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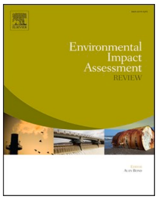

Environmental impact assessment framework for offshore wind energy developments based on the marine Good Environmental Status

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ABSTRACT

The expected increase in the offshore wind farm (OWF) developments to meet global decarbonisation targets is raising concerns in the scientific community about the ecological health of the marine environment. The present contribution has conducted an extensive literature review on the environmental effects and changes that the OWF can pose on the Good Environmental Status (GES) described by the European Marine Strategy Framework Directive (2008/56/EC). Consequently, an environmental impact assessment (EIA) checklist has been developed to encompass the construction, operative, and decommissioning phases of the OWF and aimed at enabling the evaluation of whether the OWF developments are conducted compatibly with the maintenance of the GES of the marine environment or not. We have then applied to our case study the developed EIA-GES checklist through a multi-criteria analysis, to evaluate and map the potential level of impact expected from the OWF developments over ca. 45.613,5 Km^2 of a marine area off an Atlantic archipelago. Particularly, biogeographic aspects, oceanographic conditions, and OWF location sites will ultimately determine the overall impact of the OWF development. In our study area, results suggest that the OWF developments would have a minor or null impact on the GES for ca. 78% of the marine waters assessed. Besides, we have discussed our EIA-GES checklist applicability to decide on appropriate possible impact mitigation measures, following a case-by-case approach and identifying key ecological information that could be collected by the OWF developers during the EIA study. These surveys can support environmental authorities by providing with more insights to assess the GES status while identifying information gaps and areas to improve monitoring and data gathering for the GES maintenance. Finally, we discussed performing EIAs based on the historical datasets, and recommend reinforcement of the time series of data with updated surveys within and around OWF sites to confirm the marine environment's state.

1. Introduction

It is expected that the marine environment will play a key role in the forthcoming energy transition towards clean renewable sources, especially through offshore wind energy (OWE). This sector is expected to grow significantly in the coming years, being enhanced by European and global agreements, e.g., the United Nations (Akbari et al., 2020; UN, 1992; UN, 2016). Besides, Europe relies mainly on OWE to become climate neutral by 2050 (EC, 2021), as part of its new approach to a sustainable blue economy and aims to increase the installed capacity five-fold by 2030 and to 30-fold by 2050 (EU, 2020a).

The development of OWE is not only challenging from the perspective of the ongoing European Marine Spatial Planning (MSP) processes (Abramic et al., 2021; Quero García et al., 2021; Pınarbaşı et al., 2019; Spijkerboer et al., 2020), but it is also not entirely clear what impacts the construction, operation, and decommissioning of Offshore Wind Farms (OWF) and their related infrastructure might have on the marine ecosystems and their functioning (Papathanasopoulou et al., 2015; Raoux et al., 2017; Lindeboom et al., 2011). Often perceived as environmentally benign, 'green' renewable energy technologies (including OWE)

Abbreviations: BACI, Before-After-Control-Impact; EIA, Environmental Impact Assessments; EUNIS, European Nature Information System; EC, European Commission; EEC, European Economic Community; EMODnet, European Monitoring Observation and Data Framework; EU, European Union; GES, Good Environmental Status; MSFD, Marine Strategy Framework Directive 2008/56/EC; NIS, Non-Indigenous Species; OWE, Offshore Wind Energy; OWF, Offshore Wind Farms; PLASMAR, Planning Progress on Sustainable Marine Areas in the Macaronesia; QD, Quality Descriptors.

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have ecological costs that are often overlooked (Uihlein and Magagna, 2016; Wright et al., 2020). Thus, the increasing development of large-scale projects raises environmental concerns about their cumulative effect, along with other anthropogenic maritime activities (Gill, 2005; Inger et al., 2009; Masden et al., 2010a; Garel et al., 2014; Pelc and Fujita, 2002; Shields et al., 2011).

In this sense, OWE projects need to comply with the EU Environmental Impact Assessment (EIA) Directive (the initial version 85/337/EEC and its amendments), which is the most widely used EIA tool in Europe (Josimović et al., 2021). This regulation aims to establish the minimum requirements to be considered in an EIA, while guiding the process of arbitration between the projects' promoters and the administrations to ensure the common interest of society, by preserving biodiversity and fighting climate change (Salvador et al., 2018). However, the Directive is vague regarding the environmental aspects that EIA “shall identify, describe and assess in an appropriate manner” (i.e., “land, soil, water, air and climate” and to a lesser extent “biodiversity”, as it refers to species and habitats protected under Directives 92/43/EEC and 2009/147/EC). Thus, when applied in practice, there is a risk of overlooking relevant environmental components in EIAs. Despite the latter, the European Directive 2008/56/EC establishes a framework to achieve and maintain Good Environmental Status (GES) in the marine environment. Both Directives require the collection and analysis of environmental data to enable competent authorities to make informed decisions (Greaves et al., 2016). Thus, in the present study, we aim to explore the applicability of the GES framework included in the Marine Strategy Framework Directive (2008/56/EC) to guide EIA processes vis-a-vis Offshore Wind Farm (OWF) developments, which should be conducted in compatibility with the maintenance of a healthy marine environment.

We expect our results to add to the progressive comprehension of the consequences of the introduction of OWF facilities in the sea and the possible threats and trade-offs with the marine environment that can occur during the construction, operative, and decommissioning phases. To achieve this, the main constraints to OWF development have been translated into our research questions as follows:

a. Which components of the marine environment should be considered within the EIA?
b. What are the main pressures and impacts that OWE facilities may exert on the marine environment and, how can we avoid them, if possible?
c. What type of data needs to be collected to assess the pressures and related impacts?

The geographical settings of the Canary Islands, a Spanish marine region in the North-eastern Atlantic Ocean with high potential for marine renewables (Abramic et al., 2021), have been used as a case study to test the overall developed framework.

2. Material and methods

2.1. Creating an ‘EIA-GES checklist’ for offshore wind farms

First, we conducted an extensive literature review of the offshore wind industry experiences of the past two decades in European waters, mainly in the North Sea and the Baltic Sea. We focused on the environmental impacts and practical mitigation solutions. All the gathered information was organized according to the GES framework of the European Marine Strategy Directive (2008/56/EC) to understand what exactly needs to be assessed in EIA processes to ensure environmental suitability. Thus, this study followed the definition of the Good Environmental Status (GES) of the European marine waters comprising 39 criteria described in the European Commission Decision 2017/848/EU. These criteria are classified into 11 qualitative descriptors (QD): (1QD) biodiversity components, (2QD) non-indigenous species, (3QD) commercially exploited species, (4QD) marine food webs, (5QD) human-induced eutrophication, (6QD) sea-floor integrity, (7QD) alterations of hydrographical conditions, (8QD) pollution by contaminants, (9QD) contaminants in species of human consumption, (10QD) marine litter, and (11QD) introduction of energy and underwater noise.

We have used this detailed framework to develop an EIA-GES checklist to comprehensively systematize the information derived from the literature review on the impacts associated with the construction, operational, and decommission phases of OWF facilities, the possible mitigation measures, and the spatial data and survey methods that could guide EIA studies fowling the GES framework. The EIA-GES checklist has been developed within the PLASMAR (MAC/1.1a/030) and PLASMAR+ (MAC2/1.1a/347) projects, as part of the multi-component methodological zoning approach developed and applied for a Maritime Spatial Planning process (Abramic et al., 2021; Abramic et al., 2018).

