Environmental Science and Policy 136 (2022) 772–785

Contents lists available at ScienceDirect

Environmental Science and Policy

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

Critical evaluation of ecosystem changes from an offshore wind farm: producing natural capital asset and risk registers

Paul D. Causon [a,b], Simon Jude [a,*], Andrew B. Gill [c,d], Paul Leinster [a]

[a] School of Water, Energy and Environment, Cranfield University, Cranfield, Bedfordshire MK43 OAL, UK
[b] Natural England, Guildbourne House, Chatsworth Road, Worthing, West Sussex BN11 1LD, UK
[c] The Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft Laboratory Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK
[d] PANGALIA Environmental, Bedfordshire MK45 2QX, UK

ARTICLE INFO

Keywords:
Benthic community
Ecosystem services
Environmental management
Natural capital
Offshore wind farm

ABSTRACT

Offshore wind infrastructure modifies benthic habitats, affecting ecosystem services. A natural capital approach allows risks to nature-based assets and ecosystem benefits to be assessed. The UK Natural Capital Committee produced guidance for conducting natural capital assessments to aid decision making processes. Development of an asset register and risk register are key components of this methodology. The former provides an inventory of NC stocks, and the latter considers the likelihood of changes and the scale of their impact on delivery of ecosystem services. In this study, suitability of the methodology in a marine environment context was critically evaluated. Natural capital stocks before and after installation of Greater Gabbard offshore wind farm were compared and risks to delivery of ecosystem services were assessed. It was demonstrated that incorporating an assessment of impacts on natural capital assets in planning and management decisions (as an extension to traditional environmental impact assessment approaches) could further facilitate sustainable use of marine ecosystems. For example, by preventing access to bottom-trawl fisheries activities, wind farms may promote recovery and increase value of seabed natural capital assets. By also introducing aquaculture systems loss of food provision (from reduced fishing activity) could be offset whilst allowing benthic natural capital assets to recover. Natural capital assessment is relevant to the marine context. However, application of the Natural Capital Committee's methodology was constrained by the limited coverage of standard benthic sampling tools. Given the scale of wind energy plans across the marine environment it is recommended that these shortcomings are appropriately addressed.

1. Introduction

Application of an ecosystem approach recognises the need for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. In recent years there has been an impetus for nature recovery and conservation based on an ecological - economic approach, whereby nature is considered a component of national wealth on the grounds that it supports human wellbeing and livelihoods. From this standpoint, biodiversity (including community composition and structure, genetic diversity, and biological traits) and abiotic components of ecosystems are assets which collectively make up natural capital (NC) from which ecosystem services (ES) are derived (Costanza and Daly, 1992; Hinterberger et al., 1997; Natural Capital Committee, 2014; Dasgupta, 2020). Ecosystem services are benefits from nature typically categorised as provisioning (e.g., food), regulating (e.g., carbon sequestration), cultural (e.g., tourism) and supporting (e.g., nutrient cycling) (Reid et al., 2005).

The marine environment has substantial natural capital assets (Costanza et al., 2014a,b), which are under increasing pressure from ongoing and new human activities. The period 2010–2020 saw our marine environment become the focus of major industry growth in the form of offshore wind energy generation. In 2011, the global cumulative installed capacity of offshore wind turbines was 4.1 GW (GWEC, 2020a, 2020b). By the end of the decade cumulative capacity stood at 29.1 GW, surpassing the milestone of 20 GW by 2025 (GWEC, 2020a, b). Unprecedented expansion of offshore wind energy is planned over the next decades with governments around the world prioritising plans in a

* Corresponding author.
E-mail address: s.jude@cranfield.ac.uk (S. Jude).

https://doi.org/10.1016/j.envsci.2022.07.003
Received 12 October 2021; Received in revised form 17 June 2022; Accepted 3 July 2022
Available online 17 August 2022

concerted effort to commit to decarbonising energy generation and transition to net-zero carbon emissions, to assist with climate change mitigation (Ministère de la transition écologique et solidaire, 2019; New Zealand Government, 2019; UK Government, 2019, 2020; Government of Republic Korea, 2020; Swedish Environmental Protection Agency, 2020; Yang and Yang, 2020). In the UK alone there is a commitment for quadrupling of OWF power generation to 40 GW by 2030 and aspiration for more than 75 GW of offshore wind farms (OWFs) to be operational by 2050, which would require the installation of up to 7500 turbines (Committee on Climate Change, 2019b, 2019a). The EU strategy for offshore renewable energy proposes to increase offshore wind capacity to 300 GW by 2050 (European Commission, 2020). Outside of Europe, the South-East Asian marine environment is set to become home to major offshore wind production. Of the 2.7 GW of installed offshore wind capacity in Asia, 2.4 GW is located in China (Díaz and Guedes Soares, 2020), with, China's installed capacity expected to exceed 65 GW by 2030 and 200 GW by 2050 (Zhang and Li, 2021). In North America, extensive plans for offshore wind energy are imminent in the US where construction is underway on an 800 MW OWF in Massachusetts, and the State seeks to have 3.2 GW installed by 2035 4C Offshore (2021), with further developments along the Atlantic coastal and offshore marine environment.

Although offshore wind power benefits the natural environment through low CO_2 energy production, it also has the potential to change biodiversity and modify ecosystem functions (Causon and Gill, 2018; Degraer et al., 2020). Current approaches to determine these changes and whether they represent environmental impacts of significance (Boehlert and Gill, 2010) apply Environmental Impact Assessments (EIA). Usually required for large infrastructure developments including OWFs, EIAs are intended to identify the likely significant environmental impacts of the development (UK Government, 2017). For an OWF $>$ 100 MW where concerns exist over the project's suitability or potential impacts, pre-construction, construction, or post construction monitoring is usually required as part of the EIA process (Marine Management Organisation, 2014). The main driver for post-construction monitoring is to validate predictions made by the EIA (Marine Management Organisation, 2014).

A key limitation of many of EIA studies is that they focus on negative impacts and often take a siloed approach by focussing on specific environmental issues, which compromises our ability to take an integrated systems-based approach and evaluating positive and non-local benefits (Smart et al., 2014; Hooper et al., 2017b). Furthermore, they do not effectively deal with interrelated and cumulative aspects which are recognised as essential to the overall determination of the changes occurring to the marine environment (Willsteed et al., 2018). An approach incorporating NC may offer a means to address these shortcomings and assist in achieving sustainable development in the marine environment. Properly planned infrastructure that considers NC from conception can support NC and ES, and greatly assist in the aspiration to leave the environment in better condition than the pre-development baseline (National Infrastructure Commission, 2021). Therefore, to ensure sustainable development of the growing marine renewable energy sector there is an urgent need to understand how energy installations both positively and negatively affect and potentially impact on NC condition of marine systems.

Natural capital accounts have been established to determine the extent and condition of current stocks and aid the monitoring of changes. The UK office for National Statistics (ONS) recently published experimental ecosystem service accounts for the period 1997–2015 (Office for National Statistics, 2018). Additionally, the Knowledge and Innovation Project on an Integrated system for NC and ES Accounting (KIP-INCA) is an ongoing initiative that aims to produce physical and monetary accounts for the EU (European Commission, 2015). Whilst terrestrial systems have received the greatest attention, there have also been recent attempts to produce accounts for marine and coastal habitats (Connors, 2016; Australian Bureau of Statistics, 2017; Graveland et al., 2017; Weatherdon et al., 2017). Nonetheless, largely due to the high costs of sampling approaches, monitoring systems and technology for marine systems, knowledge of the condition of NC assets in marine systems remains limited (Medcalf et al., 2012).

A NC Assessment (NCA), through which registers of NC stocks and risks to the delivery of ES are established, is a critical stage in the development of robust NC accounts. The UK Natural Capital Committee (NCC) produced guidelines for conducting a NCA to aid developers in decision making processes (Natural Capital Committee, 2017). There have been comparatively few applications of the NCC methodology in marine systems (Medcalf et al., 2012; Picone et al., 2017). Therefore, the aim of this study was to critically evaluate the suitability of the NCC approach in marine systems in the context of offshore wind energy development.

2. Case study: Greater Gabbard offshore wind farm

The Southern North Sea has become a hub of offshore wind energy production. Between Belgium, Germany, the Netherlands, and the UK, installed offshore wind capacity in the Southern North Sea exceeds 15 GW (Sea Impact, 2021). In addition, more than 14 GW is under construction or consented in these waters or those of adjacent countries (Sea Impact, 2021).

A search of the marine data exchange (Marine Data Exchange, 2020) was performed; the database was found to host benthic datasets from a number of UK OWF areas, including Dudgeon, Greater Gabbard and Galloper, Humber Gateway, Inner Dowsing, Lynn, Thanet and Westernmost Rough. However, at the time data was accessed, datasets from surveys before and after the installation of an OWF were only available for Greater Gabbard (GG).

Greater Gabbard OWF is one of the largest constructed in the last decade and is one of several OWFs in the Outer Thames Estuary, part of the Southern North Sea located within the UK EEZ. It is approximately 26 km off the Suffolk coast and occupies an area of 147 km^2 (Greater Gabbard Offshore Winds Ltd, 2013). It has an installed capacity of 504 MW, provided by 140 Siemens 3.6 MW turbines with monopile foundations (Centre for Marine and Coastal Studies Ltd, 2013). The turbines are separated into 2 arrays that straddle the Inner Gabbard Bank and Galloper Bank, occupying an area of up to 147 km^2 (Centre for Marine and Coastal Studies Ltd, 2013). It began generating energy in September 2012 and was fully commissioned in August 2013 (Centre for Marine and Coastal Studies Ltd, 2013). Although it is located adjacent to Galloper OWF, it is treated as a separate case study here.

2.1. Building the evidence base

The NCC set out a methodology for conducting a NCA and developed guidance for anyone who wants to use a NC approach in making decisions (Natural Capital Committee, 2017). Fig. 1 illustrates the steps of the NCC's approach in sequence. The first step ('setting out the vision') involves developing general aims for a natural capital plan based on which decisions would be made (Natural Capital Committee, 2017). The second step ('understanding where you are starting from') aims to understand the baseline position of natural assets. This includes defining the area covered by the natural capital plan, identifying the groups of people who benefit or bear the costs, and identifying existing or planned environmental protection or recovery activities (Natural Capital Committee, 2017). Typically step 2 is desk based performed to ensure that basic information relevant to NC is gathered, documented, and synthesised (Natural Capital Committee, 2017).

