliability, Availability, Maintainability, Survivability** – Evaluate the reliability aspects of a marine renewable energy project.
SLC	**System Lifetime Costs** – Evaluate projects from the economic perspective
EA	**Environmental Assessment** – Evaluate the environmental impacts of a given wave and tidal energy projects.
SG	**Stage Gate** – Using metrics to measure, assess and guide technology development
SI	**Structured Innovation** – Methodologies to provide a structured approach to innovation in concept creation, selection, and design

Fig. 1. List of DTO+ modules, and their main objectives (source: DTOceanPlus project)

information needed for the assessment (Appendix A). This concept also opens up access to DTO+ to a broad range of users: technology and project developers, public funding bodies and private investors.

Complexity level 1 corresponds to the concept creation and development stage (TRL 1-2-3). At this stage, the technology exists either as a numerical or prototype with experimental proof of concept.

Complexity level 2 refers to design optimization and feasibility: design, manufacturing and installation for intended final scale are identified (TRL 4-5-6).

At complexity level 3, the system is fully operational, including the inter-device energy grid, the substation, and the connection to the shore energy grid (TRL 7-8-9). A pilot scale device has been tested at a natural site.

DTO+ has a flexible design, allowing the user to run the software suite in two modes:

- integrated mode: the user runs the complete suite of tools, and all the modules share and communicate data between each other automatically
- standalone mode: the user runs only one module, focusing on a specific disciplinary area. When using this mode, the user often needs to input additional data that are not provided by the other modules.

Environmental Assessment module

A. *Assessing local environmental impacts of ocean energy projects*

1) *Endangered species*

The endangered species feature provides insight on the presence of endangered species in the area of implementation of a project farm. A local database of global geographical information, including 26 marine species, is integrated in the EA module. Once endangered species have been identified, the EA module associates the species with the main risks that can be caused by ocean energy deployment. The final result output includes advice for the EA user on appropriate surveys and mitigation measures to be considered.

Global geographical information

An initial selection of 26 species was included in DTO+ (Appendix B). The preliminary selection is based on species that are listed (i) as "Endangered" or worse by the IUCN Red List [41], (ii) in European Directives and Regional Sea Conventions (92/43/EEC, 2009/147/EC, HELCOM 2013, OSPAR 1992) and (iii) in International Conventions (Berne 1979, Bonn 1979, Washington 1973, Barcelona 1976, 1995). Five classes of animals were included: seven mammals, three Actinopterygii (bony fishes), six Chondrichthyes (cartilaginous fishes), five Aves (birds) and five Reptilia (turtles).

A database of large-scale probability maps for the presence for each species has been integrated in the DTO+ software. Each map presents the global geographical information of a given species and was downloaded from AquaMaps [42]. The maps represent the mean annual species distributions (Fig. 2). However, these maps do not account for changes in species occurrence due to seasonal migration or unusual environmental events such as El Niño. They are based on data available through online species databases such as FishBase [43] and SeaLifeBase [44] and species occurrence records from the Ocean Biodiversity Information System (OBIS; www.obis.org) or the Global Biodiversity Information Facility (GBIF; www.gbif.org). Models are constructed from estimates of the environmental tolerance of a given species with respect to depth, salinity, temperature, primary productivity, and its association with sea ice or coastal areas.

In an effort to supplement the extraction of geographical information, the EA module allows the user to report optional input on the presence of additional species in their area that may not be included in the current database. Through this, resident or migratory species specific to an area can be addressed in the recommendations.

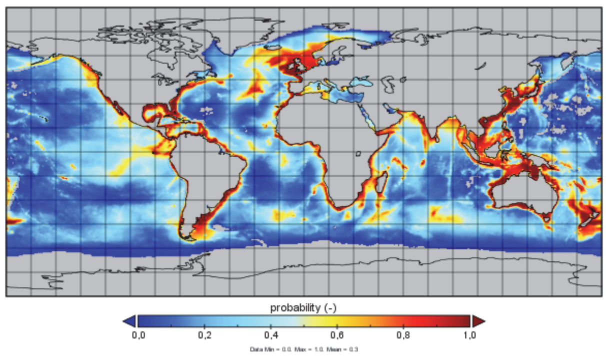


Fig. 2. Example of a global map for *Tursiops truncatus* probability of presence.

Surveys and mitigation measures

Based on the location of the project, the tool searches in the database for geographical information at the nearest coordinates in order to extract the list of probabilities of the presence of the considered species. In light of this extracted list of species, the EA module produces a list of recommendations including advices on surveys and mitigation measures to be considered by the user for future environmental monitoring of their ocean energy site. For each taxonomic class, the list of the main associated risks considered has been derived from reports on environmental impacts generated by MRE arrays [45]–[50]. For each risk, different surveys and measures are proposed which cover the different project life cycle phases (i.e. installation, operation and dismantling). The suggested recommendations may be avoidance or reduction measures, i.e. they may respectively eliminate the significant negative effects of the project at the design stage or minimize those that cannot be avoided. Both mitigation measures and surveys proposed in this features are drawn from an extensive review of measures currently applied to address these impacts and thus are in line with the different classes of instrumentation commonly used for monitoring marine animal interactions with MRE devices [47], [51]–[55].

Validation of the feature

In order to validate the outputs of the EA module's Endangered Species feature applied to the Reference Models (RMs), the IUCN database (https://www.iucnredlist.org/search) was used to compare the list of species identified in the EA module to the IUCN list. In the IUCN database, an area can be selected on a global map and filters can be applied to the search regarding the status of the species, their habitat, etc. The database returns a list of endangered species present in the corresponding area. In addition to the IUCN database, a literature review was conducted on the local presence of species in the RM areas. Both IUCN predictions and the literature review were used to evaluate and validate the EA module's capability to detect relevant species presence in RM areas.

2) *Environmental Impact Assessment*

The aim of the Environmental Impact Assessment (EIA) is to evaluate the overall impact of the different pressures produced by the ocean energy project on the environment. This feature, developed in the first version of DTOcean [56], consists of a set of functions that are able to qualify and quantify the potential pressures generated by the array of wave or tidal devices on the marine environment (Table I).

TABLE I. ENVIRONMENTAL PRESSURES GENERATED BY THE ARRAY

Function name	Brief description
Footprint	Footprint impact of the array components
Collision risk	Collision risk between fauna and devices
Collision risk with vessels	Collision risk between fauna and vessels
Energy modification	Impact of the energy modification due to the array
Reef effect	Impact of the creation of new colonizable habitats
Reserve effect	Evaluation of the reserve effect due to fishery restrictions
Resting place	Impact of emerged parts of devices as resting places for pinnipeds and birds
Chemical pollution	Potential chemical pollution due to leaks from vessels in the array
Turbidity	Intensity of the turbidity modification in the water column
Temperature modification	Water temperature modification around electrical components
Electrical fields	Electrical field modification around electrical components
Magnetic fields	Magnetic field modification around electrical components
Underwater noise	Underwater noise produced by the array

Each environmental function evaluates one pressure and links two entities:

1) the stressors are those parts of an MRE system that may cause harm or stress to a marine animal, a habitat, oceanographic process, or ecosystem process [45]. These stressors include the moving blades on turbines, mooring lines, anchors or foundations, power export cables, and the emissions that can result from any of these parts.
2) the receptors include the marine animals living in and passing through the vicinity of an MRE development; the habitats in which the devices are deployed; and oceanographic processes, such as the natural movement of waters, wave heights or sediment transport [45].

It is the intersection of stressors and receptors that defines the interactions assessed in EIA. The Environmental Impact Score is evaluated through a 3-step process considering the quantification of the 'pressure' generated by the stressors, the quantification of the receptor sensitivity and qualification of the seasonal distribution of receptors (Appendix C).

Three-step process

The scoring allocation system is generic for each environmental function and based on three consecutive main steps described in detail in [56]. For every function, the user obtains an Environmental Impact Score (EIS) which ranges from -100 to 0 for 'negative' impacts and from 0 to 50 for 'positive' impacts.

The qualification and quantification of the 'pressure' related to the farm's design choices are obtained by computing the environmental function. The result of this function can be weighted if qualitative information linked to the environment around the function is identified (e.g. depth, design of devices, and components, if the cable is unburied or not, the type of sediment etc.). In the absence of identified constraints, the precautionary principle is applied with the worst weighting: 1.

Then, the identified presence of receptors on site triggers the second step: the receptor sensitivity analysis which adjusts the pressure according to receptor sensitivity. For further analysis, the user can specify the seasonal presence in the third step which then evaluates the impact on a monthly basis. If no prior information on receptors is available, the maximum sensitivity value is applied.

TABLE II. LINKS BETWEEN THE PRESSURES CONSIDERED IN THE ENVIRONMENTAL IMPACT ASSESSMENT AND THE FOUR TECHNOLOGY GROUPS

Technology groups	Footprint	Collision risk	Energy modification	Reef effect	Reserve effect	Resting place	Chemical pollution	Turbidity	Temperature	Electromagnetic fields	Underwater noise
Hydrodynamics		√	√	√	√	√		√			√
Electrical Sub-systems	√	√		√	√	√			√	√	√
Moorings & Foundations	√	√		√							√
Logistics	√	√					√	√			√

Impact assessments

Since each pressure can be linked to one or several technology groups of an MRE project (Table II), the EIA will produce three levels of assessment:

1) A mean global assessment (mean EIS) that provides information on the array level impacts of the overall design choices (i.e. including all technology groups and all pressures associated with them).
2) A technology group level assessment (e.g. Hydrodynamics or Logistics), that reports on the specific impact of each technology group and provides associated recommendations to help improve the environmental impact.
3) A detailed mean EIS value for each pressure (e.g. Collision risk or Underwater noise), with no distinction between technology groups.

Validation of the feature

In order to appraise the EIA feature, the different pressures were evaluated with regard to the literature on environmental impact assessment and risks associated with MRE design and the marine environment (see Appendix E).

B. *Assessing the global environmental impacts of ocean energy projects: estimation of Carbon Dioxide footprint*

Life Cycle Assessment (LCA) application, including Carbon Dioxide (CO_2) footprint (i.e. greenhouse gas emissions), can have several purposes that can be illustrated with the example of electric power generation systems. On one hand, electric power generation systems can be assessed by LCA, and their environmental impacts can be compared to other electric power generators (e.g. ocean energy versus nuclear power). On the other hand, LCA measures can also allow comparison between different systems of ocean energy devices in order to make their designs converge towards the best, least impacting solution (e.g. comparing different models of tidal energy devices). In the EA module, the LCA application for the carbon footprint assessment is developed following the international standards ISO 14040 and ISO 14044 which describe four steps to follow, as outlined below.

Objectives and scope

An LCA is performed in order to (1) translate the preliminary flows (e.g. bills of material required for the production of devices, fuel required for transportation during installation) of an ocean energy conceptual array into midpoint informative indicators and (2) to situate a project among its alternative concepts and to enable a first-degree judgement of its relevance.