2.2. Applying the EIA-GES checklist to the Canary Islands

The marine waters around the Canary Islands, which have a high potential for exploiting OWE (Fig. 1), were considered a practical case study to apply and test the developed EIA-GES checklist. The Canary Islands, under the influence of the Trade Winds and upwelled waters off the Northwest coast of Africa (Violette, 1974), comprise seven major islands (and several islets) of volcanic origin and narrow shelves reaching high depths (2000–4000 m) close to the coast (Anguita and Hernán, 2000). Both prevalent winds (the Trade Winds) and currents (the Canary Current) have a predominant component from the north to the northeast and the south to the southwest, respectively (Anguita and Hernán, 2000; MAPAMA, 2012a; MAPAMA, 2012b; Palomo et al., 1997).

Performing a whole regional EIA in the Canary Islands for OWE is beyond the scope of the present study. Instead, we have tested a GES suitability analysis in application to an EIA based on the existing data on the marine environment for the study area. Spatial data regarding the qualitative descriptors (QD) of the Marine Strategies were collected from previous studies undertaken in the PLASMAR project (2017–2020; MAC/1.1a/030) (Abramic et al., 2021), the Spanish Spatial Data Infrastructure (IDEE), and the ecological Ecopath with Ecosim (EwE) models analyzing the food webs and main commercially exploited species of the Canary Islands (Couce-Montero et al., 2015; Couce Montero et al., 2021).

We have cumulatively mapped OWF impacts based on the gathered datasets related to the GES in the study area (i.e., GES spatial features–descriptions and download links provided in the supplementary information Table 1) and the EIA-GES checklist developed through the literature review. For estimating the impact level and calculating the resulting score by adding the 21 GES datasets with spatial features, we have used a decision support system (DSS), INDIMAR (freely accessible at http://www.geoportal.ulpgc.es/indimar/). This DSS has been specifically developed for sectoral zoning for marine spatial planning (MSP) purposes and has already been tested and optimized for OWF in the study area (Abramic et al., 2021).

In the present study, INDIMAR outputs are maps ranking from −5 to +5 according to either negative or positive OWF cumulatively impact level for each cell (ca. 300 × 300 m of resolution) of a grid up to 30 km offshore from the coastline of the Canary Islands. The level of impact was calculated by summing up the different GES spatial features weighted according to their expected impact in the EIA-GES checklist as:

$$R = \sum pW_i{}^{*}CV_i$$

where pW is an i GES spatial feature weight, and CV is the i GES spatial feature impact contribution (i.e., positive, neutral, or, negative). A special circumstance of CV has been the exclusion (i.e., total irreversible impact) of protected habitats in the study area, e.g. seagrass and maerl

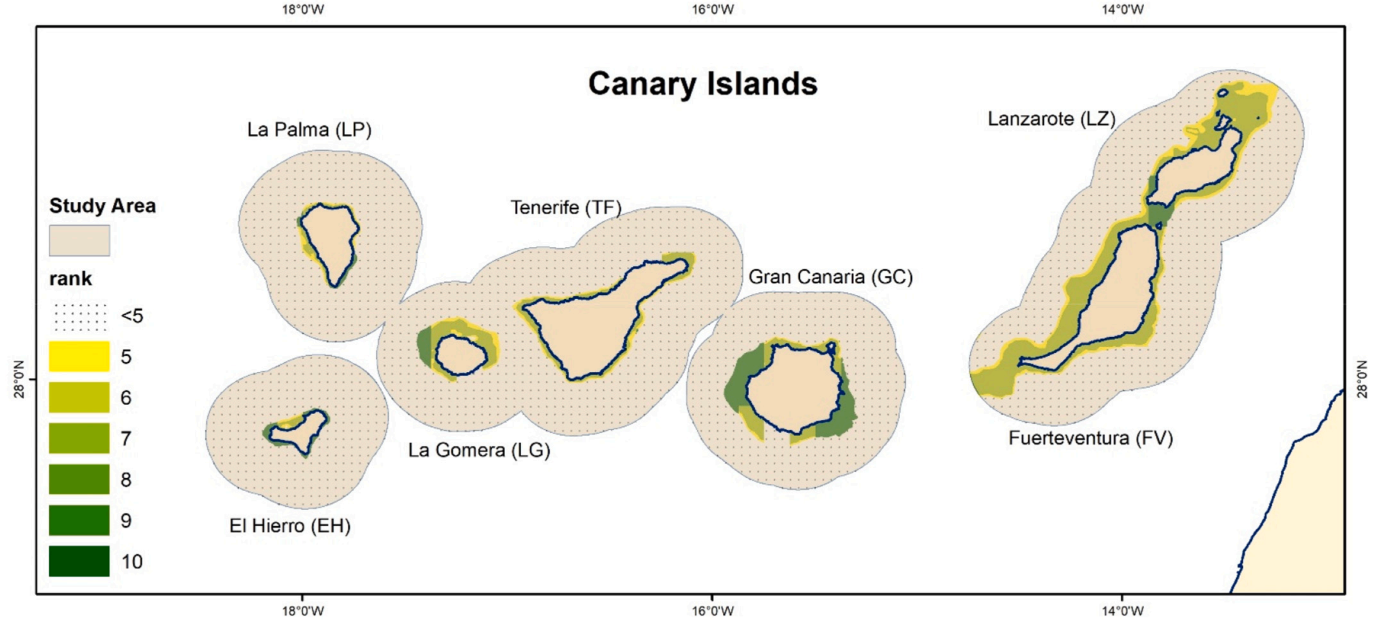

Fig. 1. OWE potential of the Canary Islands based on the Wind speed (based on the Marine Copernicus products) and sea depth (beyond 300 m was considered as restrictive). A ranking from 0 to 10 indicates the locations more suitable for OWE development projects considering wind speed and depth. Locations ranking <5 (i.e., unsuitable locations) have been obscured to facilitate the map's interpretation. Suitability analyses delivered by Decision Support System INDIMAR (Abramic et al., 2021).

beds. Each GES spatial feature's contribution was derived from the EIA-GES checklist. To assess which GES qualitative descriptors and their defining GES spatial features could be more impacted by OWF in the study area, we used the analytical hierarchy process (AHP) (Goepel, 2014; Saaty, 1990). Through this multi-criteria decision analysis, we developed three pairwise matrices, one for the qualitative descriptors (i.e., the criteria in the AHP: see supplementary information Table 2) and two for the GES spatial features (i.e., the sub-criteria in the AHP": see supplementary information Table 3). To apply AHP, comparison matrices for the GES spatial features were created only for QD comprised of three or more datasets (i.e., QD 1 and QD 3). A consistency ratio (CR) equal to or <0.10 was considered acceptable to support the pairwise comparisons (Saaty, 2001). Final weights (pW_i) introduced in INDIMAR, were thus obtained by multiplying the resulting AHP's criteria and sub-criteria impact scores.

3. Results

3.1. Building the EIA-GES checklist for OWF

We have synthesized the literature review to build the EIA-GES checklist (Table 1). Thus, the following sections (Sections 3.1.1–3.1.8) list the main impacts identified during the construction, operational, and decommissioning phases of OWF as well as the mitigation measures and spatial data needed to meet monitoring and assessment requirements.

3.1.1. Biodiversity (QD1) and food webs (QD4)

We do not have a clear picture of the marine biodiversity that might be impacted by the OWE sector (Langhamer et al., 2018). However, following the GES structure, we have defined biodiversity as the quality and occurrence of benthic and pelagic habitats and the distribution and abundance of marine species. Thus, in this section, the descriptors linked to the relevant ecosystem components have been considered, viz., species groups of birds, mammals, reptiles, fish and cephalopods (QD1), pelagic habitats (QD1), benthic habitats (QD1 and QD6) and ecosystems, including food webs (QD4).