The third step ('building the evidence base') calls for an NC asset register to be produced. The asset register provides an inventory of NC stocks within a defined area in terms of quantity (abundance/biomass), quality, and extent (physical limit of distribution within the area). Another critical component of the NCA process is a NC risk register. This highlights the status of NC stocks and associated ES that are at risk (Mace

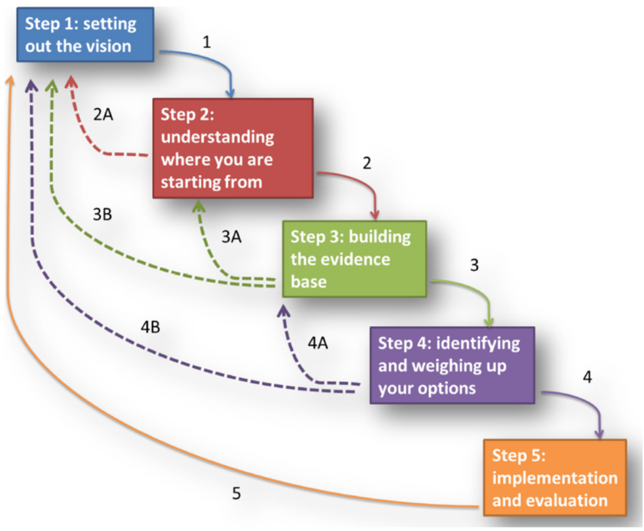

Fig. 1. Natural Capital Committee's planning cycle for the natural capital approach. Solid arrows link the major steps in the evaluation, from 1 to 5 and then back from step 5 to step 1. Dotted lines illustrate earlier stages may need to be revisited as the plan develops (Natural Capital Committee, 2017).

et al., 2015). A risk register should consider both the likelihood of a change and the scale of its impact so that the order of priority can be determined for managing risks (Natural Capital Committee, 2017). The NCC's approach to compiling a risk register considers the quantity, quality, and spatial configuration of assets and their connectivity with other features (Mace et al., 2015). Also, key to establishing a risk register is knowledge of the target level of NC and safe limits, below which degradation of NC leads to a loss of ES that presents risks to humanity (Mace et al., 2015).

Once the evidence base has been built, the fourth step ('identifying and weighing up your options') is to develop options to support NC and create new value and opportunities based on the evidence base (Natural Capital Committee, 2017). Finally, the fifth step ('implementation and evaluation') is to develop an implementable and prioritised action plan (Natural Capital Committee, 2017). This is the action taken by developers and stakeholders, as informed by the NCA. There are parallels and synergies in applying the four steps of NCA to any practical application of an ecosystem approach to consider and assess environmental, social, and economic parameters (Judd and Lonsdale, 2021).

As this is a case study of an operational OWF, utilising pre-existing datasets and technical reports generated before and after its construction, the first and second step are forgone. The assessment instead focuses on step 3. Some consideration of the fourth and fifth steps will be made but they are largely beyond the scope of this study.

2.2. *Identifying natural capital stocks before and after offshore wind farm construction*

Marine and coastal zones are among the most productive in the world (UNEP, 2006; Hattam et al., 2015), and provide ES such as coastal and flood protection, nutrient cycling, carbon sequestration and 90 % of fish catches (Costanza et al., 1997, 2014b; Böhnke-Henrichs et al., 2013; Liquete et al., 2013). Yet, there is little information on the NC stocks that support those ES, even in well surveyed regions such as the southern North Sea.

Natural capital stocks before and after the installation of GG OWF were compiled and compared as fully as practicably possible from available data. Benthic data were sampled from within and near the GG OWF extent before and after turbine installation and included data from a baseline survey conducted in November and December 2004 and a 1-year post-installation monitoring survey conducted in April and May 2013 (The Crown Estate, 2020). Post-installation monitoring included communities colonising 2 monopiles, IGE01 and GAA02 (Fig. 2), which were surveyed using a purpose built remotely operated vehicle (ROV) (Centre for Marine and Coastal Studies Ltd, 2013). Inbuilt on the ROV was a Van Veen grab sampler, which was intended to collect samples for laboratory verification of species identifications made using the mounted camera. However, only a single sample was collected from 22.3 m on GAA02, which confirmed initial taxonomic identification. Due to strong tidal currents no sample was taken from IGE01 (Centre for Marine and Coastal Studies Ltd, 2013). Samples taken from the cable route were beyond the scope of this study and were removed from the data prior to analysis.

A standard 0.1 m^2 Hamon or Day grab with a single jaw was utilised to sample from the benthos (Table 1) as it is designed to reduce sample washout in areas where a loose stone can block double grab jaws (Centre for Marine and Coastal Studies Ltd, 2005, 2013). Where possible triplicates were taken for each station.

Based on the size and number of grab samples (Table 1), an estimated cumulative 6 m^2 and 11.7 m^2 of seabed was sampled before and after the OWF installation respectively. This includes triplicate samples which, although from the same area, are likely to be separated by several metres on the seabed. Additionally, assuming a monopile diameter of 4.1–4.9 m, IGE01 and GAA02, an estimated combined surface area of up to 8.93×10^{-4} km^2 was sampled from the turbines.

Samples were fixed on the vessel prior to transport to a laboratory, where they were identified, to the lowest achievable level, and counted under a microscope (Centre for Marine and Coastal Studies Ltd, 2005, 2013, 2014). Taxa sampled from the seabed were recorded as abundance, whereas taxa sampled from the structures were recorded with respect to depth and quantified using the SACFOR scale (Hiscock, 1996). To make comparisons, abundance data were upscaled to abundance per m^2 and then transformed in to SACFOR scores. Where triplicate samples were taken, means were calculated prior to upscaling. Tables 2 and 3 show the relative abundance of taxa from soft sediments before and after in installation of GG OWF, respectively.

2.2.1. *Soft sediment communities*

Biodiversity in soft sediment habitats varies according to exposure to environmental stress. Coarse sand sediments exposed to high wave and tidal action are typically impoverished and characterised by opportunistic capitellid and spionid polychaetes and isopods, whereas soft-sediment communities in sheltered areas are among the most diverse marine habitats (Maddock, 2008). Under the right conditions, certain species, such as the polychaetes *Lanice conchilega* and *Sabellaria spinulosa* can form biogenic reefs, which stabilise sediments and can enhance NC by providing access to resources such as food and shelter (De Smet et al., 2013; Degraer et al., 2008; Maddock, 2008; Petersen and Exo, 1999; Rabauta et al., 2013).

Sediments in the region of Inner Gabbard and Galloper Banks have been classified as slightly muddy sandy gravel or slightly muddy gravelly sand, and these habitat types were designated C1a and C1b respectively (Cooper and Barry, 2017; Cooper et al., 2019). Based on metadata analysis in these habitats benthic communities are expected to be characterised by polychaetes of families Capitellidae, Cirratulidae, Glyceridae, Lumbrineridae, Serpulidae, Spionidae, Terebellidae along with the phylum Nemertea (Cooper and Barry, 2017). C1a habitats are also expected to include Sabellariidae and Syllidae, whilst C1b habitats are expected to include Ampeliscidae, Pholoidae, Phyllodocidae, Polynoidae, and Scalibregmatidae (Cooper and Barry, 2017).

Table 2 shows the relative abundance (SACFOR) of taxa recorded in grab samples during either pre- (upper) or post-installation (lower) surveys. Whereas taxa that were recorded in both pre- and post-installation surveys are shown in Table 3. Here, taxa are shown in terms of their post-installation relative abundance but changes from pre-installation are shown by the text colour (green = increase, red = decrease, black = no change) and adjacent numbers (SACFOR

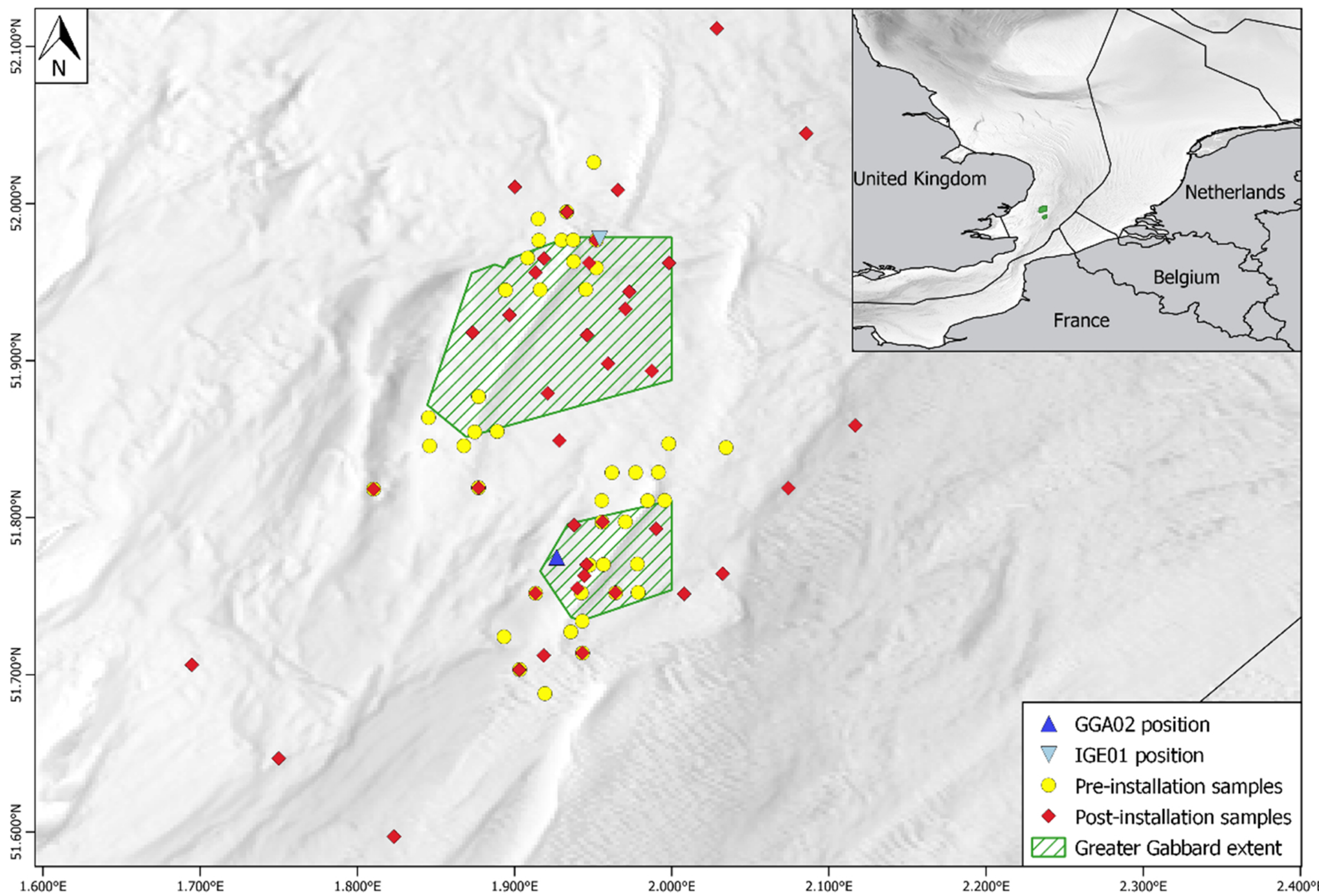

Fig. 2. Map of Greater Gabbard offshore wind farm showing the locations of the grab samples taken before (yellow) and after (red) the turbines were installed. Inset shows the location of GG OWF relative to the United Kingdom and adjacent countries.