The type of project that can be evaluated by the EA module is an array installed at sea and connected to the onshore electricity network. The array's main function is to convert renewable energy (kinetic, potential) into electrical energy and deliver it to the grid. The Functional Unit used is the kWh of electrical energy delivered to the network. The system is modelled following an attributional approach [57]. The processes it uses are therefore average (technical, geographic, economic, etc.) and fixed images of existing processes, over which the system in turn has no influence (e.g. the EA module uses a mean global warming potential for steel production considering the different manufacturing processes involved rather than calculating the exact value). This approach is different from the consequential approach, whose objectives are both to determine the changes that the system can induce on the processes that it uses (or that surround it) and to assess the impacts caused by these changes [58].

The definition of system boundaries uses the process classification scale defined in the International Reference Life Cycle Data System (ILCD) Handbook [59].

Level 0: MRE array allowing the conversion of renewable energy into electricity.

Level 1: manufacturing, assembly and processing activities of the constituent components of the MRE array.

Level 2: processes participating physically in the installation, operation and dismantling of the MRE array (e.g. maritime means for installation).

Level 3: processes involved in the installation, operation and dismantling of the MRE array, without physical involvement (e.g. design offices, administrative services).

In the current version of the EA module, the system includes the processes of ILCD levels 0 to 2 only. This limitation is mainly related to data availability at the conceptual phase of MRE design (i.e. outputs of the other modules in the DTO+ suite of design tools).

Life cycle inventory

Overall, the EA module's LCA considers five phases of the ocean energy projects' life cycle (Fig. 3) for which the inventory characterizes the flows entering and leaving the system.

The production phase corresponds to the assembly phase of the various components and materials in dedicated port facilities. During this phase, the carbon footprint generated is mainly related to the production of materials that are used to build the devices, the electrical sub-systems and the moorings and foundations. In the DTO+ suite, specific tools are included to design the different components of the array (e.g. the devices, the electrical sub-systems etc.). Each of these deployment tools provides the EA module with information on the main materials used to design the different sub-systems.

Three of the five phases consider the offshore marine operations: the installation phase, which includes site preparation, transport, installation and connection of the system; the operation phase, the longest phase during which the system produces energy; and dismantling and transport back to shore. During these marine operation phases, the carbon footprint will be driven by operations and maintenance at sea. These operations use different types of vessels and the main input to estimate the carbon

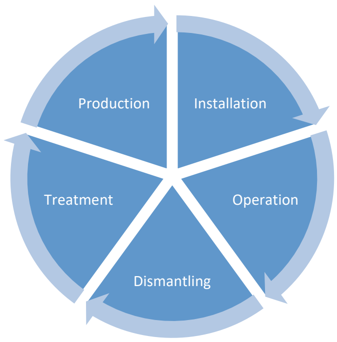


Fig. 3. Five phases considered in the Life Cycle Assessment conducted in the Environmental Assessment module of DTOceanPlus.

footprint is thus the total fuel consumption during the overall operations.

The final phase considered is treatment, which includes the sorting and transport as well as the ultimate disposal processes that will be applied to the sorted elements (recycling, incineration, landfill). At the end of the system's life, a material is recycled and then consumed again by another system. The inventory will then estimate the cumulative amount of material during the successive uses in order to obtain an average inventory per kg of material. Equitable distribution of the benefits of recycling between production and treatment phases was favored.

Life cycle impact assessment

Three mid-point indicators are calculated to assess the carbon footprint of ocean energy projects designed with DTO+ (see detailed calculations in [38]):

1) Global Warming Potential (GWP, gCO_2-eq/kWh) is the overall estimation of CO_2 produced per KWh during the whole life cycle of the ocean energy project (i.e. from production to dismantling). [60].
2) Cumulative Energy Demand (CED, MJ/kWh) investigates the energy use throughout the life cycle of the ocean energy project including the direct uses as well as the indirect or grey consumption of energy [14].
3) Energy Payback Period (EPP, Months) is defined as the time required to generate the same amount of energy that was necessary to produce the system itself [61]. It is the ratio between the CED and the annual mean energy produced.

The principal aim of this assessment is the comparability of several DTO+ designed ocean energy projects or project phases in order to identify the potential characteristics that substantially contribute to the global warming potential or cumulative energy demand. In addition to the above, the tool displays a comparison between the global life cycle results and other electrical generation technologies or other concepts of the same type of converter. Particular attention should be paid to the fact that direct comparison with values from other LCA studies should be taken with caution, as assumptions may be different and often non-conservative, not to mention problems of compliance with ISO standards. Hence the carbon footprint comparison between a DTO+ designed device and that of an external device is to be taken with precaution. However, the direct comparison between two different DTO+ designed devices is possible as the same methodology is applied.

Validation of the feature

A comparative analysis of the LCA's results for the two RMs with LCAs of other technologies will be conducted to evaluate the relevancy of the feature in the assessment of the global scale impact of MRE projects. In particular, a comparison between the GWP results of RM1 will be made with the SeaGen LCA from which it is directly inspired [14].

CASE STUDY SIMULATIONS

To exemplify the functioning and benefits of the EA tool, two case studies following the Reference Models (RMs) described in [24] have been assessed in integrated mode at complexity level 2 considering that no environmental measurements are yet available.

For each Reference Model, the DTO+ suite of design tools is used in complexity level 2 to characterize sites (Site Characterization), to design devices (Machine Characterization, Energy Capture and Energy Transformation), foundations (Station Keeping) and electrical systems (Energy Delivery) and to plan the logistics of marine operations for the different phases (Installation, maintenance and decommissioning). Following the software workflow (Fig. 1), EA collects the different outputs of the design tools and the remaining information required to run the tool is estimated based on the literature or local information (see sections A and B) in order to fully address the impacts of the projects with the features of the tool (Appendix D).

In the two reference models, the assumption is made that device and foundation parts above the seabed would be brought back to land to be recycled. This assumption is based on the decommissioning plan for the SeaGen turbine which states that the pile should be cut just above the seafloor [62]. In the case of buried cables, it is assumed that they will remain in place at the end of the project. In the

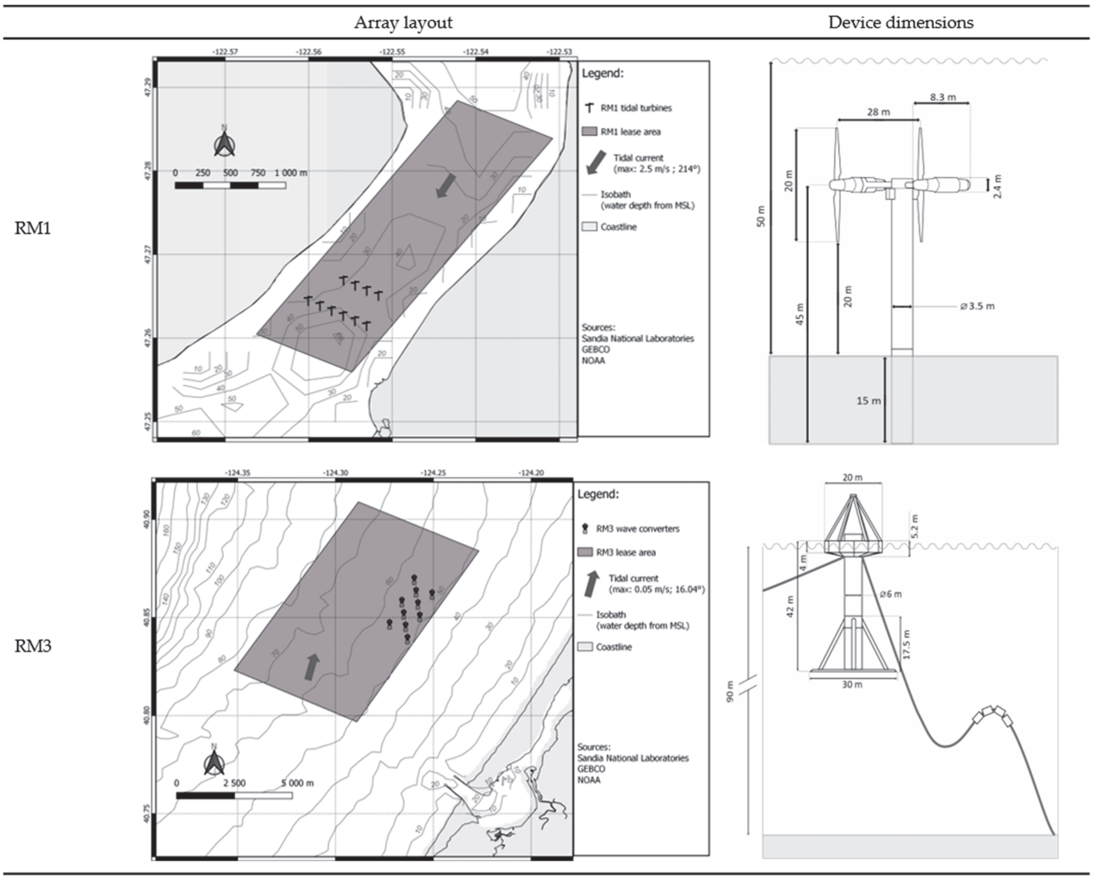


Fig. 4. Array layout and device dimensions of the two reference models: RM1 and RM3

case of floating devices, restrictions for trawler fisheries are considered in the RM3 simulation to avoid potential problems with mooring lines.

A. Reference Model 1

The RM1 was developed for a fixed tidal energy converter array of 10 dual-rotor axial-flow turbines connected in a radial network at the Tacoma Narrows site in Puget Sound, Washington (Fig. 4). In our case of a 20-year project, 10 devices with a rated power of 1MW were considered for a total mean annual energy production of 32.15 GWh.

In the total lease area, the sound's mean depth is 50m and it has a current direction for maximum velocity of 214°. The sediment is mainly composed of soft substrate benthic habitat, mainly dense sand [24]. No other prior specification is added to the receptors presence except for an endangered diving bird, the marbled murrelet (*Brachyramphus marmoratus*) resident at the Tacoma site. No specific fisheries regulations are set in the area of the farm, apart from the safety distances around devices and cables.

The SeaGen turbine design specifications were directly adopted for the RM1 device, and thus, the material composition is assumed proportional to the repartition used in the life cycle assessment of the SeaGen marine current turbine [14].

B. Reference Model 3

RM3 consists of a floating wave energy converter array of 10 wave point absorbers designed for a wave site near Eureka, in Humboldt County, California (Fig. 4). Most of the seabed in the nearshore region of the Humboldt site consists of soft sediments (sand and clay).

The device is shaped like a vertically oriented dumbbell, with a thin vertical axis, about 40m high, between two disc-shaped structures. The devices are fixed with drag embedded anchors and connected in a radial network configuration. The nominal power of each device is 286 kW for an average annual energy production of 7.99 GWh for the whole farm over the 20 years of the project. Fishery restrictions have been considered for trawlers in the case of RM3.