3.1.1.1. Marine species. The analysed studies suggest that various species of birds and marine animals may be particularly vulnerable to environmental pressure related to the OWF. The type and degree of impact are dependent on a range of factors, such as the location and type of OWF and the species present in that area. Evidence to date indicates that appropriately sited and well-designed OWFs (i.e., located away from areas of importance for wildlife), are generally not a threat to biodiversity (Bailey et al., 2014).

Wind farms, especially large establishments with tens of wind turbines, may force birds, mammals, and sea turtles to change direction, both during migrations and more locally during regular foraging activities. This barrier effect interfering with the distribution range and pattern of birds (Drewitt and Langston, 2006; Dierschke et al., 2016; Masden et al., 2010b; Masden et al., 2015; Peschko et al., 2020) has been particularly explored. On the one hand, such disturbances can lead to displacement and exclusion, and thus, loss of habitat use. On the other, marine species can be attracted to the OWF area due to the reef effect (Drewitt and Langston, 2006; Raoux et al., 2018).

Besides, OWF may increase the mortality of seabirds through collisions with turbines. The collision risk will vary for each particular species depending widely on the number of birds in the flocks and their flight behaviour, as well as the design factors of the wind farm (WF) itself, such as the use of lighting (Dierschke et al., 2016). Among the seabird species that show higher mortality risk by collision are those that generally fly at the height of the turbine blades – between 35 and 125 m (Johnston et al., 2014). A proper location of OWF based on the study of the species present in the project area can avoid most impacts. It is recommended to avoid important areas for breeding and foraging activities and areas with high densities of wintering or migratory species (Dierschke et al., 2016). The same study proposes the development of OWF far from the key areas for conservation while placing the groups of turbines avoiding alignment perpendicular to the main bird flight pathways, provision of corridors between clusters of turbines, and increase in the visibility of rotor blades.

As mentioned, when WF were located away from the generally used flying/migration areas, collision studies of terrestrial wind turbines have recorded relatively low levels of bird mortality (Erickson et al., 2001).

Table 1
Summary of the derived impacts from OWF installation, their associated mitigation measures, and the spatial data and surveys methods that could guide EIA studies following GES framework.

GES quality descriptor	Potential environmental issues and related phase	Impact mitigation measures	Spatial data requirements and survey recommendations
QD1: Biodiversity – Seabirds	Seabird mortality through collisions with turbines, barrier effect, and disturbances during migration and foraging behaviour – operational phase.	Locating OWE facilities away from important sea bird habitats and foraging/migration flight paths. Turbines may be placed to avoid perpendicular alignment to the birds' main flight pathways, be grouped to provide aerial corridors between clusters, and proper lighting systems to increase the visibility of rotor blades.	Seabirds' distribution data and migration patterns. In situ surveys and species distribution modelling.
QD1: Biodiversity – Marine mammals	Disturbances during migration and foraging behaviour. Especially relevant for marine mammals. Displacement, exclusion, and loss of habitat use – construction and decommissioning phases.	Proper location planning of OWF away from conflicting areas with sensitive species and habitat types. Avoiding high densities of wintering or migratory species, foraging or breeding areas, and special areas for conservation.	Marine mammals and aggregation of other pelagic species distribution data. In situ surveys and distribution modelling.
QD1: Biodiversity – Pelagic Habitats and species	Disturbances during migration and foraging behaviour.	Further research needed.	Pelagic species distribution, biogeographic and oceanographic features.
QD1: Biodiversity – Pelagic Habitats and species	Disturbances of behaviour, i.e., pelagic species presented the highest abundance within the OWE facilities – operational phase, as turbines act as fish aggregating devices. During the construction phase, displacement, exclusion, and loss of habitat use of pelagic species could be expected.	Further research needed.	Pelagic species distribution, and biogeographic and oceanographic features.
QD1: Biodiversity – Benthic Habitats	Reef effect – benthic habitat gains or decreases in biodiversity. Turbine submerged constructions are colonized by marine species, resulting in an additional source of food for higher trophic levels – Construction, operational, and decommissioning phases.	Avoiding the sensitive benthic habitats areas (e.g., listed in the Habitat Directive 92/43/EEC) for the development of the OWE	Benthic habitats maps obtained by surveys and modelling. Survey on habitat distribution prior to OWE construction and during the operative phase.
QD2: Non-indigenous Species	OWE structures can provide new corridors to NIS and increase their distributional range – Operational and decommissioning phases	Linking spatial data with biophysical modelling, predicting species introductions and their impacts, and analysis of vectors of introduction.	Capacity building and staff training to differentiate between local and potential NIS species. Development of an early warning monitoring system with a GIS tracking system.
QD3: Quality Descriptor 3 – Commercial Fish	Fisheries stocks can be significantly impacted if fisheries are allowed in the OWE areas – Operational and decommissioning phases.	Design management responses to restrict fisheries during defined periods and/or restrict specific fishing gear and practices.	Empirical studies applied in situ surveys. Modelling with ECOpath & ECOsim.
QD4: Ecosystems, including food webs	Specific food web guild might be impacted, increasing species mortality, potential demographic and distributional range modifications, and effects on pelagic and benthic habitat – Operational and decommissioning phases.	Further research needed.	Empirical studies applying in situ surveys. Modelling with ECOpath & ECOsim.
QD5: Eutrophication	OWF may favour local anoxia, especially in waters already rich in nutrients and semi-enclosed water bodies, due to changes in the currents regime (mixing dilutions and current velocities) and accumulation of biomass (in particular, biofouling organisms such as blue mussels with high oxygen consumption rates. – Operational phase.	Adjusting site location to ensure enough renewal of the water bodies.	In situ surveys of parameters that indicate eutrophication threats: dissolved oxygen, biochemical and chemical oxygen demand, total nitrogen, total phosphorus, and chlorophyll *a*.
QD6: Seafloor integrity	Impacts on the physical, chemical, and biological features of the sea bottom, and permanent physical loss – construction, operational, and decommissioning phases.	Adequate selection of the seabed substrate (gravel, sand, mud) for OWE foundations. Floating OWF with innovative types of foundations and anchoring solutions might be used when appropriate. Analyse whether foundations after 20 years of use should be entirely or partially decommissioned or left as artificial reefs.	Survey of physical, chemical, and biological features of the seabed.
QD7: Hydrographical Conditions	OWF is shown to enhance the turbulent vertical mixing effect and increase turbidity. A 5% of wave height reduction was shown across three times the extension of the OWF on the lee side of the turbines – Construction, operational, and decommissioning phases.	Further research needed.	Experimental modelling on hydrographical feature modifications.
QD8: Concentrations of contaminants in the sea environment	An increase in oil spill risk resulting from vessel collisions with wind farms. The contaminants contained in the sediments might be remobilized and re-introduced into the water column – Construction, operational, and decommissioning phases.	Applying commonly required safety and security measures on vessels included in the construction and maintenance operations.	Contaminants survey in the water column, seabed, and filtering organisms that colonize the artificial structures.
QD9: Contaminants in fish and other seafood	Further research needed.	Further research needed.	Contaminants survey within the commercial species sampled in the OWF.
QD10: Marine litter	Source of marine litter – Decommissioning phase.		

(*continued on next page*)

Table 1 (*continued*)

GES quality descriptor	Potential environmental issues and related phase	Impact mitigation measures	Spatial data requirements and survey recommendations
QD11: Noise pollution and energy	Marine species behavioural local disturbances. Larval mortality of fish. Hearing impairment and communication disruption of marine mammals. Local effects in the prey detection ability of elasmobranchs and disturbances in migration patterns of the European eel – Construction, operational, and decommissioning phases.	Considering whether foundations should be decommissioned or left as artificial reefs. The usage of acoustic (bubble) curtains to attenuate noise from OWF construction and reduce temporary habitat loss. Adequate design and deployment of cables to avoid sensitive species.	Marine litter survey and assessment prior to constriction and decommissioning. Analyse distribution ranges of sensible marine species such as marine mammals. Monitor the noise levels in the area before and during the construction.