Table 1
Basic information on the data used to perform the NCA. Greyed cells = NA. Monopiles, IGE01 and GAA02 were focal turbines surveyed. SACFOR = semi-quantitative categorical abundance scale.

	Benthos		Turbines	
	Pre-installation	Post-installation	IGE01	GAA02
Survey date	Nov-Dec 2004	Apr-May 2013		
Installation date			13-Aug-09	30-Jul-10
Sampling	0.1 m^2 Hamon or Day grab		Remotely operated vehicle (ROV) with mounted camera and Van Veen grab sampler	
Sites sampled	34	39		
Min depth (metres)	19	7	Intertidal	
Max depth (metres)	39	35	28.5	29.5
Fixative	4–5% saline buffered formalin solution			
Measure of abundance	Count		SACFOR	

categories). For example, the polychaete *Spirobranchus triqueter* changed from 'frequent' to 'abundant', a 2-category increase. Whereas *Amphipholis squamata* changed from 'abundant' to 'common', a 1-category decrease. Approximately 50% of taxa were recorded both before and after the installation of GG OWF. Of those, 29 % showed an increase and 13% showed a decrease in relative abundance following the installation of GG OWF. Approximately 37 % of all taxa recorded were polychaetes, many of which were of families that characterise C1a and C1b habitats (Tables 2 and 3). This includes tube building species, such as *L. conchilega* and *S. spinulosa*, which were 'abundant' and 'common' before and after installation of GG OWF respectively (Table 3). Although, despite its common occurrence, there were no significant *S. spinulosa* aggregations found following drop down video surveys at three stations within the OWF (one on the Inner Gabbard Bank and two on the Galloper Bank) (Centre for Marine and Coastal Studies Ltd, 2014).

Polychaetes were recorded in all SACFOR categories, with *Notomastus* spp., the only 'super abundant' taxa (recorded following the installation of GG OWF). There were numerous species of class malacostraca in soft sediment communities, before and after the installation of GG OWF, including arthropods, decapods, and isopods (Tables 2 and 3). However, none occurred in greater relative abundance than common. The same was true of bivalves. It is notable that the sea stars *Amphipholis squamata* and *Ophiothrix fragilis* were abundant prior to the installation of GG OWF but absent from the post construction sampling.

2.2.1.1. Soft sediment community data analysis. A total of 229 and 170 species were identified from soft sediment samples before and after the installation of GG OWF respectively. However, sampling effort differed, with 34 pre-installation and 39 post-installation samples included in the analysis. A non-parametric c2m randomization test was performed to test the hypothesis that mean species richness after construction of GG OWF was not different from that before construction, thereby giving an indication of the potential change in NC. The results of this test (Table 4) suggest differences in mean species richness were not statistically significant ($p = 0.3$). Thus, providing strong evidence that species richness did not change following construction of GG OWF.

Table 2
Relative abundance (SACFOR scale) of taxa recorded in pre- or post-installation grab samples from GG OWF. *C1a and C1b habitat characteristic taxa.

Pre-installation																	
Super Abundant (SA)			Abundant (A)	**Anthozoa**	*Alcyonium digitatum*	Common (C)	**Bivalvia**	*Barnea parva*	Frequent (F)	**Bivalvia**	*Aequipecten opercularis*	Occasional (O)	**Anthozoa**	*Cerianthus lloydii*	Rare (R)	**Gastropoda**	*Epitonium clathratulum*
				Hydrozoa	*Hydrallmania falcata*		**Gastropoda**	*Crepidula fornicata*		**Clitellata**	*Grania spp.*		**Bivalvia**	*Hemilepton nitidum*		**Hydrozoa**	*Tubularia* spp.
				Polychaeta	*Lumbrineris latreilli**		**Gymnolaemata**	*Alcyonidium diaphanum*			*Halecium spp.*			*Kellia suborbicularis*		**Leptocardii**	*Branchiostoma lanceolatum*
				Ophiuroidea	*Ophiothrix fragilis*			*Callopora dumerilii*		**Gastropoda**	*Doto spp.*			*Nucula nitidosa*		**Malacostraca**	*Acidostoma obesum*
							Holothuroidea	*Leptosynapta inhaerens*			*Euspira nitida*			*Timoclea ovata*			Aoridae
							Hydrozoa	*Nemertesia antennina*		**Gymnolaemata**	*Crisularia plumosa*		**Gastropoda**	*Calliostoma zizyphinum*			*Eurydice spinigera*
							Ophiuroidea	*Amphiura securigera*		**Hydrozoa**	*Eudendrium spp.*			*Diodora graeca*			*Metaphoxus fultoni*
							Polychaeta	*Flabelligera affinis*			*Kirchenpaueria pinnata*			*Limacia clavigera*			*Nannonyx spinimanus*
								*Odontosyllis fulgurans**		**Polychaeta**	*Amphicteis midas*		**Gymnolaemata**	*Bicellariella ciliata*			*Nototropis vedlomensis*
								Praxillella affinis			*Eulalia viridis**			*Electra monostachys*		**Polychaeta**	*Hesionura elongata**
								Schistomeringos neglecta		**Sipunculidea**	*Golfingia elongata*			*Scrupocellaria scruposa*		**Stenolaemata**	*Plagioecia patina*
													Malacostraca	*Cheirocratus spp.*			
														Ebalia tumefacta			
														Eurynome aspera			
														Iphimedia minuta			
														Iphimedia spatula			
														Othomaera othonis			
														Pandalina brevirostris			
														Thia scutellata			
													Nematoda	Nematoda			
													Polychaeta	*Jasmineira elegans*			
														Micromaldane ornithochaeta			
														Scoloplos armiger			
													Pycnogonida	*Achelia echinata*			
														Anoplodactylus petiolatus			
														Callipallene spp.			
													Sipunculidea	*Crisia* spp.			
Post-installation																	
Super Abundant (SA)	**Polychaeta**	*Notomastus* spp.	Abundant (A)	**Polychaeta**	*Euclymene oerstedii*	Common (C)	**Bivalvia**	*Hiatella arctica*	Frequent (F)	**Bivalvia**	*Heteranomia squamula*	Occasional (O)	**Ascidiacea**	*Eugyra arenosa*	Rare (R)	**Bivalvia**	*Tellimya ferruginosa*
					*Lumbrineris cingulata**		**Polychaeta**	*Dipolydora socialis**			*Spisula elliptica*		**Malacostraca**	*Apolochus neapolitanus*		**Malacostraca**	*Amphilochus manudens*
					Nephtys caeca			*Lysilla loveni*		**Echinoidea**	*Echinocardium* spp.			*Astacilla longicornis*			*Ericthonius brasiliensis*
								Nephtys kersivalensis		**Gastropoda**	*Ocenebra erinaceus*			*Bathyporeia elegans*			*Lysianassa ceratina*
										Malacostraca							

(*continued on next page*)

Table 2 (*continued*)

Pre-installation							
Nephtys longosetosa		*Caprella septentrionalis*		*Corystes cassivelaunus*			*Tryphosella sarsi*
*Protula tubularia**		*Hyas* spp.		*Dyopedos monacanthus*		**Polychaeta**	*Tharyx killariensis**
*Phyllodoce maculata**	**Polychaeta**	*Gattyana cirrhosa**		*Dyopedos porrectus*		**Rhynchonellata**	*Gwynia capsula*
		*Glycera alba**		*Gyge branchialis*			
		*Harmothoe glabra**		*Nototropis swammerdamei*			
		*Harmothoe imbricata**		*Photis longicaudata*			
		Nephtys hystricis		*Photis reinhardi*	C/F	**Anthozoa**	Actiniaria
		Pherusa plumosa	**Polychaeta**	*Janua heterostropha**	F/O	**Polychaeta**	*Aphelochaeta* spp.*
	Ophiuroidea	*Ophiocten affinis*		*Pseudopolydora pulchra**	F/O	**Bivalvia**	*Thracia* spp.
	Sipunculidea	*Phascolion strombus*			O/R	**Malacostraca**	Mysida

2.2.2. Monopile communities

Potentially the most important change to the benthic habitat comes from the installation of the turbines themselves, which reduce soft sediment availability but provide substantial hard substrate. Specifications of the monopile tower foundations installed at GG OWF were unavailable. Thus, for illustrative purposes conservative estimates were based on the 4.1 – 4.9 m diameter monopile foundations that support 3 MW turbines at the nearby Thanet OWF (Vattenfall Wind Power Ltd, 2017). For the 140 turbines installed at GG OWF the area on the seabed would be reduced by 0.002 – 0.003 km^2. However, the available area for colonisation on the monopiles could be up to 20 times that lost from the seabed. In addition, the foundations provide a habitat suitable for colonisation by intertidal species, which would otherwise be unable to survive in the offshore environment. Indeed, green algae (*Ulva* spp.) and barnacles (order Sessilia) were shown to occupy the splash zone, between high and low water, on the foundations for turbines GAA02 and IGE01 (Table 5).

Three successional phases were identified in a long term (10 year) study of epibenthic communities on wind turbine foundations. These were a short pioneer phase (0 – 2 years), an intermediate phase (3 – 5 years) characterised high abundance of several filter feeding species, and a climax stage (6 + years) which is co-dominated by plumose anemones (*Metridium senile*) and blue mussels (*Mytilus edulis*) (Kerckhof et al., 2019).

GAA02 and IGE01 appear to be in the intermediate phase, with ‘abundant’ and ‘super abundant’ records of filter feeding species, such as bivalves *Mytilus edulis* and polychaetes *S. spinulosa* and *S. tetraceros* (Table 5). Dense aggregations *M. edulis*, which increased in size with depth (Centre for Marine and Coastal Studies Ltd, 2013) provided secondary substrate for other taxa. Patches of bryozoan and hydroid turf were recorded between mussel aggregations, although at greater relative abundance on IGE01 (Centre for Marine and Coastal Studies Ltd, 2013). In addition, mobile fauna, such as the common sea star *Asterias rubens*, and crabs *Cancer pagurus* and *Necora puber* were observed feeding within mussel aggregations (Centre for Marine and Coastal Studies Ltd, 2013).

Zonation with respect to depth, which has been well documented on offshore structures (Wolfson et al., 1979; Forteath et al., 1982; Guerin et al., 2007; Kerckhof et al., 2009; Mallat et al., 2014; De Mesel et al., 2015), was seen on the foundations (Table 5). The structure of the communities colonising the monopiles appeared to be similar down to approximately 9 m. For GAA02, below 9 m dense mussel growth gave way to ‘super abundant’ bryozoan turf with occasional anemones, *Metridium senile* and *Urticina felina*. For IGE01 mussel growth thinned and along with bryozoan and hydroid turf, was gradually replaced by *S. spinulosa* aggregations. Although there were fewer polychaetae species colonising the structures than soft sediments, below 23 m *S. spinulosa* dominated with encrusting sponges, hydroids, and anemones. *A. rubens* was commonly observed feeding on the *S. spinulosa* (Centre for Marine and Coastal Studies Ltd, 2013). Notably, from the NC perspective it could be argued that *S. spinulosa* colonising hard substrate may be of lower ecological value than aggregations in soft sediments. By occupying surface area on the turbine substructure their ability to build reefs and contribute to sediment stabilisation would be diminished.