The presence of an endangered bird the Guadalupe murrelet (*Synthliboramphus hypoleucus)* breeding in Eureka, California is accounted for in the location characteristics.

III. RESULTS & RECOMMENDATIONS

IDENTIFICATION OF ENDANGERED SPECIES AND ASSOCIATED MITIGATION MEASURES

The endangered species identified as potentially present in the area of implementation of the two case study sites are presented in Table III and recommendations linked to each taxonomic class are presented in Table IV.

The EA module identifies species for four taxonomic classes in both locations. Two Chondrichthyes are potentially present in both areas. The great white shark (*Carcharodon carcharias*) has a probability of presence of respectively 0.33 and 0.63. The basking shark (*Cetorhinus maximus*) presents a high probability of presence at the two sites (0.61 in RM1 and 0.82 in RM3). After identifying both shark species, the EA module indicates the main risks described for this class (Table IV) and associated recommendations. Indeed, one of the main risks for Chondrichthyes is an increase of electromagnetic fields due to the electric cables. In order to fill the major data gap of *in situ* measurements, it is advised to characterize and measure the full electromagnetic field variation spectrum emitted by the submarine power cables and to reduce exposure of sensitive species to electromagnetic fields [63], [64].

Marine mammals have a very high probability of presence at the Eureka site. Indeed, six species (i.e. the North Atlantic right whale *Eubalaena glacialis,* the Harbor porpoise (*Phocoena phocoena)*, the Bottlenose dolphin (*Tursiops truncatus*), the Sei whale (*Balaenoptera borealis*), the Sperm whale (*Physeter microcephalus*), and the Blue whale (*Balaenoptera musculus*) were identified at a probability higher than 0.53 (Table III). In Tacoma, the possible encounter of the three first species has a probability close to 0.3. The two main considered risks for this class of species are collision and underwater noise induced by vessels. Surveys conducted by Marine Mammal Observers, drones or passive acoustic monitoring can help to determine the period for setting up acoustic mitigation measures like air bubble curtains that limit the sound speed propagation by modifying the water compressibility [47] or a soft start protocol to ensure time for animals to move away from the noise source [48].

One of the main causes of death for marine mammals is collision with vessels. The presence and vulnerability of species can be highlighted through seasonal variation and the impacts can be avoided or reduced by restricting certain activities to periods of low abundance or

TABLE III
LIST OF THE ENDANGERED SPECIES IDENTIFIED BY THE ENDANGERED SPECIES FEATURE AT REFERENCE MODEL RM1 AND RM3 SITES.

Class	Latin name	Probability of presence	
		RM1	RM3
Chondrichthyes	*Carcharodon carcharias*	0.33	0.63
	Cetorhinus maximus	0.61	0.82
Aves	*Synthliboramphus hypoleucus*	user input	-
	Brachyramphus marmoratus	-	user input
Mammalia	*Eubalaena glacialis*	0.31	0.81
	Phocoena phocoena	0.39	0.53
	Tursiops truncatus	0.29	0.88
	Balaenoptera borealis	-	0.53
	Physeter macrocephalus	-	0.55
	Balaenoptera musculus	-	0.56
Reptilia	*Dermochelys coriacea*	0.19	0.63
	Caretta caretta	0.38	0.45

TABLE IV
SURVEYS AND MITIGATION MEASURES GIVEN BY THE ENDANGERED SPECIES FEATURE TO MINIMIZE THE MAIN RISKS ASSOCIATED WITH THE FOUR TAXONOMIC CLASS IDENTIFIED IN REFERENCE MODELS RM1 AND RM3 SITES.

Class	Main risks	Recommendations	References
Chondrichthyes	Electro-magnetic fields	Bury cables 2 meters deep Favor three-phase cable for alternating current transmissions Characterize the electromagnetic field variation spectrum	[31][47][48]
	Noise	Avoidance construction during time of special sensitivity	[49]
Aves	Collision	Avoidance on the areas where it's a corridor of migration Turbine shut-down on demand, Restrict turbine operation Encourage the awareness among ship pilots	[36]
Mammalia	Noise	Use of Acoustic Mitigation Devices (AMD) Pre-watch Soft start protocol Delays and shut-down	[32][33][38]
	Collision	Vessel speed restriction for the lifetime of the project Application of the LSR method Encourage the awareness among ship pilots	[38]
Reptilia	Noise	Pre-watch, Shut-down and Soft start protocol, Monitoring Exclusion zones (construction), No construction during the night and inclement weather	[49]
	Collision	Vessel speed restriction for the lifetime of the project Encourage the awareness among ship pilots	[37]
	Artificial light	Not artificial light during the hatching period hatchling	[39]

vulnerability. During the site selection phase, it is suggested to avoid the areas where a corridor of migration is identified, or to implement turbine shut-down on demand [51].

The two Aves are not in the initial list of species included in DTO+. As these birds are undoubtedly present at the RM1 and RM3 sites [65]–[67], they were added as local information in the optional inputs of EA. As for mammals, the main risk for Aves is collision with a device or a vessel during a dive [51]. Recommendations are in line with those for mammals and avoidance of migration corridors should be emphasized (Table IV).

Both areas should consider the potential presence of several Reptilia, i.e. the Leatherback turtle (*Dermochelys coriacea*) and the Loggerhead turtle (*Caretta caretta*) especially in RM3 where the probability of presence are respectively 0.63 and 0.45. As Reptilia are also sensitive to noise and collision, the same protocol as for mammals or birds can be applied [68]. Particular attention should also be paid to the hatching season. As light is a navigational cue when the hatchling enters the water, artificial light could confuse the turtles' orientation and swimming behaviour, and thus increase the risk of predation mortality (Table IV) [54].

ENVIRONMENTAL IMPACTS AND DESIGN ADJUSTMENT

The global EIA results for RM1 and RM3 are outlined in Table V. Global scores correspond to the mean of either all positive or all negative scores and numbers in brackets correspond to the minimum and maximum scores obtained by the technology groups.

TABLE V
GLOBAL NEGATIVE AND POSITIVE SCORES OF THE ENVIRONMENTAL IMPACT ASSESSMENT FOR REFERENCE MODELS 1 AND 3.

	RM1		RM3	
Global Negative score	-15	[-28; -10]	-16	[-35; -10]
Global Positive score	7	[0; 10]	18	[10; 40]

Both models obtain similar ratings for negative impacts, close to -15 on a scale from 0 to -100. RM3 obtains a better positive score of 18, whereas RM1 scores 7 on the scale from 0 to 50. These results, which appear to be equivalent for the global negative results, should nevertheless be observed in detail for each technology group in order to identify the possible and priority design improvement aspects that could reduce the impacts.

The Hydrodynamics technology group receives the lowest negative scores for both reference models (Table VI). The lowest score for RM3 of -35 corresponds to a high level of energy extraction. In this area, monitoring of the sedimentary evolution should be considered as a priority and the position of the devices could be reconsidered to allow more space in between them, which would generate lower impact on the local resource (Table VI). The collision risk with devices should be considered a priority for RM1 which obtains a score of -28, but also for RM3 with a score of -19. The collision risk function in EA considers the placement of devices in relation to the current velocity and

TABLE IIII
SCORES OF THE ENVIRONMENTAL IMPACT ASSESSMENT FOR THE FOUR TECHNOLOGY GROUPS (HYDRODYNAMICS, ELECTRICAL SUB-SYSTEMS, MOORINGS AND FOUNDATIONS AND LOGISTICS) OF REFERENCE MODELS 1 AND 3 AND RECOMMENDATIONS TO MINIMIZE THE IMPACTS

Technology group	Function name	RM1	RM3	Recommendations
Hydrodynamics	Energy modification	-15	-35	Increase the space between devices Monitor the sedimentary evolution in the farm area
	Collision risk	-28	-19	Increase the space between devices
	Reef effect	10	11	Favor an orientation facing into the current Scour protection can increase the reef effect
	Reserve effect	10	40	Increase fishing restriction surface areas
	Resting place	0	10	Choose machine design allowing the reception of species in resting places
Electrical Sub-systems	Footprint	-10	0	Few pressures
	Collision risk	0	0	Few pressures
	Reef effect	10	0	-
	Reserve effect	10	0	-
Moorings & Foundations	Benthic impact	-10	-10	For floating technologies, favor taut lines on gravitational anchors Limit gravity type foundations, favor jacket systems
	Collision risk	-28	-18	Decrease the number of anchor lines or the number of foundations Prefer taut lines for the mooring design
	Reef effect	10	11	Prefer grainy texture Favor vertical designs
Logistics	Collision risk with vessels	-16	-12	Vessel speed limitation with special care in the sensitive areas Decrease vessel traffic at night and during bad weather Reduce vessel light which attracts some species

main direction. In this sense, the score will be influenced by the angle between the direction of the current and the alignment of the devices. Considering the presence of diving birds in both areas, the spacing of the devices could be considered to improve the score and completed by acting on the moorings and foundations technology group. Indeed, station keeping could represent a significant risk of collision with marine fauna, with a score of -28 for RM1 and -18 for RM3. To lower the score, it is possible to adjust the design by limiting the number of anchor lines. RM3 obtains a better score than RM1 even if mooring cables could be considered a greater risk of collision than pile foundations. This is due to the orientation of the farm with the main current which in RM1 induces a greater probability of encounter between devices or foundations and marine mammals or birds.

Given the density of devices in each lease area and the number and mean size of vessels particularly in RM1, the risk of collision with vessels should also be emphasized by lowering vessels' presence in the area or at least during the reproduction periods of local mammals or birds.

The Electrical sub-systems technology group receives the lowest absolute values for both positive and negative scores. The short length of cables and the absence of a collection point ensure a low score for the footprint and collision risk. Buried cables in RM3 further decrease these scores down to 0. In this configuration, there is no surface for benthic invertebrates to colonize and the reserve effect would be null.

This global positive score for RM3 is highly correlated to the fishery restriction that induces a reserve effect score of up to 40 (Table VI). In RM3, a fishing limitation for trawler gear has been assumed due to the anchor lines which extend over an area of 2.8 km².

Safety restrictions around devices and cables in RM1 already create a small reserve effect. Both device designs allow for overall limited colonization by benthic organisms that could be improved by favoring an orientation of devices facing into the current and a grainy texture of surface components. The scour protection can also be considered to increase the reef effect.

LIFE CYCLE ASSESSMENT

Fig. 5 shows the respective CO_2 emissions and embodied energy for each phase of the life cycle of the two RMs.

GWP (excluding recycling benefits from treatment phase) is respectively 22.94 and 200.59 gCO_2/kWh for RM1 and RM3 with the most significant stage being the production of materials which accounts for 59.8% and 74% of CO_2 production respectively in RM1 and RM3. Marine operations during maintenance, which represents the longest phase of the life cycle, also produce a significant amount of CO_2, i.e. 7.39 in RM1 and 47.32 gCO_2/kWh in RM3. Recycling offers a significant credit of 16% for RM1 and 23% for RM3, lowering the GWP to 19.3 and to 154.13 gCO_2/kWh.