Thus, for OWE projects, mitigation measures comprise the proper location of the turbines, away from the species' key habitats. Moreover, mitigation measures can also involve design modifications to the size of blades, the height of turbines, and configuration of the WF and associated infrastructure during the construction phase, as well as the temporal stoppage of turbines during operation (Bailey et al., 2014).

3.1.1.2. Pelagic habitats. Only a few studies have analysed the effects of OWE facilities on the pelagic ecosystem, and even fewer have included field measurements (Floeter et al., 2017). The observations revealed that pelagic fish are the most abundant within 100 m around underwater construction sites (Janßen et al., 2015). Combined modelling and in situ observations have revealed effects on the water column stratification due to the vertical mixing, generating an upwelling effect that would increase nutrients and primary production in the superficial layers, affecting the density and distribution of zooplankton and fish (Floeter et al., 2017).

In situ measurements of salinity and turbidity, combined with remote sensing (Li et al., 2014; Vanhellemont and Ruddick, 2014) and modelling (Cazenave et al., 2016; Lass et al., 2008; Rennau et al., 2012) demonstrated that each turbine can generate an upwelling effect of up to 1 km. Increased primary production in this area seemed to enhance phytoplankton biomass, increase the trophic levels, and favoured the concentration of pelagic fish. The highest pelagic fish abundances were found close to the turbine foundations (Schröder et al., 2013; Krägefsky, 2014). Still, Floeter et al. (Floeter et al., 2017) warned that it is very difficult to separate anthropogenic impacts and natural variability in the areas where OWFs are installed.

3.1.1.3. Benthic habitats. The foundations of OWE facilities act as a new type of habitat, presenting higher biodiversity of benthic organisms, which may in turn increase the use of the area by pelagic species such as fish, marine mammals, and even some seabird species (Lindeboom et al., 2011). Turbine-submerged constructions can be colonized by several marine species, resulting in an additional source of food for higher trophic levels (Bergström et al., 2013). Generally known as the “reef effect”, expected habitat gain was considered one of the most important effects on the marine environment generated by the construction of OWF (Petersen and Malm, 2006; Langhamer, 2012; De Mesel et al., 2015). The reef effect commences with the colonization and aggregation of species close to the foundations, [e.g., (Maar et al., 2009; Wilhelmsson et al., 2006)], increasing the specie abundances closer to OWF foundations (Bergström et al., 2013; Maar et al., 2009; Wilhelmsson et al., 2006; Wilhelmsson and Malm, 2008; Reubens et al., 2013a; Reubens et al., 2011; Andersson and Öhman, 2010). For soft substrate habitats, we consider OWE facilities as having a positive impact due to the expected artificial reef effect (Petersen and Malm, 2006; Langhamer, 2012; De Mesel et al., 2015), while for hard ones, we envisage a significant negative impact, especially in the construction phase (Bailey et al., 2014; Kikuchi, 2010). Further, the type of benthic habitats listed in the Habitat Directive 92/43/EEC are considered sensitive and vulnerable (e.g., seagrass beds) and should be restricted for OWF constructions, to avoid habitat loss, degradation, and smothering of the local ecosystems with direct impact during the construction phase (EU, 2020b).

3.1.1.4. Ecosystems, including food webs. Impacts on the QD4 were reflected as pelagic and benthic habitat modifications, which can alter the species distribution both by repelling and reef effects (Raoux et al., 2017). Studies have shown that several ecosystem processes and properties were sensitive to changes generated by OWE installations (Burkhard et al., 2011) and thus alter food webs. OWF can also lead to impacts on specific food web guilds, resulting from mortality (Johnston et al., 2014; Erickson et al., 2001), potential demographic modifications or changes in the species distribution range (Drewitt and Langston, 2006; Dierschke et al., 2016; Masden et al., 2010b), and the effects on pelagic and benthic habitats (Floeter et al., 2017; Schröder et al., 2013; Krägefsky, 2014).

3.1.2. Non-indigenous species (QD2)

Habitats modified by wind turbine structures – similar to artificial reefs – can foster the introduction of Non-Indigenous Species (NIS) dispersed from both natural and anthropogenic sources (Sheehy and Vik, 2010; Bulleri and Airoldi, 2005; Glasby et al., 2007). The introduction of the new artificial hard substrate provided by OWF can be used by NIS as corridors to propagate and expand beyond their normal distribution range, connecting previously unconnected areas (Langhamer, 2012; De Mesel et al., 2015; Kerckhof et al., 2011).

3.1.3. Commercial fish species (QD3)

OWE may have both negative and positive impacts on fish and shellfish (Langhamer et al., 2018). Positively, OWF foundations may increase habitat complexity, enhancing certain fish species and communities (Bergström et al., 2013; Langhamer, 2012; Stenberg et al., 2015). They may be compatible with the creation of fishery exclusion zones or to limit the usage of harmful fishing gear such as trawling and gillnetting (Ashley et al., 2014). These lead to higher sizes and fish stocks of commercially exploited species (Lindeboom et al., 2011; Reubens et al., 2011; Degraer and Brabant, 2009), as well as overall fish species within the ecosystem (Lindeboom et al., 2011; Shields and Payne, 2014; Stenberg et al., 2011). Mavraki et al. (Mavraki et al., 2021) showed that OWFs are used as feeding grounds for a prolonged period by some benthopelagic and benthic species, suggesting that OWF could potentially increase the production of these types of fish species in the area.

Negatively, OWF foundations–fixed to the sea floor or floating–act as fish aggregating devices that concentrate fish species facilitating their capture (Wilhelmsson et al., 2006; Castro et al., 1999; Fayram and de Risi, 2007). Thus, in the absence of specific management responses, combining cumulatively OWF with fisheries can be expected to increase local mortality rates of fish populations (Reubens et al., 2013a; Polovina, 1989; Pickering and Whitmarsh, 1997; Grossman et al., 1997; Brickhill et al., 2005; Simon et al., 2011; Reubens et al., 2013b). Further, as stress due to noise and electromagnetic field emissions is believed to potentially have an impact on the growth, migration, survival, and/or reproductive capacity of commercially-exploited fish species. Further scientific evidence is needed to assess the magnitude of these cumulative

Table 2
EIA-GES checklist applied to the Canary Islands.

Good environmental status		AHP approach			Impact contribution
Qualitative descriptors (QD)	Spatial datasets/ features	QD weighting	Spatial feature weighting	Final weight	(+/−)
QD1: biodiversity		0.37			
	QD 1.1. Marine benthic habitats		0.18	6.54	(−/+)
	QD 1.2.1 Marine mammals (toothed whales)		0.07	2.70	(−)
	QD 1.2.2 Marine mammals (dolphins and ziphii)		0.07	2.70	(−)
	QD 1.2.3 Marine mammals (Nature 2000 sites)		0.11	4.23	(−)
	QD 1.3.1 Seabirds (modelled)		0.20	7.57	(−)
	QD 1.3.2 Seabirds (Nature 2000 sites)		0.29	10.82	(−)
	QD 1.4.1 Turtles (modelled)		0.03	1.05	(−)
	QD 1.4.2 Turtles (Nature 2000 sites)		0.04	1.45	(−)
QD2: Non-indigenous species (NIS)		0.06			
	QD 2.1. Entrance vectors of NIS		1.00	6.13	(−)
QD3: Commercial fish species		0.21			
	QD 3.1. Benthic sharks and rays		0.09	1.82	(−)
	QD 3.2. Coastal pelagic fish		0.39	8.26	(+)
	QD 3.3. Molluscs		0.05	0.98	(+)
	QD 3.4. Moray eels		0.09	1.82	(−)
	QD 3.5. Oceanic pelagic fish		0.39	8.26	(+)
QD4: marine food webs		0.17			
	QD 4.1. Benthic invertebrates		0.20	3.43	(+)
	QD 4.2. Seagrass/ seaweed		0.80	13.72	(−)
QD6: sea floor integrity		0.06			
	QD 6.1. Substrate types: rock, coarse, sand, mud, mixed, unknown.		1.00	6.13	(−)
QD7: hydrographical conditions changes		0.02			
	QD 7.1. Accumulated pressures affecting hydrographical conditions		1.00	2.24	(−)
QD10: Marine litter		0.02			
	QD 10.1. Terrestrial accumulated pressures leading to marine litter		0.50	1.12	(−)
	QD 10.2. Marine accumulated pressures leading to marine litter		0.50	1.12	(−)
QD11: Underwater noise		0.08			
	QD 11.1. Accumulated pressures that generate underwater noise		1.00	7.92	(−)
TOTAL		1.0	8.0	100.0	