Differences in community structure between GAA02 and IGE01 may be due to the different ages of the structures. IGE01 was installed early in the OWFs construction and was a year closer to the climax stage. When the structures have been in place for 6 years or longer the communities on the foundations are expected to be similar.

2.3. Identifying natural capital risks and opportunities

Through modifying benthic habitats, OWFs effect accessibility of resources and alter ecosystem functioning the delivery of ES (Hooper et al., 2017b; Causon and Gill, 2018). The NCC guidance calls for the development of a risk register to assess current and future likelihood and

Table 3
Post-installation relative abundance (SACFOR scale) of taxa recorded in both pre- and post-installation surveys of GG OWF. Changes in relative abundance from pre-installation are indicated by text colour (green = increase, red = decrease, black = no change) and adjacent numbers (SACFOR categories) respectively. *C1a and C1b habitat characteristic taxa.

Pre- and Post-installation Taxa				
Category	**Class**	**Taxon**	**Text colour**	**Change (SACFOR categories)**
Super Abundant (SA)				
Abundant (A)	Polychaeta	*Eunereis longissima*	black	
Abundant (A)	Polychaeta	*Glycera lapidum**	black	
Abundant (A)	Polychaeta	*Lanice conchilega**	black	
Abundant (A)	Polychaeta	*Marphysa sanguinea*	green	1
Abundant (A)	Polychaeta	*Paucibranchia bellii*	black	
Abundant (A)	Polychaeta	*Phyllodoce groenlandica**	black	
Abundant (A)	Polychaeta	*Spirobranchus triqueter**	green	2
Abundant (A)	Polychaeta	*Sthenelais boa*	green	1
Abundant (A)	Polychaeta	*Thelepus cincinnatus**	green	1
Common (C)	Ascidiacea	*Polycarpa fibrosa*	green	1
Common (C)	Ascidiacea	*Polycarpa pomaria*	green	1
Common (C)	Bivalvia	*Barnea candida*	black	
Common (C)	Bivalvia	Anomiidae	black	
Common (C)	Bivalvia	Mytilidae	black	
Common (C)	Echinoidea	*Psammechinus miliaris*	black	
Common (C)	Fibulariidae	*Echinocyamus pusillus*	black	
Common (C)	Malacostraca	*Ampelisca spinipes*	green	1
Common (C)	Malacostraca	*Callianassa subterranea*	black	
Common (C)	Malacostraca	*Pagurus bernhardus*	green	1
Common (C)	Malacostraca	*Pisidia longicornis*	black	
Common (C)	Malacostraca	*Upogebia deltaura*	black	
Common (C)	Ophiuroidea	*Amphipholis squamata*	red	1
Common (C)	Polychaeta	*Aonides oxycephala**	black	
Common (C)	Polychaeta	*Chaetozone zetlandica**	green	1
Common (C)	Polychaeta	*Clymenura* spp.	black	
Common (C)	Polychaeta	*Eteone* spp.*	green	1
Common (C)	Polychaeta	*Eulalia mustela**	black	
Common (C)	Polychaeta	*Glycera oxycephala**	black	
Common (C)	Polychaeta	*Goniada maculata*	green	1
Common (C)	Polychaeta	*Laonice bahusiensis**	red	1
Common (C)	Polychaeta	*Lepidonotus squamatus**	black	
Common (C)	Polychaeta	*Malmgrenia* spp.*	black	
Common (C)	Polychaeta	*Mediomastus fragilis**	black	
Common (C)	Polychaeta	*Nephtys cirrosa*	black	
Common (C)	Polychaeta	*Ophelia borealis*	black	
Common (C)	Polychaeta	*Ophiura albida*	black	
Common (C)	Polychaeta	*Owenia fusiformis*	green	1
Common (C)	Polychaeta	*Petaloproctus borealis*	black	
Common (C)	Polychaeta	*Poecilochaetus serpens**	black	
Common (C)	Polychaeta	*Polycirrus* spp.	black	
Common (C)	Polychaeta	*Pseudopotamilla reniformis*	black	
Common (C)	Polychaeta	*Sabella* spp.	black	
Common (C)	Polychaeta	*Sabellaria spinulosa**	black	
Common (C)	Polychaeta	*Scalibregma inflatum*	black	
Common (C)	Polychaeta	*Schistomeringos rudolphi*	black	
Common (C)	Polychaeta	*Spiophanes bombyx**	green	1
Common (C)	Polychaeta	*Spirobranchus lamarcki**	black	
Common (C)	Polychaeta	*Syllis armillaris**	black	
Common (C)	Polychaeta	*Syllis cornuta**	black	
Common (C)	Polychaeta	*Syllis variegata**	black	
Common (C)	Polychaeta	*Terebellides stroemii*	black	
Common (C)	Styelidae	*Dendrodoa grossularia*	green	1
Common (C)	Thecostraca	*Balanus crenatus*	green	2
Frequent (F)	Bivalvia	*Abra alba*	black	
Frequent (F)	Bivalvia	*Abra prismatica*	green	2
Frequent (F)	Bivalvia	*Diplodonta rotundata*	green	1
Frequent (F)	Bivalvia	*Nucula hanleyi*	green	1
Frequent (F)	Bivalvia	*Polititapes rhomboides*	black	
Frequent (F)	Bivalvia	*Sphenia binghami*	black	
Frequent (F)	Gastropoda	*Steromphala tumida*	green	1
Frequent (F)	Malacostraca	*Anthura gracilis*	black	
Frequent (F)	Malacostraca	*Ebalia tuberosa*	green	1
Frequent (F)	Malacostraca	*Ericthonius punctatus*	black	
Frequent (F)	Malacostraca	*Liocarcinus* spp.	black	
Frequent (F)	Malacostraca	*Pilumnus hirtellus*	black	
Frequent (F)	Malacostraca	*Pseudoprotella phasma*	black	
Frequent (F)	Malacostraca	*Unciola crenatipalma*	green	1
Frequent (F)	Polychaeta	*Amaeana trilobata**	black	
Frequent (F)	Polychaeta	*Ampharete lindstroemi*	black	
Frequent (F)	Polychaeta	*Asclerocheilus intermedius*	green	1
Frequent (F)	Polychaeta	*Autolytus* spp.*	green	1
Frequent (F)	Polychaeta	*Caulleriella alata*	black	
Frequent (F)	Polychaeta	Echiuridae	black	
Frequent (F)	Polychaeta	*Eumida* spp.*	black	
Frequent (F)	Polychaeta	*Glycinde nordmanni*	black	
Frequent (F)	Polychaeta	*Harmothoe extenuata**	black	
Frequent (F)	Polychaeta	*Harmothoe impar**	black	
Frequent (F)	Polychaeta	*Lagis koreni*	red	1
Frequent (F)	Polychaeta	*Lysidice unicornis*	black	
Frequent (F)	Polychaeta	*Nicolea venustula**	black	
Frequent (F)	Polychaeta	*Paradoneis lyra*	black	
Frequent (F)	Polychaeta	*Pisione remota*	black	
Frequent (F)	Polychaeta	*Polygordius* spp.	red	1
Frequent (F)	Polychaeta	*Scalibregma celticum**	black	
Frequent (F)	Polychaeta	Serpulidae*	black	
Frequent (F)	Polychaeta	*Thelepus setosus**	green	1
Frequent (F)	Polyplacophora	*Leptochiton asellus*	black	
Frequent (F)	Thecostraca	*Verruca stroemia*	black	
Occasional (O)	Bivalvia	*Asbjornsenia pygmaea*	black	
Occasional (O)	Bivalvia	*Goodallia triangularis*	green	1
Occasional (O)	Bivalvia	*Kurtiella bidentata*	red	1
Occasional (O)	Bivalvia	*Moerella donacina*	red	1
Occasional (O)	Bivalvia	*Nucula nucleus*	black	
Occasional (O)	Malacostraca	*Anapagurus hyndmanni*	green	1
Occasional (O)	Malacostraca	*Galathea intermedia*	red	1
Occasional (O)	Malacostraca	*Gammaropsis maculata*	black	
Occasional (O)	Malacostraca	*Ione thoracica*	green	1
Occasional (O)	Malacostraca	*Janira maculosa*	green	1
Occasional (O)	Malacostraca	*Maerella tenuimana*	black	
Occasional (O)	Malacostraca	*Monocorophium sextonae*	black	
Occasional (O)	Malacostraca	*Phtisica marina*	red	1
Occasional (O)	Malacostraca	*Stenothoe marina*	green	1
Occasional (O)	Malacostraca	*Urothoe brevicornis*	green	1
Occasional (O)	Malacostraca	*Urothoe elegans*	green	1
Occasional (O)	Malacostraca	*Urothoe marina*	green	1
Occasional (O)	Phoronida	*Phoronis* spp.	red	1
Occasional (O)	Polychaeta	*Aonides paucibranchiata**	red	2
Occasional (O)	Polychaeta	*Dipolydora coeca**	green	1
Occasional (O)	Polychaeta	*Pholoe baltica*	black	
Occasional (O)	Polychaeta	*Protodorvillea kefersteini*	red	1
Rare (R)	Malacostraca	*Abludomelita obtusata*	black	
Rare (R)	Malacostraca	*Leptocheirus hirsutimanus*	red	1
Rare (R)	Polychaeta	*Pholoe inornata*	red	1
Rare (R)	Polychaeta	*Sphaerosyllis bulbosa*	red	1
Rare (R)	Polychaeta	*Syllidia armata**	red	1
C/F	Ascidiacea	*Molgula* spp.	green	1
F/O	Gastropoda	*Onchidoris* spp.	red	1

Table 4
Results of c2m randomisation test where µ1 represents the pre-installation observed mean species richness and µ2 represents the post installation observed mean species richness.

µ1	28.237
µ2	25.727
µ1-µ2	2.510
p-value	0.291
Quantile 0.025	-8.588
Quantile 0.975	8.285
Randomised µ1-µ2	-0.024
Randomisations	10,000

scale of changes to the delivery of ES (Natural Capital Committee, 2017). Given reasonable estimates of quantity, quality, and spatial extent of NC assets, risks can be quantified as a product of trend in assets and the status of ES (Mace et al., 2015). However, inherent limitations in standard benthic sampling methodology meant that the quantity, quality, and extent of NC stocks associated with the seabed and benthic taxa could not be determined. Development of the risk register, which illustrates risks to the benthic asset-benefit relationship following the installation of GG OWF, was attempted (Table 6a) using evidence from the survey data in conjunction with published literature. Risks were evaluated with respect to their likelihood and the scale of their impact, designated small, medium, or large (Table 6b). Where changes were considered likely or very likely an indication of the expected direction of change (positive, negative, or strongly negative) was provided (Table 6c). Uncertainty in the assessment of risks was scored as low, moderate, or high depending on the strength of the evidence available (Table 6d).