The total energy consumed is 0.27 and 2.18 MJ/kWh with a similar proportion represented by the production phase for each of the RMs. With a mean annual energy production of 31.15 GWh and 6.99 GWh, it would take 6 months for the RM1 farm and 43 months for RM3 to produce as much energy as was consumed for its own development. The RM3 carbon footprint score is 10 times higher than that of RM1. Indeed, RM3's mean annual energy production is far lower than that of RM1, respectively 7.99 and 32.15 GWh, which greatly influences the gap between both designs. In addition, RM3 devices are 3 times heavier than those of RM1, which requires much more steel. Also the quantity of electrical cables greatly influences the results in the production phase with the amount of copper, polyethylene and polypropylene being almost 20 times higher in RM3 than RM1 (Appendix D). Despite a lower number of vessels planned during the maintenance phase for RM3, a greater amount of fuel was expected to be consumed by the LMO module in DTO+.

Results of carbon emissions for the two projects can be compared to other energy generating technologies (Fig.6). Tacoma's farm has a carbon footprint comparable to those of other renewable technologies and is far lower than that of fossil fuel generation. RM1's GWP falls between that of terrestrial wind farms (10 gCO_2/kWh) and Photovoltaics (30 gCO_2/kWh) [69], its EPP is even lower than that of wind turbines [70]. RM3 carbon emissions are far higher than other renewable energy sources and slightly higher than nuclear or geothermal technologies [69], [71]. An EPP of 43

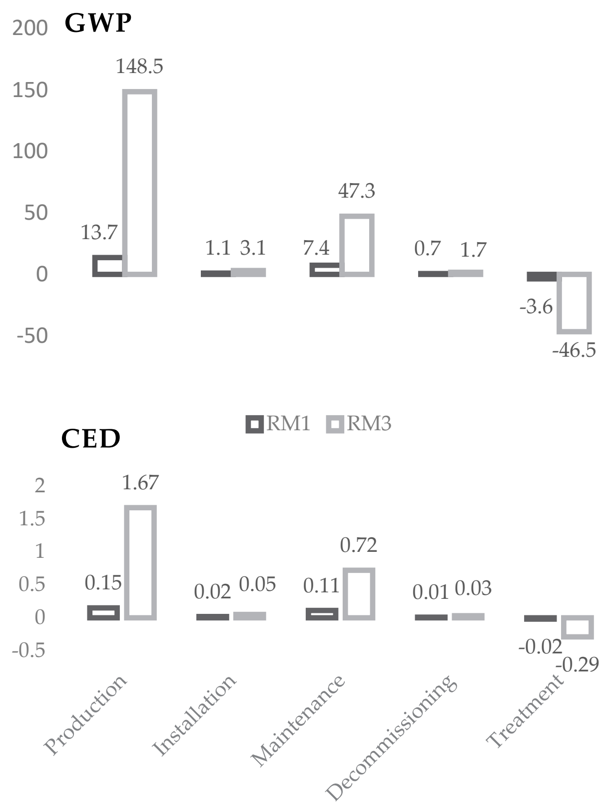


Fig. 5. Global Warming Potential (GWP, gCO_2/kWh) and Cumulative Energy Demand (CED, MJ/kWh) for each phase of the life cycle of Reference Model 1 and 3.

months is also similar to the 42 months measured for ocean thermal energy conversion [72].

IV. Discussion

The EA module aims at assessing ocean energy projects in terms of environmental impacts at local and global scales. To carry out this integrative assessment, the module retrieves information on a project's location, design of the devices, implementation of the electrical sub-systems and the marine operations plan from the several design tools included in DTO+ (Fig. 1, Appendix D). The user is also asked for required and optional complementary inputs to complete or refine the information. The ability of the tool to provide relevant information at local and global scales in order to minimize environmental impacts was investigated for the two reference models.

The Endangered Species feature focuses on potential impacts at local level and was able to identify several Mammals, Aves, Reptilia and Chondrichthyes potentially present in the two areas and for which surveys and mitigation measures were provided to better apprehend the main risks associated with the farms. The IUCN Red List database extant maps were used to evaluate EA's capability to detect the presence of endangered species relevant to the studied sites [41]. In both areas, two of the species identified by the IUCN database extant maps were not identified by the module, i.e. the Tope shark (*Galeorhinus galeus*) and the Hawksbill turtle (*Eretmochelys imbricata*). These two species were not included in the EA module database because they are not listed in more than two international or European conventions. Nevertheless, their wide distribution range and "critically endangered" status could justify their addition to EA's database in future development. On the other hand, the EA module retrieved five additional species for RM1 that were not identified by the IUCN database extant maps, i.e. the Great White shark (*Carcharodon carcharias*), the North Atlantic right whale (*Eubalaena glacialis*), the harbor porpoise (*Phocoena phocoena*), the Bottlenose dolphin (*Tursiops truncatus*) and the loggerhead turtle (*Caretta caretta*) and again three more in RM3, i.e. the sei whale (*Balaenoptera borealis*), the sperm whale (*Physeter microcephalus*) and the blue whale (*Balaenoptera musculus*). The Great White shark is identified at both the Tacoma and Eureka sites. While the IUCN does not provide distribution information for this species, the coast of California has been widely documented as a hot spot [73] and three known aggregation sites were studied along the central coast leading to the identification of 419 Great White sharks in the area between 2011 and 2018 [74]. In the case of RM3, the probability of presence is far lower than in RM1 as the presence of this large shark in Puget Sound would be a rather exceptional event. The maps used in the module represent the degree of habitat suitability, meaning that in Puget Sound, the habitat suitability for *Carcharodon carcharias* would be 30%. In order to apply the precautionary principle, the module gives recommendations even for species with a low probability of presence, and it is up to the user to evaluate the relevance of applying recommendations in these cases.

Several marine mammals are identified for the two areas. The Humboldt site faces onto the open ocean and the California coast is a migration path for many marine species [75], [76]. The probability of presence is far higher than for Tacoma but large mammals are also commonly sighted in the sound, e.g. Harbor porpoise, Grey whale, Humpback whale, Minke whale and Orca [77]–[79].

The ability of the module to extract relevant information for each location is thus considered as satisfactory in the sense that it is able to advise about mitigation measures for all classes identified in the two locations. However, some

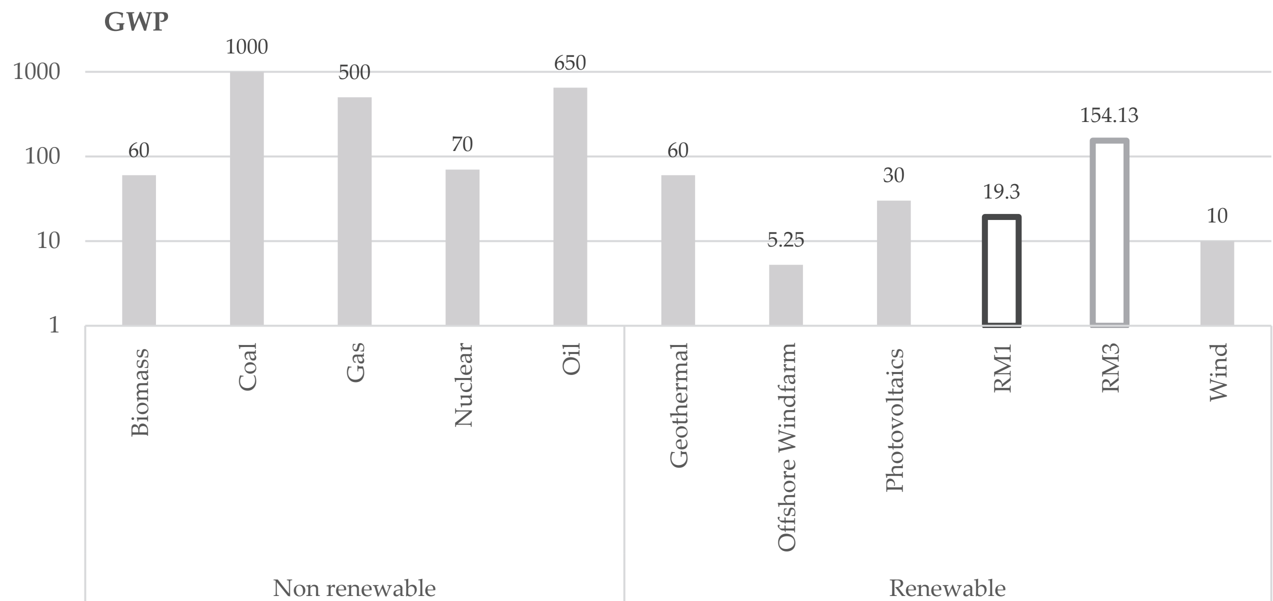


Fig. 6. Global Warming Potential (GWP, gCO_2/kWh) of non-renewable energies: Biomass, Coal, Gas, Nuclear, Oil [49]; renewable energies: Geothermal, Offshore windfarm, Photovoltaics, Onshore windfarm [49], [51] and the reference models 1 and 3.

classes should be completed in future versions of the EA module. For instance, the Actinopterygii class contains only three species in EA, i.e. Atlantic blue tuna (*Thynnus thunnus),* the European eel (*Anguilla anguilla*), and the sturgeon (*Acipenser sturio*) (Appendix B). In semi closed areas such as Tacoma, it could be interesting to consider more catadromous or anadromous species (such as Salmonidae) that are commonly found in sounds or sea loch entrances which are considered as interesting areas for MRE development. Even though the current EA module is not able to retrieve all endangered species potentially present in a location, the possibility for the user to specify the presence of additional local endangered species and the ability of the module to provide recommendations at the taxonomic class level allow the establishment of mitigation measures that will benefit a large variety of species.