AHP approach scores indicate the impact level considered during the pairwise of criteria (i.e., qualitative descriptors) and sub-criteria (i.e., GES spatial features). The impact contribution sign indicates whether the GES was considered within INDIMAR as being positive (+), negative (−), or both (+/−), depending on the spatial feature of the dataset, affected by OWF development.

impacts (Floeter et al., 2017; Kikuchi, 2010; Gill et al., 2012; Wahlberg and Westerberg, 2005).

3.1.4. *Eutrophication (QD5)*

The reviewed studies have shown that OWF foundation and structures generate a turbulent wake that contributes to a localized vertical mixing and induces nutrient concentration (Broström, 2008; Nerge and Lenhart, 2010; Ludewig, 2014). However, there is evidence for both an increase and decrease in the primary production due to micro upwelling/down-welling processes (Floeter et al., 2017; Cazenave et al., 2016; van der Molen et al., 2014). According to Janßen et al. (Janßen et al., 2015), the development of large OWF in areas already sensitive to eutrophication (i.e., with poor oxygen conditions and significant stratification of different salinity layers) can lead to anoxia, due to changes in the currents regime (mixing dilutions and current velocities) and accumulation of biomass (in particular, biofouling organisms such as blue mussels with high oxygen consumption rates). Local anoxia was reported by studies performed in the Baltic Sea, which showed that this increase in benthic biomass also led to higher rates of oxygen consumption through the respiration of the living biomass and especially the degradation of organic matter (Janßen et al., 2015). The risk of suffering eutrophication is particularly relevant in semi-enclosed water bodies.

3.1.5. *Seafloor integrity (QD6)*

The construction of OWF modifies the seafloor integrity in diverse ways, depending on the configuration, dimension, and design of the wind turbine fixation structures. Thus, the anchoring methods would determine the extent of the permanent physical loss of the seabed, but also the increase of habitat complexity that would affect communities positively (Bergström et al., 2013; Langhamer, 2012; Stenberg et al., 2015; van Hal et al., 2017).

During the construction phase, impacts from the foundations can be minimized by the adequate selection of the marine substrate (e.g., sand, gravel, mud, etc.). OWF constructed near-shore up to 20 m in depth have shown to enhance suspended sediments, interfering with the sedimentation rates and the longshore sediment transportation in shallow waters (Bailey et al., 2014; Vanhellemont and Ruddick, 2014; Bergström et al., 2014). Thus, the spatial extent of changes in the sedimentation rates needs to be considered, especially regarding geomorphological changes in soft substrates. Further, processes such as cutting, water jetting, and/or explosives can be used during the construction and decommissioning of the turbine's foundations (particularly for the monopile type), which will lead to wider and more significant impacts on the seabed (Topham and McMillan, 2017).

3.1.6. *Hydrographical conditions (QD7)*

Offshore platforms and marine renewable energy installations were identified as one of the main pressures changing the hydrographical conditions, though large data sets are required to observe and detect them. OWF has been shown to enhance the turbulent vertical mixing effect (Floeter et al., 2017; Cazenave et al., 2016; Carpenter et al., 2016) that can be exacerbated by biofouling organisms (Krägefsky, 2014; Baeye and Fettweis, 2015). Christensen et al. (Christensen et al., 2013) demonstrated through experimental modelling that, though dissipation of wave energy due to surface friction and vortex shedding by OWF structures is negligible, a reduction of around 5% of wave height was shown across three times the extension of the OWF, due to the wind speed reduction on the lee side of the turbines.

Changes in the hydrographical conditions can have significant and varied effects on marine ecosystems (Shields et al., 2011). Elevated turbidity may harm sensitive organisms such as juvenile fish (Partridge and Michael, 2010; Auld and Schubel, 1978; Lowe et al., 2015), though derivate impacts are considered low to moderate, as sandy seabed organisms are generally tolerant to turbidity (Bergström et al., 2014). Other potential effects that should be further researched include biomass production and growth of plankton and fish species and the modification of larval dispersion and habitat creation species.

3.1.7. Concentrations of contaminants in the environment (QD8), fish, and other seafood (QD9)

Although OWF structures are not per se considered sources of contaminants, during the construction phase, the contaminants contained in the remobilized sediments can be re-introduced in the water column (Zaborska et al., 2017). This impact is directly linked to the influence of riverine inputs and land sources, with higher influences in semi-enclosed marine areas such as the Baltic Sea. Additionally, during the construction phase and maintenance activities, an increase in oil spill risk resulting from the collision of vessels with wind farms was observed (Gee, 2010). However, this risk can be reduced by applying the commonly required safety and security measures.

Despite no technical reports or scientific publications having been found concerning OWF and contaminant concentrations in fish and seafood, it is recommended to determine baseline levels of contaminants in marine species for future studies near OWF.

3.1.8. Marine litter (QD10)

Marine litter is a global concern affecting all the oceans of the world. Every year, millions of tons of litter end up in the ocean worldwide, posing all environmental, economic, health, and aesthetic problems (GESAMP, 2015; Lusher et al., 2017). Regarding the life cycle of the OWF, only decommissioning processes have been identified as possible direct sources of marine litter, though it will depend on the type of foundation and whether appropriate preventive measures are taken (Topham and McMillan, 2017). Further, Wang et al. (Wang et al., 2018) showed that hydrodynamic changes due to OWF structures reduced microplastic abundance in the water and sediment in shallow sea areas (maximum 8 m in depth).

3.1.9. Introduction of underwater noise (QD11)

Impulsive noise from OWF will impact differently according to the life cycle phases: the short-term potential impact during pre-construction, the short-term intensive impact during both construction and decommissioning, and the long-term physiological and/or masking effects during operation (Kikuchi, 2010). Disturbances and displacement of species by OWF can be compared to that of harbours, which may include habituation of the species to these effects over time (Teilmann and Carstensen, 2012), though this will differ among species (Popper and Hastings, 2009). The pressure extent varied depending on the local conditions. Stronger impacts might be expected in pristine areas, compared to areas where ambient noise is already high (Scheidat et al., 2011). Cumulative effects should be also considered using the operative noise registries (Hooper et al., 2003; Slabbekoorn et al., 2010; Slabbekoorn, 2012; Slabbekoorn, 2016).