The installation of GG OWF could potentially positively and negatively affect the delivery of ES. For example, it could have a positive effect on nutrient cycling and waste remediation through the displacement of fisheries (Table 6). Trawling causes physical damage to the seabed and mortality in non-target species, reducing biomass of benthic fauna, removing biogenic structures and resuspending contaminated sediments (Hutchings et al., 1990; Bergman and Hup, 1992; Auster et al., 1996; Watling and Norse, 1998; Kaiser et al., 2006). Turbine foundations present a hazard to fishing gear; concerns over safety, as well as legal and insurance reasons, have meant that fishers are reluctant to set gear within or near OWFs (Mackinson et al., 2006; Alexander et al., 2013; Hooper et al., 2015). As such, OWFs can provide benthic ecosystems with a reprieve from fishing pressure and offer an opportunity to recover. The recovery of suspension feeding fauna, including mussels, *S. spinulosa* and Serpulid polychaetes, inhabiting the benthos can improve water quality and facilitate transfer of organic matter and dissolved materials from the water column to sediments (Davies et al., 1989; Welsh, 2010; Pearce et al., 2011). Repeated high resolution acoustic surveys of the nearby Thanet OWF, using side-scan sonar and a multibeam echosounder, has indicated recovery of *S. spinulosa* reefs (Pearce et al., 2014). Prior to the construction of Thanet OWF, *S. spinulosa* reefs recorded in the south of the site decreased from 2.57 km^2 in 2005–0.48 km^2 in the 2007 pre-installation survey. It was suggested that the decline in *S. spinulosa* reefs occurred as a result of commercial fishing pressure (Pearce et al., 2014). Scars along the seabed, likely to have been caused by commercial fishing gear, were identified in high-resolution acoustic data (Marine Ecological Surveys Ltd, 2005, 2007). By 2012, after the installation of Thanet OWF, *S. spinulosa* reefs increased to 0.90 km^2 in the south. When considering the development site as a whole, *S. spinulosa* reefs had increased from 2.59 km^2 to 2.91 km^2 over the same period (Pearce et al., 2014).

From the data available there was no evidence of the recovery of *S. spinulosa* reefs or other biogenic structures on the seabed following the installation of GG OWF. However, surveys of GG OWF covered an area considerably smaller area than acoustic surveys at Thanet OWF. Although dense aggregations of *M. edulis* were recorded on both GAA02 and IGE01, any detectable change in water quality and nutrient cycling may only be in close proximity to the turbine foundations. Therefore, uncertainty in this assessment was considered to be moderate (Table 6a and c).

Table 5
Relative abundance of taxa colonising the turbines GAA02 and IGE01.

Turbine GAA02				Turbine IGE01			
Depth	Taxa	Relative abundance	Notes	Depth	Taxa	Relative abundance	Notes
Splash zone	Barnacles	C		Splash zone	Barnacles	C	
	Green algae				Green algae		
0–4 m	*Mytilus edulis*	S		0–6 m	*Mytilus edulis*	S	
	Hydroids	C			Bryozoa	F	Colonising mussel shell
	Bryozoan turf	O			Barnacles		
	Spirobranchus tetraceros				Hydroids		
	Ulva lactuca	R			Bryozoan turf	O	Thin layer
4.8–21.8 m	*Mytilus edulis*	S		6.1–8.7 m	*Mytilus edulis*	A	
	Cancer pagurus	C			Bryozoan turf	A/C	
	Necora puber				Hydroids		
	Bryozoan turf	R			Encrusting Porifera	O/R	Orange sponge
	Hydroids			9.2–18 m	*Mytilus edulis*	A	
23.6–27.6 m	Bryozoan turf	A			*Sabellaria spinulosa*		
	Spirobranchus tetraceros				Encrusting Porifera	O	Orange sponge
	Mytilus edulis	F			Bryozoa		
	Encrusting Porifera	O	Orange sponge		Hydroids		
28.7 m (base of monopile)	Bryozoan turf	S			*Necora puber*		
	Alcyonium digitatum	F		13–23.2 m	*Sabellaria spinulosa*	S/A	With overlying faunal turf
	Hydroids				Mytilus edulis	A	
	Spirobranchus tetraceros				Bryzoa	O	
	Encrusting Porifera	O	Orange sponge		*Spirobranchus tetraceros*		
	Metridium senile				*Asterias rubens*	C	
	Urticina felina				Encrusting Porifera		
Scour protection	Bryozoan turf	S		23.2–27.7 m	*Sabellaria spinulosa*	S	With overlying faunal turf
	Necora puber	C			*Asterias rubens*	O	
	Spirobranchus tetraceros	F			Ascidians		
	Barnacles	O			Hydroids		
				29 m (base of monopile)	*Urticina felina*	A	
					Metridium senile		
					Encrusting Ascidians		
					Encrusting Porifera		
					Sabellaria spinulosa	F/O	
					Spirobranchus tetraceros	O	
				Seabed	*Asterias rubens*	Single	Fine to medium sand, mussel shell.
					Necora puber		

Conversely, it was considered that displacement of fishing following the installation of GG OWF would negatively affect food provision in the area. In addition to preventing access to previously exploited fishing grounds, displacement of fishing activities to other areas may lead to competition between fishermen and detrimentally effect otherwise less impacted sensitive habitats (Gill et al., 2020). It has been argued that offshore wind farms can encourage recovery of commercially exploited fish stocks through overspill to surrounding areas (Busch et al., 2011; Langhamer, 2012; Lengkeek et al., 2013), which could enhance food provision. Yet, evidence of overspill has been inconclusive (Mangi, 2013). Also, intense fishing pressure around an OWF can continue (Langhamer, 2012; Roach et al., 2018), which may mean increases in catch per unit of effort (CPUE) remain localised. So, uncertainty in this assessment was high (Table 6a and c).

Offshore wind turbines introduce intertidal habitat which can provide opportunities for invasive non-native species (INNS) (Kerckhof et al., 2011; De Mesel et al., 2015), which may threaten commercially valuable native fauna (Shiganova et al., 2003; Nieweg et al., 2005; Javidpour et al., 2009). For example, pacific oyster, *Crassostrea gigas*, are thriving in the southern North Sea (Troost, 2010) and this species can compete with native *M. edulis* and has been shown to invade mussel beds in the Wadden Sea (Kochmann et al., 2008; Markert et al., 2010). Whilst both species may co-exist, exploitation of valuable coastal mussel beds is limited if they contain wild *C.* gigas, which are not of commercial value (Kerckhof et al., 2011). *C. gigas* has been shown to colonise turbine substructures in the southern North Sea, thus OWFs could act as footholds facilitating its spread (Kerckhof et al., 2011). This notwithstanding, surveys of the turbines GAA02 and IGE01 found no INNS colonising the foundations (Centre for Marine and Coastal Studies Ltd, 2013). As such, there is no evidence from the survey data to suggest delivery of ES would be changed by non-native species. Nonetheless, even if INNS had not colonised the turbine foundations at the time of the survey, this does not preclude them doing so in the future. It seems likely they would, given that colonisation of wind turbines by INNS has been well documented (Wilhelmsson and Malm, 2008; Kerckhof et al., 2011; Adams et al., 2014; De Mesel et al., 2015). For this reason, uncertainty in this finding was high (Table 6a and c).

During operation, turbines introduce mechanical noise from gears, generators, hydraulic systems, and rotor blades (Lindeboom et al., 2011). Noise levels from OWFs in production are lower than those emitted by pile driving during construction, and not significantly higher than background levels (Nedwell et al., 2007) but are long-term (Hawkins et al., 2014). Most noise emitted by operational offshore wind turbines is low frequency ($<$1000 Hz) and is detectable by sound sensitive fish and invertebrates over several kilometres (Andersson et al., 2011; Hawkins and Popper, 2017). Another chronic source of

Table 6
(a) Risks to the asset-benefit relationship associated with GG OWF assessed using evidence from the survey data and published literature. (b) Colour key for likelihood (Unlikely, Likely, or Very Likely) and scale of change (small = near turbine, medium = within or near OWF extent, large = far beyond OWF). (c) Direction of change (positive = P, negative = N, or strongly negative = SN). (d) Scoring system for epistemic uncertainty (1 = low, 2 = moderate, 3 = high) based on availability of evidence from data or published literature (modified from Algers et al., 2009).

(a)

	Fisheries displacement	Invasive species	Noise	EMF	Hydrodynamic flow change	Maintenance	Decommissioning
Cultural enjoyment	3	3	2	2	3	3	3
Equitable climate	1	1	1	1	1	1	1
Food	3N	3	2	2	3	3	3
Nutrient cycling	2P	3	2	2	3	3	2SN
Waste remediation	2P	3	2	2	3	3	2SN

		Scale of change		
		Small	Medium	Large
Likelihood of change	Unlikely			
	Likely			
	Very Likely			

(b)

Direction of change	Score
Positive	P
Negative	N
Strongly negative	SN

(c)

Evaluation	Score	Description
Low	1	Robust and complete data available; strong evidence in multiple references with most authors coming to the same conclusions; **or** considerable and consistent experience from field observations.
Moderate	2	Some or only incomplete data available; evidence provided in small number of references; authors' or experts' conclusions vary; **or** limited evidence from field observations; **or** solid and complete data available from other species which can be extrapolated to the species being considered.
High	3	Scarce or no data available; evidence provided in unpublished reports; **or** few observations and personal communications; **and/or** authors' or experts' conclusions vary considerably.

(d)

disturbance are submarine cables that interconnect turbines and transport energy onshore which generate electromagnetic fields (EMF) of a similar strength to that of the Earth's magnetic field (Walker, 2001; Gill et al., 2005, 2012; Hutchison et al., 2020). Cable EMFs interact with the Earth's magnetic field and have the potential to attract or repel EM-sensitive species, which are considered to be sensitive to the Earth's magnetic field (e.g., migratory fish, elasmobranchs, mammals, chelonians, and crustaceans) (Wiltschko and Wiltschko, 1995; Gill et al., 2012).

The effects of chronic exposure to turbine noise and EMF are unclear. Given the persistence of complex communities inhabiting the soft sediment and turbine substructures following the installation of the GG OWF (Tables 2, 3 and 5) it is unlikely that the provision of ES would be affected by turbine noise and EMF. With limited supporting empirical evidence there was moderate uncertainty in this assessment (Table 6a and c).