To complete the assessment at a local level, the Environmental Impact Assessment feature allows an overview of the pressures that the different design choices could have on local receptors. The 13 pressures considered in the EA module are in line with the state of the science report about the environmental effects of marine renewable energy development around the world [45]. In complexity 2, seven potential pressures are assessed and the tool evaluates which of them should be considered as a priority to optimize the design of the MRE project in terms of environmental impacts. Among these functions, three evaluate potential "positive" impacts of the implementation of wave energy converter or tidal energy converter farms (Appendix E). Originally highlighted by offshore windfarms, the reef effect corresponds to the introduction of a hard substrate into the marine environment where it will be colonized by marine organisms [80]. This effect is of interest as it increases the available habitat area and attracts marine life in search of food, hence providing prey for large predators or species that are of potential interest from a heritage or commercial perspective (e.g. large crustaceans) [81]. Even if both reference models obtain similar scores for the reef effect, RM3 receives a better score regarding the reserve effect which enhances the positive effect on fish stock. Indeed, the closure of the MRE array zone to other human anthropogenic activities for security reasons would be greater with mooring lines. In addition to the concentration of prey, this configuration of floating devices in RM3 offers a resting place for birds that are attracted by this structure in the open sea [82]. Although RM3 is given the highest "positive" scores, it also induces noticeable potential negative impacts. With a resource reduction of over 10%, Energy modification (Appendix E) was identified as the main impact to consider for RM3 as it could affect the resuspension and accumulation of sediment, and thus have a direct impact on benthic habitats [83], [84]. Major wave converters can also reduce wave action and height by the physical presence of the structures in the sea [85]. Another main potential impact for RM3 and RM1 is the collision risk (Appendix E). Despite the uncertainty and gaps in knowledge about collisions, the risk of encountering and colliding with tidal and wave turbines continues to receive particular attention in relation to marine mammals, fish species and endangered seabirds in authorization processes. Indeed, the device design, the organization of devices in an array as well as the location itself are important factors with regards to collisions. Marine megafauna may be affected by MRE devices in terms of entanglements with anchor lines or electrical components, which can induce injuries and/or mortality [86]. As the collision risk is also related to the type and size of species [87]–[89], the tool considers species sensitivity in order to refine the risk estimation. The collision risk with vessels is also considered as the density in a small area may increase encounters with marine megafauna [87]. The presence of vessels may also enhance underwater noise that may exceed animals' adaptive capacity and result in physical injuries [90]. Considering this potential modification of noise (Appendix E), and to account for other changes in environmental parameters like temperature, turbidity, chemical pollution or even modification of electromagnetic fields, six additional functions are available at complexity level 3 which imply knowledge and measurements on site before and after implementation of the farm (Appendix E).

In general, the tool succeeds in highlighting the main areas of impact that the developer should focus on if they wish to optimize the design. Some ways of improving the functions have already been identified and are part of developments under study. For example, the function evaluating the collision risk is currently based on a physical approach which estimates the number of intersections, between a large number of parallel lines aligned with the mean current axis [38]. This approach is most probably very conservative and the risk estimated potentially greater than reality due to the fact that biological information is not considered (e.g. avoidance rate of animals, their behavior etc.). In the updated version of EA, the feasibility of including Collision Risk Models should be considered in order to integrate, in the collision risk assessment, the species' particular behavior and avoidance rate [91].

At a global scale, the EA module is able to estimate the carbon footprint of ocean energy projects. The feature carries out an LCA and retrieves three widely used mid-point indicators in MRE's LCA, i.e. Global Warming Potential (GWP), Cumulative Energy Demand (CED) and Energy Payback Period (EPP). Considering the different information provided by the different modules of DTO+, the feature was able to carry out a complete LCA for each references model. The results for RM1 are consistent with other renewable energy GWPs. Overall, RM1's carbon emission estimations are in line with the emissions of other tidal technologies [14], [69], [92]. More precisely, the RM1 design is inspired by the SeaGen turbine and the results

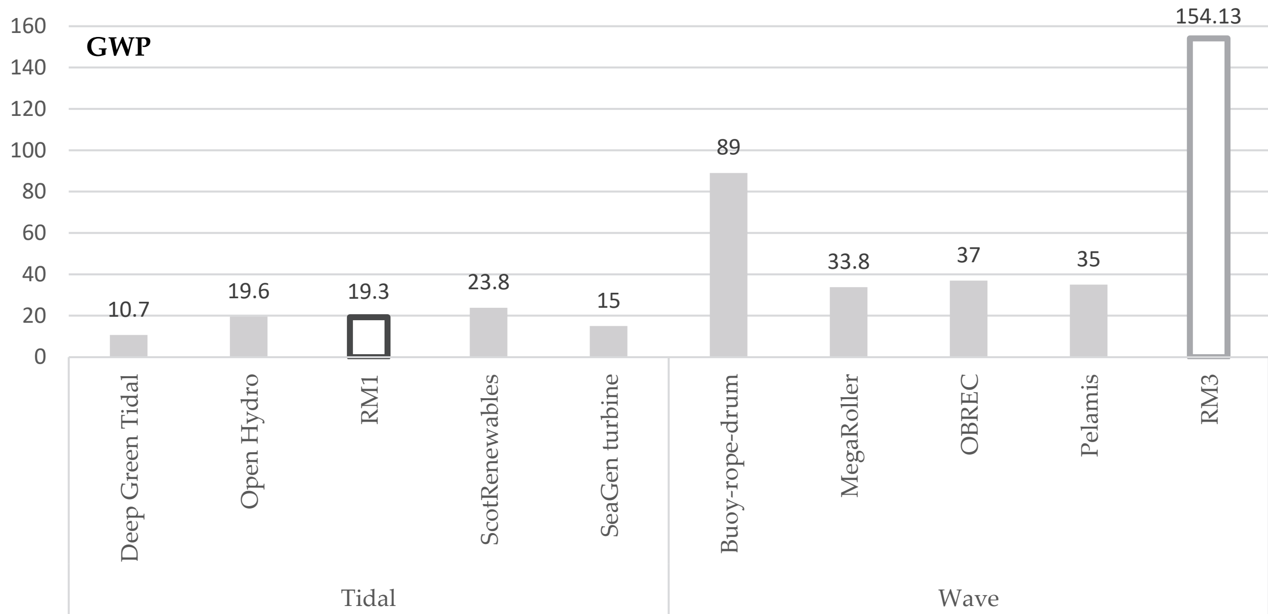


Fig. 7. Global Warming Potential (GWP, gCO_2/kWh) of tidal energy converters: RM1, Deep Green Tidal, Open Hydro, ScotRenewables, SeaGen [97], [74], [19] and wave energy converters: RM3, Buoy-rope-drum, MegaRoller, OBREC, Pelamis [23], [98]-[100].

are very close to those of the SeaGen's LCA itself [14](Fig. 7). The results for RM3 are considerably higher than other wave energy convertors' carbon emissions [18], [93]–[95] (Fig. 7). The main reason that the overall carbon footprint results are far higher for RM3 is the comparably low production of annual energy estimated by the Energy Delivery module, 32.15 GWh for RM1 and 7.99 GWH for RM3. Moreover, two aspects of the design of the farm add to this difference. First, the total length of cables needed for the whole RM3 farm is far greater than for RM1 which induces a notable increase in quantity for the different materials (Appendix D). Secondly, the greater quantity of fuel consumed by vessels during the maintenance phase amplifies this trend. Nevertheless, there could be several sources in the construction of the life cycle assessment that can lead to uncertainties. At this stage of DTO+ development, the transportation between the construction site and the assembly site is not considered in the LCA due to a lack of data. Also, not all DTO+ modules are able to detail all materials constituting a component and thus a small amount of certain materials may be overlooked even though they could participate significantly in carbon emissions. To overcome this aspect, the user has the possibility to add details for materials to refine the analysis. The EA module can handle a finite list of materials which could nevertheless be extended in future developments. Overall, if the user considers that it is necessary to refine a parameter calculated by the other modules, they have the possibility to make the modifications accordingly.

The EA module achieved an assessment of the potential environmental impact of a fixed tidal energy converter array (RM1) and a floating wave energy converter array (RM3) at two different scales. At the local scale, the EA module detected the potential presence of endangered species in both areas of RM1 and RM3 and produced an Environmental Impact Assessment score that is similar for both areas. However, at the global scale, the EA module detected a significant difference between RM1 and RM3, with the latter registering a GWP ten times higher than RM1, with an energy production for RM3 that is four times lower than RM1 for the same number of devices. These case studies are a good example of the information the EA module can provide to the user in terms of environmental impact when comparing different MRE development options. In our case, it was a comparison of tidal vs wave systems. However, this application would also be relevant for comparing, for the same system, different configuration options. The EA tool thus provides supplementary information to the user, in addition to information on the LCOE and on the reliability of the designed systems which is also produced by the DTO+ suite of tools. This offers the user additional leverage in his choice to be made to strike a balance between the productivity of the system designed and its environmental impact, ensuring a sustainable development of these renewable energies.

To our knowledge, no open source tools allow such a complete assessment of the environmental impacts of ocean energy with the complementary features developed at local and global scales. The carbon footprint of the technology as well as the level of environmental impact can thus be evaluated and optimized. The recommendations provided then allow the developer to obtain an indicative list of environmental monitoring to implement as well as recommendations on impact reduction. To integrate a social dimension, a fourth feature is under development regarding the social acceptability of MRE projects. This feature aims to highlight the opportunities created by MRE projects, such as job creation, that developers could take into account in the construction of their project and design choices.

V. CONCLUSION

Included in the integrative suite of design and assessment tools DTOceanPlus, the EA module is able to provide an overview of the environmental impacts of ocean energy projects. The complementary features developed in the module allow users to assess impacts at different levels. At local scale, it succeeded in identifying oceanic species potentially present in both Reference Model areas and providing advice on mitigation measures to limit the potential risks. It also helped to highlight the priority areas for technical improvements in the ocean energy design concept in order to reduce their environmental impacts. At global scale, the contribution to global warming was well evaluated and could support technology innovation processes in the objective of reducing greenhouse gas emissions.

The added value of the EA module lies in the fact that it is connected to other ocean energy design tools in order to evaluate the environmental impacts of the design choices at the earliest stage in ocean energy concept creation. Linked to other tools in an integrated mode, this interconnection offers the ability to design every component for each technology group. Within this framework, the main module gives the opportunity to create several sub-studies for a single project in order to compare the different effects of design choices on the overall environmental impacts and thus evaluate the different possibilities to optimize design.