Construction often includes an array of activities, including profiling, shipping, pile-driving, trenching, and dredging (Nedwell et al., 2003; Nedwell and Howell, 2004; Bolle et al., 2016; Bolle et al., 2012). Noise and vibration from pile-driving and other works may affect species over large areas (van Hal et al., 2017; Thomsen et al., 2006; Embling et al., 2014; Dolman and Simmonds, 2010), displacing them or interfering with their normal behaviour (Erbe et al., 2016; Carroll et al., 2017; Williams et al., 2015). Extreme noise from OWF monopiles or jacket foundations pile-driving can cause significant behaviour disruption and hearing loss under extreme circumstances in marine mammals (Carstensen et al., 2006; Bailey et al., 2010; Brandt et al., 2011; Dähne et al., 2013; Tougaard et al., 2009a; Tougaard et al., 2009b) and lead to larval mortality of fish (Popper and Hastings, 2009; Nedwell et al., 2003; Nedwell and Howell, 2004; Popper et al., 2007). OWF using gravity foundations would have a lower acoustic impact than monopiles (Hammar et al., 2016; OSPAR, 2016; OSPAR, 2014), and if the generated noise is temporary and not loud enough to cause hearing impairment, the alterations of species' behaviour can be minor (Madsen et al., 2006). Additionally, during the planning and construction period, avoidance of biologically sensitive seasons can significantly reduce animal disturbance (Hammar et al., 2014). Nevertheless, mitigation measures can be deployed using acoustic (bubble) curtains to attenuate noise from OWF construction and reduce temporary habitat loss (Würsig et al., 2000; Oestman et al., 2009; Lucke et al., 2011; Dähne et al., 2017).

During operation, underwater sound levels are unlikely to reach dangerously detrimental levels for species (Madsen et al., 2006) or mask the acoustic communication of marine mammals (Tougaard et al., 2009a). Although vibrations caused by wind turbines transmitted to the sea floor should be considered, in most cases, operational noises are considered of minor importance in the marine environment (Petersen and Malm, 2006; Wilhelmsson et al., 2006; Westerberg and Lagenfelt, 2008) and highly local (Nedwell et al., 2003; Andersson, 2011). For example, for porpoises and seals, high-frequency noises imitating operational 2 MW turbines resulted in minor responses from these species, limited to a 60–200-m perimeter around the sound source (Koschinski et al., 2003). However, marine renewable energy devices showed the potential to impact marine sessile organisms through long-term exposure to constant low noise (Gill, 2005). Thus, despite being very limited to a few meters around the cables, electromagnetic fields affected the prey detection ability of elasmobranchs (Westerberg and Lagenfelt, 2008; Westerberg and Begout-Anras, 1998), and disturb the migration patterns of the European eel (Gill et al., 2012; Karlsson, 1985). Impacts from the electromagnetic field, though, can be mitigated by an appropriate design and deployment of cables (Bergström et al., 2014) to avoid sensitive species. In this sense, studies have judged so far that impacts from electromagnetic fields tend to be small, although available results are not conclusive (Petersen and Malm, 2006; Gill et al., 2012; Meißner and Sordyl, 2006).

3.2. Application of the EIA-GES checklist to the Canary Islands

The Canary Islands are surrounded by high-energy oligotrophic waters, where islands rise abruptly from the seafloor, most of them with a very narrow insular platform. Thus, the possibility of OWF contributing to eutrophication (QD5) has been ignored. Besides, no information was found regarding contaminant concentration (QD8) or contaminants in fish and seafood (QD9). In total, 21 different datasets (i.e., GES spatial features) related to eight relevant QD were collected. These were employed to cumulatively map and assess the impact level that OWE could have on the GES of the marine waters of the Canary Islands (Fig. 2). Considering the biogeographic characteristics, the EIA-GES checklist was applied to the study area through the weighed GES components. Weight/significance was calculated for each parameter within the related QD by applying the AHP approach (Table 2).

We have classified GES QD as follows, considering the expected impact of OWF: (1) very highly impacted, i.e., marine biodiversity (QD1); (2) highly impacted, i.e., commercial fish species (QD3), marine food webs (QD4), and underwater noise (QD11); (3) moderately impacted, i.e., seafloor integrity (QD6) and non-indigenous species (QD2); and (4) lightly impacted, i.e., hydrographical condition changes (QD7) and marine litter (QD10). No QD were considered as very lightly impacted.

To pairwise the spatial features defining the GES in our study area, we have followed a process similar to that for GES QD, giving greater impact recognition to those expected during the operational phase (i.e., in the long-term) than those occurring during construction and decommissioning (Table 2).

The Canary Islands are considered a marine biodiversity hot spot. Its surrounding waters sustain one of the highest diversity of marine mammals worldwide (Carrillo et al., 2010; Pérez-Vallazza et al., 2008) and seabird species (see supplementary information Tables 4, 5, and 6) that could be affected by OWF during their foraging or migration behaviour, e.g., the Bulwer's Petrel *Bulweria bulwerii (*Rodríguez et al., *2013)* or *Calonectris* shearwaters (Alonso et al., 2018; Navarro and

González-Solís, 2009; Romero et al., 2021). Thus, within QD1, seabirds were ranked the highest, as their mortality is expected to increase during the operative phase, whereas marine mammals, sea turtles, and benthic habitats would be punctually disturbed during construction and decommissioning. Further, benthic habitats and seafloor integrity were also given a high score, considering that OWF foundation construction could imply their complete loss. Besides, when sensitive and valuable habitats were identified in the Canary Islands (e.g., *Cymodocea Nodosa*, Maerl, and *Halophila* beds), very high impact (a cell value of −5, see Fig. 2) was directly applied in INDIMAR, suggesting that OWE development should be avoided and restricted. Further, regarding seafloor integrity (QD6), a negative contribution impact was applied in INDIMAR for all rocky and hard substrata, whereas a neutral value was assigned to muddy and sandy sea bottom.

Marine species, both of commercial interest (QD3) and the main groups of food webs (QD4), have been assessed from existing ecological models for the Canary Islands (Couce-Montero et al., 2015; Couce Montero et al., 2021). Both QD3 and QD4 can be affected positively due to the reef effect and new habitat gain, or negatively due to favouring overfishing, acting as fish aggregation devices. This impact sign will depend on the management responses, e.g., the creation of fishery exclusion zones. As currently there are no active OWF in the Canary Islands, we have assumed that some management responses to limit fisheries will be taken and thus, we would mainly expect a positive impact. Moreover, we have considered in this particular case that the punctual behaviour disturbances of all pelagic species expected during the construction and decommissioning would be surpassed by the previously mentioned positive impacts in the long-term during operation. Benthic elasmobranchs (i.e., sharks and rays), and moray eels have been the exception, and negative values have been attributed to them, as the EIA-GES checklist showed that negative impacts on these species are possible during the operational phase.

Due to the archipelago's geostrategic location, the islands are an important stop-over for international maritime transport traffic, increasing the island's exposure to the introduction of non-indigenous species (QD2) (EASME, 2017; Toledo Guedes et al., 2009) (see supplementary information- Table 7). Alterations of hydrographical conditions (QD7) were not considered significant due to the existing depth gradients of the islands. Marine litter (QD10) was not considered significant, due to the relatively low relation of OWE as sources of pollution or litter.