Turbulence resulting from local changes in hydrodynamic regimes, due to turbine foundations, cause resuspension of fine sediments which can reduce light penetration and smother existing benthic communities (Hiscock et al., 2002). At nearby Thanet OWF, plumes of suspended particulate matter > 10 km have been reported downstream of turbines (Vanhellemont and Ruddick, 2014). For Belwind OWF in Belgian waters, it was concluded that rather than scouring at the seabed resuspending sediment, organic matter deposited by epibenthic communities on the structure and scour protection were the main source of suspended particulate matter in plumes (Baeye and Fettweis, 2015). There is little information on how changes in hydrodynamic regime may influence NC. Again, given the persistence of complex communities within GG OWF it is unlikely that the delivery of ES would be affected by changes in hydrodynamic flow. However, with scarce information, uncertainty in this assessment was high (Table 6a and c).

Following the installation of multiple offshore wind turbines there would be the need for regular maintenance. Above the waterline, maintenance includes inspection, replacement of fluids and servicing of mechanical parts, and is typically carried out at 6-month intervals (Chan and Mo, 2017). Below the waterline, maintenance can include inspection and cleaning of the foundation (Buck and Langan, 2017). Whilst inspection of foundations is recommended after a period of 5–10 years (Buck and Langan, 2017) cleaning is likely to be an irregular activity. Although benthic organisms removed from the structure during cleaning would be deposited on the seabed, the biomass removed by cleaning over the life of the OWF would be low compared with typical levels deposited from epibenthic communities. Maintenance would result in increased vessel traffic, introducing additional noise to the environment. As vessels manoeuvre close to the turbines there is a risk of collision with the structure (Presencia and Shafiee, 2018). A ship-turbine collision could damage or destroy the foundation and could cause oil or chemical spills from the vessel (Presencia and Shafiee, 2018). Few ship-turbine collisions have been recorded, although this may be due to accidents going unreported (Presencia and Shafiee, 2018). As the offshore wind energy industry expands there would be an increase in the number of maintenance vessels close to turbines, increasing the risk of collisions and therefore the potential threat to the benthic communities present. Given its low frequency of occurrence, turbine maintenance in GG OWF was considered unlikely to change the delivery of ES. Although information was again scarce, so uncertainty in this assessment was high (Table 6a and c).

Impacts associated with construction of OWFs have received extensive coverage in the literature (Inger et al., 2009; Mueller-blenkle et al., 2010; Wilson et al., 2010; Perrow et al., 2011; Bailey et al., 2014). Yet the decommissioning process would also cause considerable disturbance to offshore ecosystems (Smyth et al., 2015; Fowler et al., 2018). Complete removal of wind turbine substructures and cables would temporarily cause destruction of the local seabed and benthic communities. This would resuspend contaminated sediments, potentially spread non-native species should they be present, and reduce biological connectivity (ETSU, 2000; Fowler et al., 2014, 2018), which is important when considering regional effects on community connection and spatial dispersal (Tidbury et al., 2020). Large plumes of suspended sediments may obstruct fish from feeding, and smother benthic communities and newly settled larvae (ETSU, 2000; Januario et al., 2007). Along with damage caused by the physical removal of the foundations, equipment used, such as jack-up vessels, anchors, and remote ploughs, would disturb the sediment and cause localised removal of benthic communities (Januario et al., 2007). The disposal of materials, such as turbine oil and coolants, onshore may pose further risk to the environment (Januario et al., 2007).

Removing substructures would also remove potential benefits associated with epibenthic communities upon them. For example, dense communities of deposit feeding organisms would be lost, which have a role in remediating waste and improving water quality (Iyer et al., 2005; Lange et al., 2010; Mangi, 2013; Hooper et al., 2017a). Moreover, removal of the turbines would allow some displaced fishing activities to recommence, which could result in sustained damage to the benthic habitat and loss of NC. Therefore, decommissioning was considered to have a strongly negative effect on the remediation of wastewater and nutrient cycling ES, for which uncertainty was moderate (Table 6a and c).

Owing to the shallow water it is unlikely that communities either on the turbine substructures or inhabiting the soft sediment within the OWF extent would make an effective contribution to long-term sequestration of atmospheric CO_2 ES. Thus, for all pressures associated with the installation of GG OWF the risk to the support of equitable climate would not change, for which uncertainty was low (Table 6a and c).

3. Discussion

The approach developed by the NCC is intended to enable decision-makers and stakeholders to improve the ability to protect and potentially enhance NC. However, application of this methodology in marine systems has been limited and the study here indicates that when applied to an OWF and the benthic NC there remains work to be done to address the limitations and knowledge gap to effectively enable a NC approach to be used.

Under the NCC guidance a natural asset register that is fit for purpose should include the quantity, quality, and extent of NC (Natural Capital Committee, 2017). Pre-construction baseline and post-installation monitoring surveys, routinely conducted under certain licensing conditions for OWF developments (Marine Management Organisation, 2014), are a useful source of data to compare changes in benthic communities. Nevertheless, limitations in the benthic sampling methodology meant that the true quantity, quality, and extent of NC stocks could not be determined. Pre- and post-construction benthic monitoring sampled from < 0.01 % of the respective 501.1 km^2 and 1362.7 km^2 pre- and post- construction survey area (based on measurements in QGIS version 3.14.0). Equally, only 2.2 % of the conservatively estimated 0.04 km^2 surface area introduced by turbines at GG OWF were sampled. In addition, the turbines had been installed approximately a year apart and their epibenthic communities were at different stages of maturity. The relatively small area, and few turbine substructures, sampled means that large gaps in our knowledge of NC before and after the installation of GG OWF exist.

An advantage of the risk register is that it can be compiled in absence of a full knowledge of the system, especially where expert opinion can provide indications of risk (Mace et al., 2015). This is particularly useful for marine systems where knowledge gaps exist. In terrestrial and freshwater systems proxies (habitats with similar biophysical components and processes) have been used to fill knowledge gaps (Mace et al., 2015). However, there are few suitable proxies for marine ecosystems due to a lack of available data and agreed methods to derive proxies (Medcalf et al., 2012). Using evidence from the pre- and post-installation survey data, the risk register (Table 6a) illustrates where current or potential declining trends in NC can affect the delivery of ES. Where knowledge gaps could not be addressed using evidence from the data, they were addressed through expert opinion and evidence from a review of published literature. The method was effective in demonstrating where changes, or potential changes, in NC could threaten the continued supply of benefits, albeit with varying degrees of uncertainty. It is not clear, for example, whether NC would be affected by noise and EMF introduced by an operational OWF. These effects have not been as intensively investigated as the effects as invasive species and fishing.

Further surveys would assist in filling knowledge gaps, however the methods and technology required would be prohibitively expensive (Medcalf et al., 2012). Remote sensing technology may assist in filling some knowledge gaps. For instance, sidescan sonar has been used to map *S. spinulosa* reefs (Pearce et al., 2014), measure seagrass cover (Greene et al., 2018), and to classify seabed topography and substrate (Fakiris et al., 2015; Buscombe, 2017). There are trade-offs; sidescan sonar can gather data on benthic communities over larger areas but cannot record species beneath the sediments. Therefore, a survey of benthic NC would require a mixture of remote sensing and physical sampling. This would provide greater information about NC stocks, but knowledge gaps would persist.

Natural thresholds, or tipping points, exist whereby a small change in conditions can lead to a large, irreversible change in structure or function of a system (Natural Capital Committee, 2017). Communities with greater species richness are typically more resilient to change because they exhibit higher functional diversity (Schmid et al., 2001; Palumbi et al., 2009). They are more likely to have multiple species that occupy the same niche, allowing ecological processes to continue if functional biodiversity is reduced (Ricotta et al., 2016). Monitoring and evaluating the condition of a system is important in establishing moderate and precautionary management strategies (Natural Capital Committee, 2017). Unfortunately, due to the limited coverage of sampling before and after the installation of GG OWF thresholds for natural capital could not be identified. It is thought that species richness would increase following construction of GG OWF as turbine substructures provide artificial hard substrate that are rapidly colonised. However, there was evidence that species richness in the soft sediments did not significantly change following the installation of GG OWF (Table 4). Based on the species richness alone it would be tempting to conclude that soft sediment communities would remain as resilient to further disturbance following construction of GG OWF as they were before. Yet, functional diversity is underpinned by the functional traits expressed within the community rather than species richness itself (Snelgrove, 1997; Díaz and Cabido, 2001; Schmid et al., 2001). Based on the available evidence it is unknown whether the shift in community structure would lead to a change in functional trait expression. Biological trait analysis (BTA) provides a method of reducing taxonomic diversity to functional diversity based on the expression of biological traits. Thus, with an appropriate set of data to assign traits to OWF associated benthic taxa, BTA could be used to quantify differences in functional diversity following the construction of GG OWF, allowing for risks to ecological resilience to be estimated.

Despite the challenges involved, there is good reason for establishing NC accounts for marine ecosystems. Natural capital accounts allow for development and implementation of management options to support and enhance NC. For OWFs this may mean initiatives such as co-use for decapod fisheries or mussel and oyster aquaculture. Co-location could mitigate some of the societal and economic impact on the fishing industry and help developers to engage with local fishing communities (Christie et al., 2014). Some developers have already taken steps to support commercially exploited decapod communities. Recently Ørsted used large stones of various sizes to create 25 artificial reefs at Anholt OWF in Denmark (Ørsted, 2019). It is expected that cavities would attract lobsters, crabs and Gadidae spp. (Ørsted, 2019). Were the status of NC known prior to reefs being constructed, monitoring changes in NC would demonstrate the effectiveness of such a strategy in sustaining resources. Indeed, after the Westernmost Rough OWF was opened to lobster fishing increases in CPUE were reported to be short-term. The unfished population of larger lobsters was rapidly reduced by intense fishing pressure (Roach et al., 2018).

As plans for decommissioning are generally included in the licensing and consent proposals for OWFs as part of the EIA process (Januario et al., 2007; Smyth et al., 2015) an NC approach could also support developers in making decisions about the end of life of an OWF. At present, decommissioning aims to return the habitat to preinstallation conditions and calls for full removal of structures from the seabed (Smyth et al., 2015; Fowler et al., 2018). For much of the southern North Sea this would mean returning the site to one with little hard substrate. This may have been the state prior to the installation of an OWF, but it does not necessarily reflect the state before negative impacts of human activity. There is evidence that hard substrate was once common in the southern North Sea. Historical maps show 20–35 % of the Dutch continental shelf was once covered by hard substrate, such as oyster beds and coarse peat banks (Olsen, 1883; Whitehead and Goodchild, 1909; Lengkeek et al., 2013). Oyster beds were largely lost due to overexploitation (Reise, 1982; Franke and Gutow, 2004). It is also understood that *Sabellaria* reefs were once more extensive in the North Sea and were lost due to fishing activities (Reise, 1982; de Groot, 1984). It is conceivable that ecological thresholds have already been exceeded. This would mean recovery to a habitat with substantially greater natural hard substrate is probably an unrealistic expectation.