APPENDIX

APPENDIX A
AVAILABILITY OF THE ENVIRONMENTAL ASSESSMENT TOOL'S FEATURES AT THE THREE COMPLEXITY LEVELS

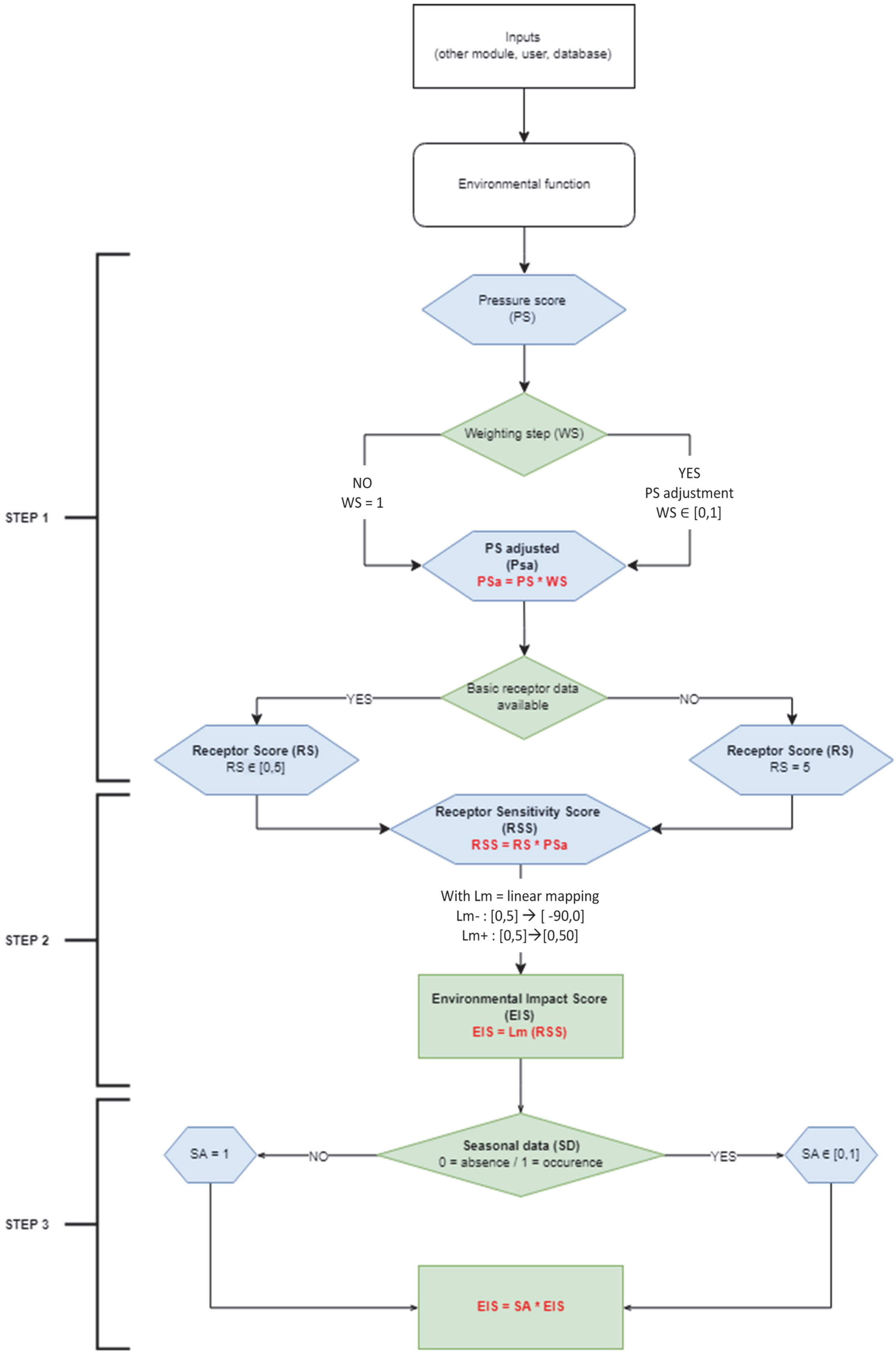
Features	Indicators	Complexity level		
		Early	Mid	Late
Endangered species	Probability of presence	√	√	√
Environmental impact assessment	Footprint		√	√
	Collision risk		√	√
	Energy modification		√	√
	Reef effect		√	√
	Reserve effect		√	√
	Resting place		√	√
	Chemical pollution			√
	Turbidity			√
	Temperature modification			√
	Electromagnetic field			√
	Underwater noise			√
Carbon footprint	Global Warming Potential		√	√
	Cumulative Energy Demand		√	√
	Energy Payback Period		√	√
Social acceptance	Number of jobs		√	√
	Cost of consenting		√	√

APPENDIX B

IUCN STATUS AND EUROPEAN/INTERNATIONAL CONVENTION PRESENCE OF THE 26 ENDANGERED SPECIES INCLUDED IN THE DTOCEANPLUS DATABASE

Class	Latin name	Common name	IUCN status (years)	Berne	Bonn	Habitats Directive	Birds Directive	Ospar	Helcom	Barcelona	Washington
Mammalia	Balaenoptera borealis	Sei whale	EN (2018)	√	√	√	-	-	-	√	√
	Balaenoptera musculus	Blue whale	EN (2018)	√	√	√	-	√	-	-	√
	Balaenoptera physalus	Fin whale	VU (2018)	√	√	√	-	-	-	√	√
	Eubalaena glacialis	NA right whale	EN (2017)	√	√	√	-	√	-	√	√
	Phocoena phocoena	Harbor porpoise	LC (2008)	√	√	√	-	√	√	√	√
	Physeter macrocephalus	Sperm whale	VU (2006)	√	√	√	-	-	-	√	√
	Monachus monachus	Mediterranean Monk seal	EN (2015)	√	√	√	-	-	-	√	√
Actinopterygii	Acipenser sturio	Sturgeon	CR (2009)	√	√	√	-	√	-	√	√
	Anguilla anguilla	European Eel	CR (2008)	-	-	-	-	√	√	√	-
	Thunnus thynnus	Atlantic blue tuna	EN (2011)	-	-	-	-	√	-	√	-
Chondrichthyes	Carcharodon carcharias	Great white shark	VU (2005)	√	√	-	-	√	-	√	-
	Lamna nasus	Porbeagle	VU (2006)	√	-	-	-	√	√	√	-
	Cetorhinus maximus	Basking Shark	VU (2005)	√	-	-	-	√	-	√	√
	Dipturus batis	Common skate	CR (2006)	-	-	-	-	√	√	-	-
	Rostroraja alba	White skate	EN (2006)	-	-	-	-	√	-	-	-
	Squatina squatina	Angelshark	CR (2017)	√	-	-	-	√	-	√	-
Aves	Branta ruficollis	Red breasted goose	VU (2016)	√	√	√	√	-	-	-	√
	Polysticta stelleri	Steller's eider	VU (2018)	√	√	√	√	√	√	-	-
	Numenius tenuirostris	Slender-billed Curlew	CR (2018)	√	√	√	√	-	-	√	√
	Puffinus mauretanicus	Balearic Shearwater	CR (2018)	√	-	√	√	√	-	-	-
	Puffinus yelkouan	Yelkouan Shearwater	VU (2018)	√	-	√	√	-	-	√	-
Reptilia	Eretmochelys imbricata	Hawksbill turtle	CR (2008)	√	√	√	-	-	-	√	√
	Lepidochelys kempii	Kemp's ridley turtle	CR (2019)	√	√	√	-	-	-	√	√
	Dermochelys coriacea	Leatherback turtle	VU (2013)	√	√	√	-	√	-	√	√
	Caretta caretta	Loggerhead turtle	VU (2015)	√	√	√	-	√	-	√	√
	Chelonia mydas	Green sea turtle	EN (2004)	√	√	√	-	-	-	-	√

APPENDIX C
THREE-STEP SCORING ALGORITHM USED FOR EACH ENVIRONMENTAL PRESSURE IN THE ENVIRONMENTAL IMPACT ASSESSMENT FEATURE



APPENDIX D

LIST OF INPUTS OF THE ENVIRONMENTAL ASSESSMENT TOOL FOR REFERENCE MODELS 1 AND 3. INPUTS ARE PROVIDED BY THE OTHER MODULES OF DTOCEANPLUS (SITE CHARACTERIZATION (SC), MACHINE CHARACTERIZATION (MC), ENERGY CAPTURE (EC), ENERGY DELIVERY (ED), STATION KEEPING (SK), LOGISTICS AND MARINE OPERATIONS (LMO)) OR BY THE USER.

	Parameter Name	Unit	Provided by	RM1 values	RM3 values
Farm information	x-coordinates of the farm	Decimal degrees	SC	47.28	40.81
	y-coordinates of the farm	Decimal degrees	SC	-122.55	-124,21
	Project lifetime	Years	SC	20	20
	Zone type	-	User	Sound	Open water
	Water depth	m	SC	50	70
	Current direction	°	SC	214	16.04
	Total surface area	m²	SC	14510290	4320000
	Sediment type	-	SC	Dense sand	Sand and clay
	Fisheries	-	User	No restriction	Trawler prohibition
Protected species	Class	-	User	Aves	Aves
	Name	-	User	Brachyramphus marmoratus	Synthliboramphus hypoleucus
Receptors		-	User	Soft substrate habitat	Soft substrate habitat
		-	User	Medium diving birds	Medium diving birds
Device information	x-coordinates of devices	UTM	EC	[5234315.1, 234381.6, 5234448.1, 5234514.6, 5234581.1, 5234647.6, 5234918.3, 5234851.8, 5234785.3, 5234718.8]	[393359.9, 93429.8, 393499.5, 394597.5, 393908.9, 393978.8, 393290.2, 392741.2, 394048.5, 93839.2]
	y-coordinates of devices	UTM	EC	[533811.7, 533705.8, 533599.9, 533494.1, 533388.3, 533282.4, 533599.7, 533705.5, 533811.4, 533917.2]	[4523067.0, 4522366.5, 4521665.9, 4524174.7, 4524321.4, 4523620.9, 4523767.6, 4522513.2, 4522920.3, 4525021.9]
	Machine type	-	MC	TEC	WEC
	Dimensions				
	Height	m	MC	30	42
	Width	m	MC	3.5	6
	Length	m	MC	26	6
	Wet area	m²	MC	255*	1102
	Dry area	m²	MC	0	565
	Floating	-	MC	False	True
	Number of devices	-	EC	10	10
	Resource reduction	%	EC	0.013	0.1
	Materials				
	Unalloyed steel	kg	MC	450052,4	1605310
	Low alloyed steel	kg	MC	13162.0	
	Copper	kg	MC	21937.0	
	Fiberglass	kg	MC	30711.8	
	Cast iron	kg	MC	160140.0	
	Epoxy resin	kg	MC	10968.5	
	Materials to recycle				
	Unalloyed steel	kg	MC	450052,4	1605310
	Low alloyed steel	kg	MC	13162.0	
	Copper	kg	MC	21937.0	
	Fiberglass	kg	MC	30711.8	
	Cast iron	kg	MC	160140.0	
	Epoxy resin	kg	MC	10968.5	
Foundation	Materials				