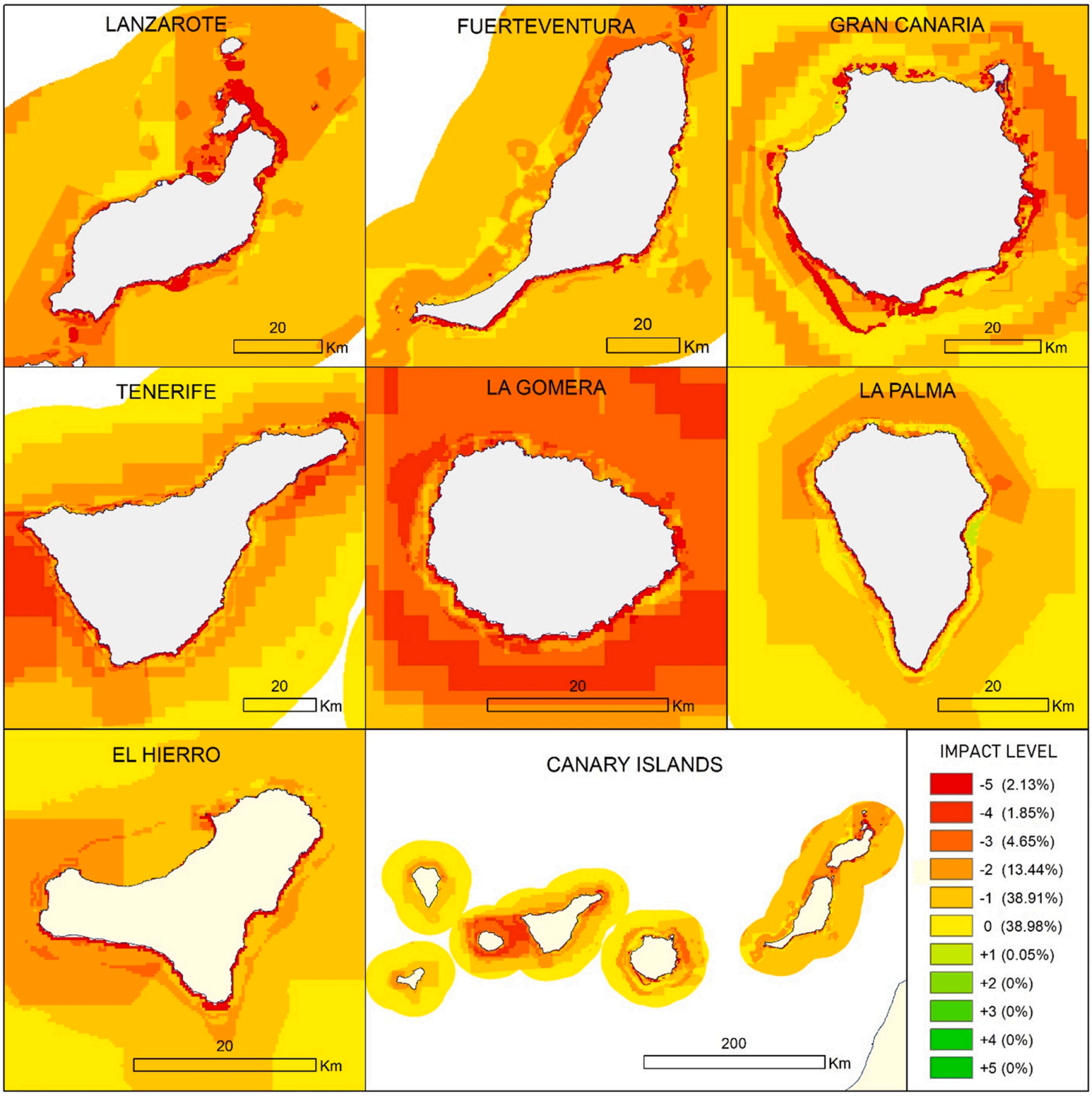

Fig. 2. Map showing the level of OWE's expected impact on the GES of ca. 45.613,5 Km2 of marine area off the Canary Islands. Negative/positive values indicate negative/positive cumulative impacts. Percentages indicate the proportion of cells (i.e., 300 × 300 meters) in INDIMAR presenting each value.

4. Discussion

In this study, we have reviewed most of the potential impacts of OWE on the marine environment and organized them into an "EIA-GES checklist" (Table 1). The checklist highlights the relevant issues and the environmental receptors recommended to be covered by EIA studies, being useful both for OWE promoters and environment protection authorities. Besides, we expect that our results would also positively contribute to the justification of the selection among different development scenarios that EIA studies examine. The case study application of the presented EIA-GES checklist framework illustrated a useful approach to promote the development of OWE while contributing to the MSFD GES maintenance.

4.1. Achieving GES supported by EIA

The marine environment is expensive to survey and both temporal and spatial variations add complexity to the monitoring and modelling systems, which is often translated into gaps in data and information. Hence, efficient survey strategies that provide information with the required spatial coverage and targeted parameters are necessary (Abramic et al., 2014; Franco et al., 2015). Thus, we propose the GES as a pivotal point around which EIA could revolve, to help gather the required data for its assessment, while maintaining it through OWE developments.

The elaborated EIA-GES checklist based on the literature review can support environment protection authorities to evaluate the adequacy and quality of EIA studies (Ramos et al., 2021), as well as trade-offs with the marine environment. EIA is not based unilaterally on available historical data. Environment authorities can ask for in situ surveys when considered necessary, to evaluate the expected impacts of the different development scenarios and alternatives. In the long term, defining baselines to compare and assess the degree of OWE impacts is important (Bailey et al., 2014). We reinforce the usefulness of understanding the status of the critical environmental parameters prior to the construction and operation of the OWE facility, to establish the reference conditions. These could then be compared with the GES QD and criteria surveyed during the operational phase, enabling the detection of environmental disturbances and measurement of the current impact. This type of survey strategy is established by Underwood (Underwood, 1994) and called Before-After-Control-Impact (BACI) monitoring.

In this sense, GES QD and criteria could clarify and guide the specific elements that EIA would need to evaluate, while OWF project promoters could survey both prior to construction of OWE facilities and during the operational and decommissioning phases. This could promote the engagement of the private sector as an actor to contribute to the maintenance of the GES and monitoring of the marine environment. In this sense, our EIA-GES checklist approach may be useful for public administrations to reinforce their role in implementing the MSFD by adding private initiatives for new data acquisition efforts, within EIA studies. Integrating policy, decision-making, all sources of information, and means of surveying GES QD and criteria could improve GES assessments, especially considering future scenarios of blue growth and a changing ocean in the face of climate change. This is so especially in the frame of EIA, where environmental authorities can add further elements to be assessed apart from regulatory requirements derived from EIA laws. Hence, based on the evidence and gaps of knowledge derived from the literature reviewed regarding OWF impacts on the GES (Table 1), we recommend a series of aspects to be assessed and particularly encouraged within EIA by environmental administrations:

- Performing BACI monitoring of benthic habitats within OWF could help assess whether potential (positive or negative) impacts will be translated into habitat gain or decrease in biodiversity (Bakran-Petricioli et al., 2006).
- Addressing conveniently the distribution of pelagic species, biogeographic and oceanographic features (Roberson et al., 2017) within and around OWE projected areas.
- If fisheries are allowed within OWF, the synergistic relationship between these activities and biological resources due to the fish aggregation effect should be considered, to avoid potentially overexploited fishing grounds in the long term.
- If fisheries are banned from OWF locations and/or specific fishing gears and practices are regulated (Halouani et al., 2020), ecological modelling should be promoted (e.g., through Ecopath with Ecosim and Ecospace) to estimate the reef effect and biomass gain in commercial species (QD3).
- We reiterate the fostering of ecosystem modelling of the food web guilds (QD4) to evaluate the potential gain/loss in biodiversity (Raoux et al., 2017; Inger et al., 2009; Halouani et al., 2020; Raoux et al., 2019; Pezy et al., 2020).
- Connectivity studies should be encouraged that spatially link potential NIS introduction vectors with biophysical modelling to assess OWF location scenarios (Sheehy and Vik, 2010), preventing the corridor effect of OWF favouring NIS introduction and spreading (QD2).
- Hydrological changes should be estimated (QD7), especially in relatively shallow, low seabed gradients and/or nutrient-rich areas, to assess the eutrophication (QD5) risk.
- Evaluation of whether OWF foundations should be left as artificial reefs, partially or entirely, during the decommissioning phase.
- Evaluation of the concentration of pollutants in the OWF projected area's sea floor, especially in shallow areas proximate to highly industrialized coastlines, where construction operations may remobilise contaminants back into the water column (QD8 and QD9). This could also be considered a land-sea interaction within MSP plans to allocate OWE.
- Carefully analyzing underwater noise generation (QD11) during the construction phase and promoting BACI monitoring of potentially affected marine mammals and fish larvae.