Whilst well intentioned, the goal of restoring pre-installation conditions may be arbitrary and ultimately counterproductive. One thing that became apparent through this study was that OWFs provide a substantial amount of hard substrate. It was estimated here that the installation of the turbines could provide up to 20 times the surface area they occupy on the seabed. Although not equivalent in community structure to the habitat it replaces it may serve to enhance functioning in an already impacted ecosystem. Alternative options for the end of life for an OWF include repowering or replacing turbines, allowing for continued exploitation of wind resources (Smyth et al., 2015), and partial decommissioning. The latter has been applied to oil and gas structures under rigs-to-reefs programs in the US and similar programs throughout Southeast Asia (Cripps and Aabel, 2002; Macreadie et al., 2011). Dubbed renewables-to-reefs (Fowler et al., 2015; Smyth et al., 2015), partial decommissioning of an OWF involves removal of the structural elements above the waterline. Under this option, the foundations could be toppled in situ or cut close to the seabed, so as not to present a hazard to navigation (Smyth et al., 2015; Fowler et al., 2018). As zonation occurs in respect to depth on offshore structures (Wolfson et al., 1979; Forteath et al., 1982; Guerin et al., 2007; Kerckhof et al., 2009; Mallat et al., 2014; De Mesel et al., 2015) intertidal communities would be removed. As such, a partially decommissioned OWF may differ from an active OWF in the delivery of ES. Nonetheless, much of the artificial habitat, and associated NC, would remain whilst mitigating further habitat disturbance.

Recent updates to guidelines acknowledge the potential for colonisation of structures to provide ecological benefit, as well as risks to the environment from decommissioning. For instance, under the UK Energy Act 2004 alternatives to complete decommissioning may be considered, amongst other reasons, if the structure can be re-used or serves a new use, or if removal presents an unacceptable risk to personnel or the environment (Department of Energy and Climate Change, 2011). However, without considerable revision to current policies alternative decommissioning strategies are unlikely to become common practice. The NC approach could provide a much-needed shift from the conservation perspective to one that is ecosystem-based which recognises ES and acknowledges that the pre-development seabed may already be impacted from human activities.

4. Conclusion

It is increasingly being recognised that to maintain the benefits society receives from nature NC must be protected and enhanced. The NCC methodology was intended to provide a framework through which trends in NC could be established and included within decision making processes. This critical evaluation of the NCC methodology demonstrated its limitations in assessing marine NC stocks associated with an OWF. A comprehensive asset register showing stocks of seabed and benthos NC could not be compiled using pre- and post-installation survey data as samples did not cover a large enough area. Moreover, information from similar habitats was not sufficient to be applied as proxies. To fill these knowledge gaps, comprehensive surveys of benthic NC beyond the scope of current pre- and post-installation monitoring practices would be required. To do this using standard sampling tools would be prohibitively expensive and impractical. Surveys of NC would require using multiple sampling techniques to greatly improve our knowledge of benthic NC, but some knowledge gaps are likely to persist.

Although still hampered by knowledge gaps, the asset risk register allowed for greater quantitative and qualitative information to be incorporated in its development, along with expert opinion. From this, the likelihood and scale of certain risks could be reasonably estimated and used to inform decisions regarding options to enhance NC within GG OWF and mitigate impacts. Thus, the NC approach (building on the ecosystem approach) would appear to be a suitable method to further enable policy makers, developers, and stakeholders to invest in nature.

CRediT authorship contribution statement

Paul Causon: conceptualisation, methodology, investigation, writing, review and editing. Simon Jude: conceptualisation, methodology, writing, review and editing, PhD review panel. Andrew Gill: conceptualisation, methodology, writing, review and editing, supervision, funding acquisition. Paul Leinster: conceptualisation, methodology, review, 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.

Acknowledgements

This work was supported by grant EP/L016303/1 for Cranfield University, Centre for Doctoral Training in Renewable Energy Marine Structures (REMS) (http://www.rems-cdt.ac.uk/) from the UK Engineering and Physical Sciences Research Council (EPSRC). The author would like to the Centre for Marine and Coastal Studies (CMACS) Ltd for making their data available for this research.

References

4C Offshore , 2021 Vinyard Wind 1. ⟨https://www.4coffshore.com/windfarms/united-states/vineyard-wind-1-united-states-us0g.html⟩ (accessed 6 February 2021).
Adams, T.P., Miller, R.G., Aleynik, D., Burrows, M.T., 2014. Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. J. Appl. Ecol. 51, 330–338.
Alexander, K.A., Potts, T., Wilding, T.A., 2013. Marine renewable energy and Scottish west coast fishers: exploring impacts, opportunities and potential mitigation. Ocean Coast. Manag. 75, 1–10.
Algers, B., Blokhuis, H.J., Bøtner, A., Broom, D.M., Costa, P., Domingo, M., Greiner, M., Hartung, J., Koenen, F., Müller-Graf, C., Morton, D.B., Osterhaus, A., Pfeiffer, D.U., Raj, M., Roberts, R., Sanaa, M., Salman, M., Sharp, J.M., Vannier, P., Wierup, M., 2009. Species-specific welfare aspects of the main systems of stunning and killing of farmed eels (Anguilla anguilla): scientific opinion of the panel on animal health and welfare. EFSA J. 1014, 1–42.
Andersson, M.H., Sigray, P., Persson, L.K.G., 2011. Operational wind farm noise and shipping noise compared with estimated zones of audibility for four species of fish. J. Acoust. Soc. Am. 129, 2498. https://doi.org/10.1121/1.3588249.
Auster, P.J., Malatesta, R.J.R.W.L., Watting, L., Valentine, P.C., Donaldson, C.L.S., Langton, E.W., Shepard, A.N., Babb, W.G., 1996. The impacts of mobile fishing gear on seafloor habitats in the Gulf of Maine (Northwest Atlantic): implications for conservation of fish populations. Rev. Fish. Sci. 4, 185–202.
Australian Bureau of Statistics , 2017. Experimental environmental-economic accounts for the great barrier reef. ⟨https://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/4680.0Main+Features12017?OpenDocument⟩ (accessed 27 April 2020).
Baeye, M., Fettweis, M., 2015. In situ observations of suspended particulate matter plumes at an offshore wind farm, southern North Sea. Geo-Mar. Lett. 35, 247–255.
Bailey, H., Brookes, K.L., Thompson, P.M., 2014. Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future. Aquat. Biosyst. 10, 8.
Bergman, M.J.N., Hup, M., 1992. Direct effects of beamtrawling on macrofauna in a sandy sediment in the southern North Sea. ICES J. Mar. Sci. 49, 5–11.
Boehlert, G.W., Gill, A.B., 2010. Environmental and ecological effects of ocean renewable energy development: a current synthesis. Oceanography 23, 68–81.
Böhnke-Henrichs, A., Baulcomb, C., Koss, R., Hussain, S.S., de Groot, R.S., 2013. Typology and indicators of ecosystem services for marine spatial planning and management. J. Environ. Manag. 130, 135–145.
Buck, B.H., Langan, R., 2017. Aquaculture Perspective of Multi-use Sites in the Open Ocean. Springer Open.
Busch, M., Gee, K., Burkhard, B., Lange, M., Stelljes, N., 2011. Conceptualizing the link between marine ecosystem services and human well-being: the case of offshore wind farming. Int. J. Biodivers. Sci. Ecosyst. Serv. Manag. 7, 1–14.
Buscombe, D., 2017. Shallow water benthic imaging and substrate characterization using recreational-grade sidescan-sonar. Environ. Model Softw. 89, 1–18.
Causon, P.D., Gill, A.B., 2018. Linking ecosystem services with epibenthic biodiversity change following installation of offshore wind farms. Environ. Sci. Policy 89, 340–347.
Centre for Marine and Coastal Studies Ltd, 2005. Great Gabbard Offshore Wind Farm Marine Ecology EIA: Interim Technical Report of Benthic Grab Survey.
Centre for Marine and Coastal Studies Ltd, 2013 Greater Gabbard Offshore Wind Farm: Post-construction Turbine Colonisation Survey.
Centre for Marine and Coastal Studies Ltd, 2014. Greater Gabbard Offshore Wind Farm: Year 1 Post-construction Benthic Ecology Monitoring Survey.
Chan, D., Mo, J., 2017. Life cycle reliability and maintenance analyses of wind turbines. Energy Procedia 110, 328–333.
Christie, N., Smyth, K., Barnes, R., Elliott, M., 2014. Co-location of activities and designations: a means of solving or creating problems in marine spatial planning? Mar. Policy 43, 254–261.
Committee on Climate Change , 2019a. Net Zero: The UK's contribution to stopping global warming.
Committee on Climate Change , 2019b. Reducing UK emissions - 2019 Progress Report to Parliament.
Connors E. , 2016. Scoping UK coastal margin ecosystem accounts.
Cooper, K.M., Barry, J., 2017. A big data approach to macrofaunal baseline assessment, monitoring and sustainable exploitation of the seabed. Sci. Rep. 7, 1–18.
Cooper, K.M., Bolam, S.G., Downie, A.L., Barry, J., 2019. Biological-based habitat classification approaches promote cost-efficient monitoring: an example using seabed assemblages. J. Appl. Ecol. 56, 1085–1098.
Costanza, R., Daly, H.E., 1992. Natural capital and sustainable development. Conserv Biol. 6, 37–46.
Costanza R., Anderson S., Bohensky E., Butler J., Howe S., Kirkman H., Kubiszewski I., Pert P. , 2014a. Ecosystem services from healthy cceans and coasts: white paper to support the national marine science plan.
Costanza, R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R., Paruelo, J., Raskin, R., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014b. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158.
Cripps, S.J., Aabel, J.P., 2002. Environmental and socio-economic impact assessment of Ekoreef, a multiple platform rigs-to-reefs development. ICES J. Mar. Sci. 59, S300–S308.
Dasgupta P. , 2020. The Economics of Biodiversity: The Dasgupta Review. Abridged Version.
Davies, B., Stuart, V., de Villiers, M., 1989. The filtration activity of a serpulid polychaete population (Ficopomatus enigmaticus (Fauvel) and its effects on water quality in a coastal marina. Estuar. Coast Shelf Sci. 29, 613–620.
De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., Degraer, S., 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia 756, 37–50.
De Smet, B., Godet, L., Fournier, J., Desroy, N., Jaffré, M., Vincx, M., Rabaut, M., 2013. Feeding grounds for waders in the Bay of the Mont Saint-Michel (France): the Lanice conchilega reef serves as an oasis in the tidal flats. Mar. Biol. 160, 751–761.
Degraer, S., Moerkerke, G., Rabaut, M., Hoey, G., Van, Du, Vincx, I., Henriet, M., Lancker, J., Van, V., 2008. Very-high resolution side-scan sonar mapping of biogenic reefs of the tube-worm Lanice conchilega. Remote Sens Environ. 112, 3323–3328.
Degraer, S., Carey, D.A., Coolen, J.W.P., Hutchison, Z.L., Kerckhof, F., Rumes, B., Vanaverbeke, J., 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: a synthesis. Oceanography 33, 48–57.
Department of Energy and Climate Change , 2011. Decommissioning of offshore renewable energy installations under the Energy Act 2004. 1–62.
Díaz, H., Guedes Soares, C., 2020. Review of the current status, technology and future trends of offshore wind farms. Ocean Eng. 209, 107381.
Díaz, S., Cabido, M., 2001. Vive la différence: plant functional diversity matters to ecosystem processes. Trends Ecol. Evol. 16, 646–655.
ETSU, 2000. An assessment of the environmental effects of offshore wind farms - ETSU W/35/00543/REP.
European Commission, 2015. EU ecosystem accounting The 'INCA KIP': Knowledge Innovation Project for an Integrated system for Natural Capital and ecosystem services Accounting. 2:106.
European Commission , 2020. Boosting Offshore Renewable Energy for a Climate Neutral Europe. ⟨https://ec.europa.eu/commission/presscorner/detail/en/IP_20_2096⟩ (accessed 9 February 2021).
Fakiris, E., Zoura, D., Papatheodorou, G., Ferentinos, G., 2015. Automatic benthic habitat maping in Lourdas gulf, Kefalonia, combining side-scan sonar and sub-bottom profiler data. In: Proceedings of the 11th Panhellenic Symposium on Oceanography and Fisheries, Mytilene, Lesvos Island, Greece. pp. 1017–1020.
Forteath, G., Picken, G., Ralph, R., Williams, J., 1982. Marine growth studies on the North Sea oil platform Montrose Alpha. Mar. Ecol. Prog. Ser. 8, 61–68.
Fowler, A.M., Macreadie, P.I., Jones, D.O.B., 2014. A multi-criteria decision approach to decommissioning of offshore oil and gas infrastructure. Ocean Coast Manag. 87, 20–29.
Fowler, A.M., Macreadie, P.I., Booth, D.J., 2015. Renewables-to-reefs: participatory multicriteria decision analysis is required to optimize wind farm decommissioning. Mar. Pollut. Bull. 98, 368–371.
Fowler, A.M., Jørgensen, A.M., Svendsen, J.C., Macreadie, P.I., Jones, D.O., Boon, A.R., Booth, D.J., Brabant, R., Callahan, E., Claisse, J.T., Dahlgren, T.G., Degraer, S., Dokken, Q.R., Gill, A.B., Johns, D.G., Leewis, R.J., Lindeboom, H.J., Linden, O., May, R., Murk, A.J., Ottersen, G., Schroeder, D.M., Shastri, S.M., Teilmann, J., Todd, V., Van Hoey, G., Vanaverbeke, J., Coolen, J.W., 2018. Environmental benefits of leaving offshore infrastructure in the ocean. Front. Ecol. Environ.
Franke, H.D., Gutow, L., 2004. Long-term changes in the macrozoobenthos around the rocky island of Helgoland (German Bight, North Sea). Helgol. Mar. Res. 58, 303–310.
Gill A., Gloyne-Phillips I., Neal K., Kimber J. , 2005. The potential effects of electromagnetic fields generated by sub-sea power cables associated with offshore wind farm developments on electrically and magnetically sensitive marine organisms – a review.
Gill, A.B., Degraer, S., Lipsky, A., Mavraki, N., Methratta, E., Brabant, R., 2020. Special issue on understanding the effects of offshore wind energy development on fisheries setting the context for offshore wind development effects on fish and fisheries. Oceanography 33, 118–127.
Gill, A.B., Huang, Y., Spencer, J., Gloyne-philips, I., 2012. Electromagnetic fields emitted by high voltage alternating current offshore wind power cables and interactions with marine organisms. In: Proceedings of the electromagnetics in Current and Emerging Energy and Power Systems Seminar, Institution of Engineering and Technology. pp. 1–5.
Government of Republic Korea , 2020. National Strategy for Great Transformation: KOREAN NEW DEAL.
Graveland, C., Remme, R., Schenau, S., 2017. Exploring the possible setup and uses of natural capital accounts for the Dutch North Sea area.
Greater Gabbard Offshore Winds Ltd , 2013. Greater Gabbard Offshore Wind Farm environmental statement. 672.
Greene, A., Faiz, A., Kline, R., Rahman, S., 2018. Estuarine, coastal and shelf science side scan sonar: a cost-efficient alternative method for measuring seagrass cover in shallow environments. Estuar. Coast. Shelf Sci. 207, 250–258.
de Groot, S.J., 1984. The impact of bottom trawling on benthic fauna of the North Sea. Ocean Manag. 9, 177–190.
Guerin, A., Jensen, A., Jones, D., 2007. Artificial reef properties of North Sea oil and gas production platforms. Ocean 1–6.
GWEC , 2020a. Global Offshore Wind: Annual Market Report 2020.
GWEC , 2020b. Wind Power a cornerstone of the Global Economic Recovery Wind: 'Re-building Better' for the future.
Hattam, C., Atkins, J.P., Beaumont, N., Börger, T., Böhnke-Henrichs, A., Burdon, D., De Groot, R., Hoefnagel, E., Nunes, P.A.L.D., Piwowarczyk, J., Sastre, S., Austen, M.C., 2015. Marine ecosystem services: Linking indicators to their classification. Ecol. Indic. 49, 61–75.
Hawkins, A.D., Popper, A.N., 2017. A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. ICES J. Mar. Sci. 74, 635–651.