	Unalloyed steel	kg	SK	1497953.2	96076.7
	Materials to recycle				
	Unalloyed steel	kg	User	1497953.2	96076.7
	Footprint	m²	SK	96.21	
	Submerged surface	m²	SK	3298.67	
Electrical information	Energy produced	kWh	ED	32149088.42	7996494.04
	Surface area of electrical parts	m²	ED	1711.63	0.0
	Footprint	m²	ED	1973.76	5822.72
	Total length of cable	m	ED	1711.63	
	x-coordinates of collection points	UTM	ED	/	/
	y-coordinates of collection points	UTM	ED	/	/
	Collection point dimensions			/	/
	Height	m	ED	/	/
	Width	m	ED	/	/
	Length	m	ED	/	/
	Wet area	m²	ED	/	/
	Dry area	m²	ED	/	/
	Substation	-	ED	False	False
	Burial	-	ED	True	True
	Fishery Restriction Surface area around cables	m²	User	0.0	0.0
	Materials				
	Low alloyed steel	kg	ED	12285.95	78765,83
	Copper	kg	ED	3601.44	61202,73
	Polyethylene	kg	ED	3465.42	13823,23
	Polypropylene	kg	ED	2494.65	13385,01
	Materials to recycle		ED		
	Low alloyed steel	kg	User	0	0
	Copper	kg	User	0	0
	Polyethylene	kg	User	0	0
	Polypropylene	kg	User	0	0
Logistics information	Installation				
	Number of vessels	-	LMO	5	4
	Mean size of vessels	m	LMO	86.5	62,4
	Number of passengers	-	LMO	159.0	44
	Fuel consumption	kg	LMO	182649.6	124809.05
	Exploitation				
	Number of vessels	-	LMO	46	15
	Mean size of vessels	m	LMO	73.7	57
	Number of passengers	-	LMO	2197	612
	Fuel consumption	kg	LMO	1191623.825	1929985.85
	Decommissioning				
	Number of vessels	-	LMO	3	3
	Mean size of vessels	m	LMO	52.8	54,5
	Number of passengers	-	LMO	159.0	44
	Fuel consumption	kg	LMO	110 911.13	70338.2375

APPENDIX E
DETAILED EXPLANATION OF THE ENVIRONMENTAL IMPACT ASSESSMENT'S 13 FUNCTIONS: BACKGROUND AND APPLICATION

Interactions between stressors and receptors (i.e. MRE systems and the marine environment) are developed here. Stressors are those parts of an MRE system that may cause harm or stress to a marine animal, a habitat, oceanographic processes, or ecosystem process [45]. These stressors include the moving blades on turbines, mooring lines, anchors or foundations, power export cables, and the emissions that can result from any of these parts. The receptors include the marine animals living in and traversing the vicinity of an MRE development; the habitats in which the devices are deployed; and oceanographic processes, such as the natural movement of waters, wave heights or sediment transport [45]. It is the intersection of stressors and receptors that defines the interactions that are described in this section (Fig.1 below). The functions included in the EA module are a representation of the interaction between stressors and receptors.

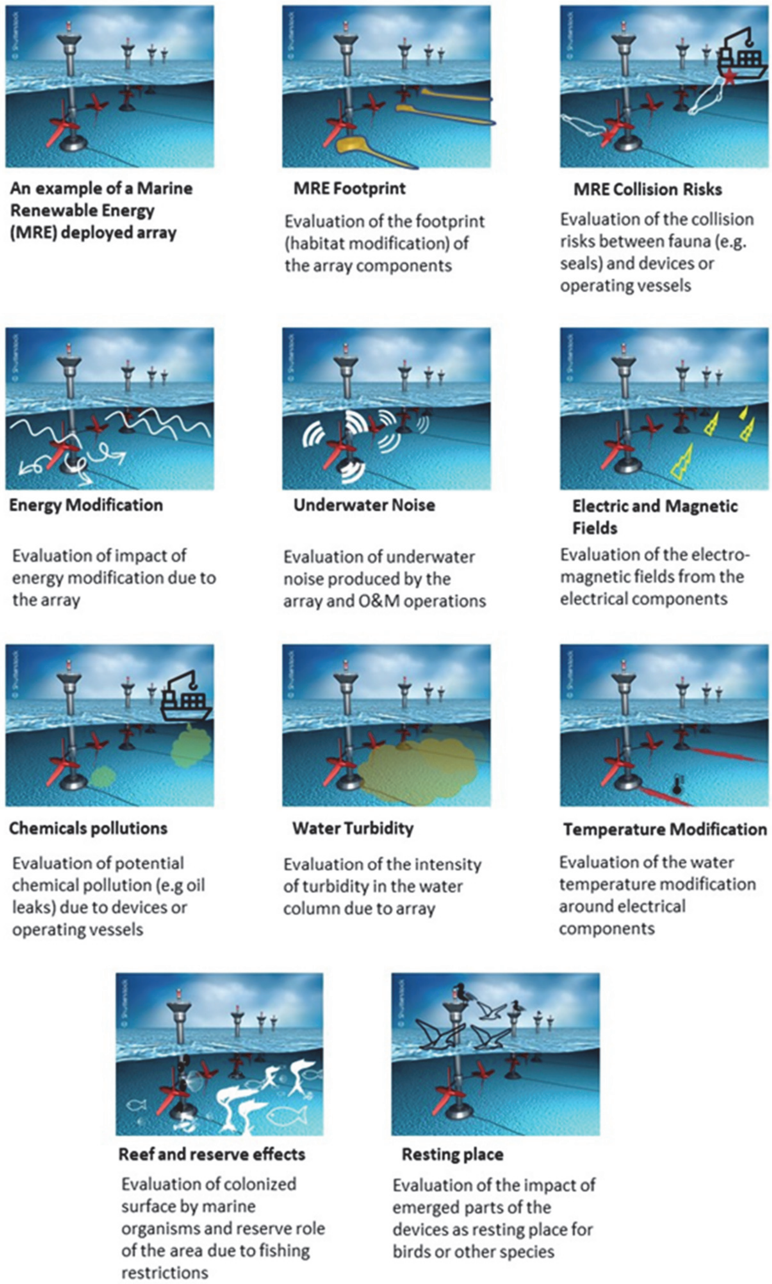


Figure 8. The potential stressors or modifications generated by marine renewable energy (wave or tidal array) deployment.

4) MRE seabed Footprint

Background – The Footprint of an MRE is mainly related to its foundation, the dragging of the moorings lines and the cable route. The environmental impact of the foundations is directly related to the area of seabed contact under the footprint of the foundation structure. Most of the data and reviews come from the offshore wind sector [96]–[98]. These reviews show that the seabed can be directly affected by the nature of the foundations as well as their placement that ultimately modify the local hydrodynamics and therefore the sediment transport. The main direct biological effect of foundations and moorings on the seabed is habitat removal affecting infauna (organisms living within the sediment) for mobile sediment (usually sands), epifauna (organisms attached to coarse sediments and rock) for coarser sediments like gravels, pebbles and cobbles. The recovery time after alteration may vary from months to years. Hill et al. estimated that biotopes can recover within a period ranging from 6 to 24 months for high energy environments with medium fine sediment [99]. Biotopes associated with coarser sediment are expected to recover over longer times ranging from 8 to more than 15 years [97]. Dernie et al. also studied recovery rates of benthic communities following physical disturbance [100]. These authors showed that clean sand communities had the most rapid recovery rate following disturbance, whereas communities from muddy sand habitats had the slowest physical and biological recovery rates. Depending on the selected methods, cable burial operations can locally cause severe damage to habitats but which is relatively limited to a few meters either side of the cable. Overall, impacts remain limited in time, usually the duration of burial operations. The most affected parts are benthic habitats and less mobile species [64], [101]. As such, the knowledge of habitats in the vicinity of cable routes is determinant to evaluate the impact of the burial operation. Footprint impacts can also occur during the installation phase (logistics). During logistic operations, footprint issues can then be generated either by vessels' anchorages, subsea cable installation/removal or preparation for foundations. The level of seabed disturbance depends on the nature of the sediments as well as the nature of the operations [102].

Function and application – In the EA module, the footprint function aims at evaluating the pressure on the seabed occupied by electrical components, moorings and/or foundations, and by equipment and anchors of vessels on benthic species (living on the hard and soft substrate) and some other species such as fishes classified in the ecosystem group (hard and soft substrates). The function applied is the ratio of the total area surface area occupied or disturbed by the array, cables or operating vessels to the total lease surface area of the array. An increase in the function score means an increase in pressure. To qualify footprint scores and calibrations, an empirical approach has been carried out. This approach is based on 5 ratio ranges of footprint areas vs. lease area. Details of the footprint function equation, weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

5) MRE Collision Risks

Background - The collision risk of marine species (receptors) with MRE systems comprise collisions (1) with the devices installed (either fixed or floating devices), (2) with the moorings and foundations of the devices, (3) with the electrical components, especially for floating devices and (4) with the vessels operating on site during logistics and marine operations. Receptor species can be impacted by marine renewable devices through the direct effect of collision. Studies conducted on offshore renewable energy devices show that the risk of collision is likely to be species- and site-specific. For marine birds, different factors will influence the risk of collision for birds such as their flight behavior, their avoidance capacity, the proximity of the MRE devices to birds' migratory corridors and feeding areas, the weather conditions and structure lighting [87]. The collision risk is also related to species-specific parameters including the depth attained in the water column, swimming speed, diurnal rhythm of foraging etc. [87]–[89]. As for birds, marine megafauna (e.g. marine mammals, fish species or turtles) may be affected by MRE devices. Overall the risk of collision is a function of species, body size, swimming behavior and skills, the capacity to detect devices as well as the device type (e.g. [49], [101], [103], [104]). The device design, the organization of devices in an array as well as the location of the array itself are also important factors with regards to collisions. Marine megafauna may be affected by MRE devices in terms of entanglements with anchor lines or electrical components, which can induce injuries and/or mortality [86]. The risk of collision and entanglement depends on the species. Large whales appear to be more vulnerable than smaller species due to their size and bulk [49], [101]. The collision risk for birds and marine megafauna is also increased with the presence of operating vessels on site. Although not very well documented, ships strikes are a known cause of mortality for both whales and dolphins worldwide and strikes are far from infrequent as the majority go unnoticed [87]. The main drivers identified to influence the number and severity of ship strikes are the vessel types, as most fatal casualties are due to large vessels (more than 80 m long), underwater noise as high levels of ambient noise can result in difficulties in detecting approaching vessels, weather conditions and time of navigation that can directly affect the ability of the crew to detect or avoid marine mammals, species-specific behavior during specific feeding, predation or resting times.

Function and application – The Collision Risk in EA is the product of the probability of collision weighted by the ratio between device height and depth. The function estimates the number of intersections, between a large number of parallel lines aligned with the mean current axis. The probability of collision will be the ratio of the number of lines with at least one intersection to the total number of lines. Details of the Collision Risks equations, weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

6) Energy Modification

Background –Tidal and wave marine energy converter devices operate by using the kinetic energy provided by currents and waves, respectively. This energy is often harnessed using a turbine unit that will extract energy from the surrounding environment possibly resulting (at least for tidal energy converters) in changes in the water column velocity structure [105]. The flow upstream of a device will be decelerated, and a turbulent wake with a reduction of velocity will appear downstream of the device [85]. An acceleration of flow around the device will also usually result. These modifications will directly affect the resuspension, and accumulation of sediment. Overall, the water flow remains a major process in the repartition of species in the water column and any changes can have an effect on marine ecosystems [83]. As tidal stream arrays are expected to modify natural water flows, they can affect benthic habitats and substrates, sediment composition and wave structure during both installation and operation phases of multiple turbines [84]. The level of energy reduction can have a direct impact on benthic habitats. These benthic habitats are essential, because some benthic species stabilize the normal sedimentary process. If these natural skills are altered, there may be major long-term consequences on the sedimentary process in the area [83]. Wave converters can also reduce wave action and wave height by the physical presence of the structures in the sea [85]. However, the impact on perturbations of the water flow and their consequences on sedimentary processes are expected to be much less significant than for tidal energy converters.