4.2. GES spatial data dependency and limitations for EIA

Currently, there is only one experimental prototype of a turbine installed in the Canary Islands, but the Spanish Marine Spatial Plan has already planned priority marine areas for OWF development (MITERD, 2021). Thus, this maritime sector is expected to be operational in the coming years. However, there is still no information available on the impacts of OWF on the marine biogeographic specificities of the Canaries. Despite this, Fig. 2 illustrates a simulation of the level of impact expected for the archipelago based on the literature reviewed from the North Sea and the Baltic Sea, where OWE have been operating for >20 years. Nevertheless, the marine environmental conditions of Northern Europe differ greatly from the open Atlantic Ocean in our case study. This indicates the convenience of applying the GES-EIA checklist through a case-by-case approach, adapting it as we have done in the present research for the Canary Islands.

Being based on the best available knowledge, the applicability of the EIA-GES checklist to our case study presents information gaps around OWF impacts on the marine environment similar to the reviewed literature. For example, alterations concerning the food webs (QD4) in pelagic habitats and the possible relation to the concentration of contaminants in the environment or the fish/seafood (QD 8 and 9) (Raoux et al., 2017; Inger et al., 2009; Raoux et al., 2019; Pezy et al., 2020) have not been assessed. We acknowledge this as a source of uncertainty and thus recommend considering our results through the lens of the precautionary principle.

Using the decision support system INDIMAR, which is based on geospatial data, has revealed the importance of spatial data in visualizing how the different criteria within GES QD might be impacted by OWE location planning (Fig. 2). Thus, several limitations related to key

GES spatial features have been detected to accurately assess the level of impact of OWF. For example, the lack of usable datasets on species distribution hampers the application of some of the mitigation measures described in Table 1, such as the proper location of OWF to avoid foraging and migration routes for seabirds and marine mammals to minimize losses (Bailey et al., 2014; Dierschke et al., 2016). As an approximation, we have used the available Ecopath and Ecosim modelled biomasses of the main elements integrating the marine food web in the Canary Islands (Couce-Montero et al., 2015; Couce Montero et al., 2021). However, these models are configured based on artisanal fishery data for a punctual point in time, recognizing that these datasets should be considered with a certain level of caution. Part of this has been completed by giving higher scores in INDIMAR to datasets related to existing protected marine areas and special protection areas for birds. Although these Nature 2000 sites correspond to jurisdictional-administrative borders and not particularly to ecological boundaries or species distribution patterns, we recognize that they are based on scientific criteria, including the most suitable areas for seabird species vulnerable to OWF. Thus, ca. 4.65% of the marine area studied, mainly composed of Nature 2000 sites, is under a relatively high expected impact level of −3 (see Fig. 2). This relatively high level of impact on MPAs is in line with the criteria adopted by the Spanish MSP draft plans for locating OWE outside conservation sites (MITERD, 2021).

Weighting the gathered GES datasets according to the EIA-GES checklist through INDIMAR has resulted in 77.89% of the study area being under either a very low or neutral impact level (i.e., values −1 and 0 in Fig. 2). This may be due to several reasons. Firstly, the data coverage of environmental information is more detailed and accurate in coastal areas. For example, in the coastal strip within 50 m of depth, we have precise and detailed information on benthic habitats (PLASMAR Consortium, 2020). It is clearly identified that some benthic habitats can suffer irreversible impacts during the OWF construction, while others can increase their biodiversity through the reef effect. Conversely, benthic habitats analysed beyond the 50 m of depth are difficult to survey and are mapped mainly through modelling techniques. These models have extensive coverage, but a low level of detail, which hampers the understanding of where the impacts could be more significant.

The second reason derives from the characteristics of the datasets employed in the assessment. The GES spatial features considered to have a positive impact contribution to the impact level assessment are based on species distribution models. These species being highly mobile coastal and oceanic pelagic fish, their presence has been considered throughout all the study areas.

The third reason relates to the mathematics within the AHP approach and the limited data availability related to the GES. The impact level on the eight QD has been assessed through the GES spatial information-data (i.e., GES spatial features (see Table 2), though these have been collected unevenly across QD due to the paucity of data. For example, the impact level on QD1 or QD3 has been evaluated, respectively, through eight and five spatial datasets, compared to the rest of QD assessed through one or two datasets. Thus, initially, QD weightings were also distributed unevenly (e.g., eight and five times in the case of QD1 and QD3 respectively, and in one or two times for the rest of QD), contributing to the decrease of their corresponding GES spatial feature weighting and, consequently, the final weight introduced in INDIMAR for those GES datasets. This has led to the assignment of almost 20% of the final weight (see Table 2) to coastal and pelagic fish datasets (QD3). Thus, the high final weight attributed to pelagic species present across all the study areas contributed to extensive marine areas coming under neutral or very low levels of impact.

This denotes the importance of understanding EIA-GES historical spatial datasets regarding their quality, coverage, and level of detail to evaluate whether they represent properly the current realities of the marine environment. To better address the spatial and temporal changing dynamics of the marine environment, available historical information-data should be confirmed with in situ surveys of OWF sites.

5. Conclusion

Ecological concerns in the GES of marine ecosystems arise considering the present development of OWF and the expected future increase to meet global decarbonisation targets. For this research, an extensive literature review was conducted, aimed at gathering scientific evidence on environmental impacts around the GES to create an EIA-GES checklist that could guide competent authorities in EIAs and ensure that no relevant environmental aspect is left unconsidered. Thus, we have aimed to pave the way for OWE development, while contributing to the GES maintenance. Besides, our EIA-GES checklist includes both the possible impact mitigation measures and key ecological information that could be collected by OWF developers during the EIA study. These surveys can support environmental authorities by providing more detailed insights to assess the GES status while identifying key gaps and areas to improve monitoring and data gathering for the GES maintenance.

In our case study, we have mapped areas potentially impacted by OWF following the GES. This has reinforced the importance of following a case-by-case approach when applying the EIA-GES checklist in practice. Particularly, biogeographic aspects, oceanographic conditions, and OWF location sites will ultimately determine the overall impact of OWE development.

Our results, applying historical data to the offshore waters of the Canary Islands, suggested that OWF developments would have a minor or null impact on the GES for ca. 78% of its marine waters. This denotes the importance of spatial (surveyed or modelled) data characteristics such as quality, level of detail, and consistent historical time series to assess whether the employed data reflects the real current state of the marine environment. Thus, we encourage applying and reusing historical data for the EIA, but always supported by focused in situ surveys which confirm that we have reliable ecological information within and around OWF sites. This, again, reinforces the idea that applying the GES framework to EIA supports the implementation of the MSFD. Additionally, it should be considered that MSFD is a legal instrument for integrated marine (environmental) management, incorporating other related EU environmental instruments applicable to the sea. Thus, our proposed approach would indirectly support the implementation of other EU environmental Directives, such as the Strategic Environmental Assessment (2001/42/EC), Maritime Spatial Planning (2014/89/EU), the requirements of the Good Ecological Status for coastal waters (Water Framework Directive, 2000/60/EC), and the preservation of marine habitats and marine species within the Natura 2000 (Habitat Directive 92/43/EEC and the Birds Directive 2009/147/EC).

CRediT authorship contribution statement

A. Abramic: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **V. Cordero-Penin:** Formal analysis, Writing – original draft, Writing – review & editing. **R. Haroun:** Writing – review & editing, Supervision.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2022.106862.

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