Function and application – The energy modification is induced by the extraction of energy by the devices. Incoming and outgoing energy from arrays is used to calculate the percentage of energy extracted by the arrays. The energy reduction is then estimated and the Energy Modification function in EA produces a percentage of the resource reduction. If the energy reduction is less than 10%, the pressure score is low. If the energy reduction scores higher than 30%, the pressure score is at its maximum. Details of the Energy Modification weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

7) Underwater Noise

Background – The underwater noise related to MRE deployment can be due to (1) devices installed (either fixed or floating devices), (2) mooring and foundations of the devices, (3) electrical components, especially for floating devices and (4) vessels operating on site during logistics and marine operations. Underwater noise is device-specific and also directly related to the number of devices. Each device has a range of associated noise spectra and their source can be multiple, e.g. noise generated by turbulence and vortex shedding, noise from moorings or rotating machinery [106]. When anthropogenic sounds are excessive in level, frequency or even duration, they might exceed the mammal's adaptive capacity and cause physical injuries with permanent threshold shifts or loss of hearing sensitivity [90]. As with mammals, fish are characterized by a wide range of hearing structures, resulting in different capacities and sensitivities to noise. Fishes that receive high intensity sound pressures may be negatively impacted to some degree, whereas those at distances of 100 to 1000 meters may exhibit behavior responses [107]. The quantification of underwater noise due to moorings and foundations after being installed is mostly restricted to the sounds of mooring lines chafing on the seabed [106]. During the operational phase of the project some noise could be produced by the electrical components. This could be cable vibration for example [108]. These noises are probably weaker than those emitted during the installation phase but their production will last throughout the exploitation phase.

Function and application - This function evaluates the impact of underwater noise produced by the vessels and equipment during the installation phase, by the devices during the operational phase, by the underwater electrical substation and by the mooring lines on the seabed. This function is a user input (i.e. the user needs to specify the acoustic level before/after array installation). Details of the Underwater Noise weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

8) Electric and Magnetic Fields

Background - Electromagnetic fields are generated by current flow passing through operating power cables of the MRE array. The high voltages that generate a significant electromagnetic field in a cable can affect marine life. This was demonstrated on fish, sharks and marine mammals which are able to use the earth's magnetic field to navigate [109]. In particular, elasmobranchs (sharks, rays) have specific electro-receptors that enable them to detect and locate very small sources of electromagnetic fields, which makes them very sensitive to them [107], [109]. Although ecological impacts associated with submarine power cables can be considered weak or moderate, many uncertainties remain, particularly concerning electromagnetic effects [63].

Function and application – This function evaluates the electromagnetic field modification induced by the electrical components. This function is a user input (i.e. the user needs to specify the electromagnetic field before/after array installation). Details of the Electromagnetic Field weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

9) Chemical pollution

Background - The chemical pollution related to marine renewable development is linked to increased vessel traffic during the main 3 phases of the project (installation, operation/maintenance, and decommissioning) through potential fuel or oil leakages/spills and burial operations. Oil pollution in coastal ecosystems is a well-known and growing global problem [110].

Associated harmful effects include organism death, stress for benthic communities [111] and major disturbance to the food chain [112]. Polmear et al. have also shown evidence of toxicity of lubricants on phytoplanktonic communities [111]. The devices themselves can also contribute to chemical pollution during unexpected damage causing hydraulic fuel leaks or during maintenance operations through the release of anti-fouling agents. Anti-fouling paints use a wide range of chemicals which have very different physico-chemical properties and therefore differing environmental impacts, behavior and effects. Copper has been used as an anti-foulant for centuries. Biocides have also been widely used over a number of decades, for example Irgarol 1051 and diuron. Organic biocides appear to be particularly toxic for phytoplankton species compared to other aquatic animals. For instance, Irgarol 1051 appears to be especially toxic to the freshwater diatom *Navicula pelliculosa* and the macrophytes *Chara vulgaris* [113]. There are also new or candidate biocides such as triphenylborane pyridine, Econea, capsaicin and medetomidine for which there is very little information in the public domain. Marine organisms can directly accumulate antifouling contaminants and transfer contaminants to higher trophic levels. If the uptake of the contaminants exceeds the organism's ability for excretion and detoxification, this can reduce normal metabolic functioning [114], [115]. Overall, issues related to water quality may also generate temporary displacement from surrounding areas and affect mammals via their influence on prey or habitat [116]. However, tidal and wave devices will be located in energetic environments and impacts linked to water quality generated by point source pollution will probably be most largely attenuated due to the high dispersive capacity of the area [101].

Function and application – This function is a user input (i.e. the user needs to specify whether a pollution risk is possible, for example due to the use of a toxic antifouling agent). The scoring system follows the three-step process described in the main paper. Details of the Chemical Pollution weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

10) Water Turbidity

Background – The MRE development can modify the turbidity of ecosystems, especially during construction phases, while some activities involve interaction with the sediment. Thus, the concentration of re-Suspended Particulate Matter (SPM) can substantially increase locally. During operational phases, higher concentrations of SPM exceeding the natural variability can occur when tidal currents exceed a certain velocity [117] due to the interaction of the current with devices. The main environmental impact generated by turbid waters is light adsorption, which may limit primary production. Indeed, light attenuation by suspended sediments confines the photic zone to a small fraction of the water column, such that light limitation is a major control on phytoplankton production and turnover rate [118]. Turbid waters can also affect benthos animals like filter-feeders and have an impact on the development and growth of different species. An SPM concentration increase can cause a decrease in respiration (due to clogging of filtration mechanisms), a behavioral alteration of species and a risk for eggs and larvae [48]. Such impacts are identified in high turbidity due to dredging activity. In contrast, the impact of an increase in turbidity on other species like marine mammals or birds is poorly known. Marine mammals often reside in turbid waters, so significant impacts from turbidity are improbable [48]. However, high turbidity may affect the ability to hunt, and the visual resolution power of diving-birds [48], [119]. Finally, turbid waters can generate high sedimentation rates (often locally) in areas where hydrodynamic conditions are more favorable, thus changing the sediment structure and the associated benthic communities. In general, regularly disturbed habitats characterized by fine sands and fast-growing opportunistic species are less affected, and recover quicker, than stable habitats monopolized by coarse gravels and slow-growing sessile flora and fauna [120]. In addition to changing the community structure, sediment deposition can smother or bury marine organisms associated with the seabed. Non-mobile organisms and organisms at early life stages that are unable to move are most at risk [48].

Function and application – This function evaluates the intensity of the modification of turbidity due to (1) the installation phase in the area, (2) the installation of the electrical components and (3) turbidity modification intensity in the water column due to the array and the installed devices. This function is a user input (i.e. the user needs to specify the turbidity levels before/after array installation). Details of the Water Turbidity weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

11) Temperature modification

Background – Electrical cables produce heat when electrical current flow through them. The temperature can reach around 90°C within cables [121]. These high temperatures can produce thermal radiation during the operation of electrical components and therefore can potentially affect marine life. According to [64], heat dissipation is greater for alternating current than direct current (at equal transmission rates). For unburied cables, the heat produced at the cable's surface is directly dissipated by the water capacity. However, in the case of buried cables, the temperature at the cable surface usually stays higher with less heat dissipation due to the surrounding sediment. When the temperature reaches 90°C within cables, the temperature at the cable edges is about 65°C [122]. This represents potential environmental impacts for species that are directly in contact with the cable or close to the cable. Species likely to be more affected by overheating cables are benthic species as they can be located within the vicinity of electrical components and are usually less mobile than pelagic species. Most of these organisms live at the sediment-water interface and up to 35 cm below this interface [46], [63], [122].

Function and application – This function is a user input (i.e. the user needs to specify the water temperature before/after electrical cable installation). The scoring system follows the three-step process described in the main paper. Details of the Temperature Modification weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

12) Reef Effect

Background –MRE deployment underwater (either fixed or floating) can provide new hard substrates for colonization by marine organisms, thus playing the role of artificial reefs. As such they can generate new or enhance existing habitats with an increased heterogeneity in the area which is important for species diversity. This "reef" effect was initially highlighted on the structure base of offshore wind turbines [80]. These artificial reefs may create a refuge for some species, which find favorable habitats between the artificial structures. Certain protective structures for laid cables can accommodate for instance benthic species that are of potential interest from a heritage or commercial perspective (e.g. large crustaceans) [81]. Recent investigations at the tidal site of Paimpol-Bréhat (France) showed that concrete mattresses could be used as a new habitat by crustaceans [123].

Function and application – This function evaluates the intensity of the reef effect due to the colonized surface of the underwater devices, moorings and foundations and electrical components. The function reflects the ratio of the sum of immersed surface areas of turbines and their moorings and foundations divided by the total lease surface area of the array. Details of the Reef Effect weighting coefficients and Receptor Sensitivity analysis that are applied are detailed in [38].

13) Reserve Effect

Background – The reserve effect is related to the closure of the MRE array zone to other human activities for safety reasons (e.g. fishing, extraction of aggregates, boating, scuba diving, etc.) [101]. A total restriction on fishing creates a marine protected area (MPA) that will have positive impacts on biodiversity conservation and the protection of juveniles and reproductive adults [64]. These effects have already been observed in offshore windfarms [124]. Inger et al. highlight the fact that MPAs, where all fisheries and other forms of extraction are excluded, can be used as a fisheries management, conservation and ecological restoration tool [82]. As well as protecting and enhancing fish stocks, the implementation of such MPAs will also enrich benthic biota, by lifting the pressure from bottom towed fishing gear [125], which has chronic effects on seabed communities and is likely to affect ecosystem functioning [120].

Function and application – The function applied is the ratio of the surface of the protected area to the total lease surface area of the array. An increase in the function score means an increase in the reserve area. A ratio of one means that the whole lease area is closed to other human activities (particularly fishing). Details of the Reserve Effect function are detailed in [38].

14) Resting Place

Background – Emerged MRE structures can be used as resting platforms mainly for birds and pinnipeds depending on their accessibility. This positive impact is of course only considered during the operation phase of the project. In the open sea where resting places could be rare, these structures will create new habitats for species. Species such as gulls, terns and cormorants show no avoidance response to emerged MRE structures and may instead be attracted to theses installations through prey aggregation and their use as resting/foraging platforms [82].

Function and application – This function evaluates the impact of emerged parts of devices and electrical components as a resting place for pinnipeds (marine mammals) and birds. The function applied is the ratio of the surface area of the emerged structures of the MRE devices and electrical components to the total lease surface area of the array. An increase in the function score means an increase in the resting places available. Details of the Resting Place function are detailed in [38].

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