Hawkins, A.D., Pembroke, A.E., Popper, A.N., 2014. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish. Biol. Fish. 25, 39–64.
Hinterberger, F., Luks, F., Schmidt-bleek, F., 1997. Material flows vs. 'natural capital' What makes an economy sustainable? Ecol. Econ. 23, 1–14.
Hiscock K. , 1996. Marine Nature Conservation Review: Rationale and methods.
Hiscock K., Tyler-Walters H., Jones H. , 2002. High level environmental screening study for offshore wind farm developments–marine habitats and species project.
Hooper, T., Ashley, M., Austen, M., 2015. Perceptions of fishers and developers on the co-location of offshore wind farms and decapod fisheries in the UK. Mar. Policy 61, 16–22.
Hooper, T., Beaumont, N., Griffiths, C., Langmead, O., Somerfield, P.J., 2017a. Assessing the sensitivity of ecosystem services to changing pressures. Ecosyst. Serv. 24, 160–169.
Hooper, T., Beaumont, N., Hattam, C., 2017b. The implications of energy systems for ecosystem services: a detailed case study of offshore wind. Renew. Sustain Energy Rev. 70, 230–241.
Hutchings, P., Museum, T.A., Box, P.O.A., South, S., 1990. Review of the effects of trawling on macrobenthic epifaunal communities. Aust. J. Mar. Freshw. Res. 41, 111–120.
Hutchison, Z.L., Gill, A.B., Sigray, P., He, H., King, J.W., 2020. Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. Sci. Rep. 10, 1–15.
Inger, R., Attrill, M.J., Bearhop, S., Broderick, A.C., James Grecian, W., Hodgson, D.J., Mills, C., Sheehan, E., Votier, S.C., Witt, M.J., Godley, B.J., 2009. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. J. Appl. Ecol. 1145–1153.
Iyer, A., Mody, K., Jha, B., 2005. Biosorption of heavy metals by a marine bacterium. Mar. Pollut. Bull. 50, 340–343.
Januario C., Semino S., Bell M. , 2007. Offshore windfarm decommissioning: a proposal for guidelines to be included in the European Maritime Policy. EWEC.
Javidpour, J., Molinero, J.C., Lehmann, A., Hansen, T., Sommer, U., 2009. Annual assessment of the predation of Mnemiopsis leidyi in a new invaded environment, the Kiel Fjord (Western Baltic Sea): a matter of concern? J. Plankton Res. 31, 729–738.
Judd, A., Lonsdale, J.-A., 2021. Applying systems thinking: the ecosystem approach and natural capital approach – convergent or divergent concepts in marine management? Mar. Policy 129. https://doi.org/10.1016/j.marpol.2021.104517.
Kaiser, M.J., Clarke, K.R., Hinz, H., 2006. Global analysis of response and recovery of benthic biota to fishing. Mar. Ecol. Prog. Ser. 311, 2006.
Kerckhof, F., Norro, A., Jacques, T., & Degraer, S., 2009. Early colonisation of a concrete offshore windmill foundation by marine biofouling on the Thornton Bank (southern North Sea). Offshore wind farms in the Belgian part of the North Sea: State of the art after two years of environmental monitoring. Degraer, S., Brabant, R. (Eds.) Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Marine Ecosystem Management Unit, 2009: 39-51.
Kerckhof, F., Degraer, S., Norro, A., and Rumes, B., 2011. Offshore intertidal hard substrata: a new habitat promoting non-indigenous species in the Southern North Sea: an exploratory study. Offshore wind farms in the Belgian Part of the North Sea: Selected findings from the baseline and targeted monitoring. Degraer, S., Brabant, R., and Rumes, B. (Eds.), Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Marine Ecosystem Management Unit, 2011: 27-37.
Kerckhof, F., Rumes, B., & Degraer, S., 2019. About "mytilisation" and "slimeification": A decade of succession of the fouling assemblages on wind turbines off the Belgian coast. Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Marking a Decade of Monitoring, Research and Innovation. Degraer, S., Brabant, R., Rumes, B., and Vigin, L. (Eds.), Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management, Brussels 2019: 73-84.
Kochmann, J., Buschbaum, C., Volkenborn, N., Reise, K., 2008. Shift from native mussels to alien oysters: differential effects of ecosystem engineers. J. Exp. Mar. Biol. Ecol. 364, 1–10.
Lange M., Burkhard B., Garthe S., Gee K., Kannen A., Lenhart H., Windhorst W. , 2010. Analyzing coastal and marine changes - offshore wind farming as a case study - coastal futures, synthesis report.
Langhamer, O., 2012. Artificial reef effect in relation to offshore renewable energy conversion: state of the art. Sci. World J. 2012, e386713.
Lengkeek, W., Coolen, J.W.P., Gittenberger, A., Schrieken, N., 2013. Ecological relevance of shipwrecks in the North Sea. Ned. Faun. Meded. 40, 49–58.
Lindeboom, H.J., Kouwenhoven, H.J., Bergman, M.J.N., Bouma, S., Brasseur, S., Daan, R., Fijn, R.C., De Haan, D., Dirksen, S., Van Hal, R., Hille Ris Lambers, R., Ter Hofstede, R., Krijgsveld, K.L., Leopold, M., Scheidat, M., 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. Environ. Res. Lett. 6, 035101.
Liquete, C., Piroddi, C., Drakou, E.G., Gurney, L., Katsanevakis, S., Charef, A., Egoh, B., 2013. Current status and future prospects for the assessment of marine and coastal ecosystem services: a systematic review. PLOS One 8, 1–15.
Mace, G.M., Hails, R.S., Cryle, P., Harlow, J., Clarke, S.J., 2015. Towards a risk register for natural capital. J. Appl. Ecol. 52, 641–653.
Mackinson, S., Curtis, H., Brown, R., Mctaggart, K., Taylor, N., Neville, S., Rogers, S., 2006. A report on the perceptions of the fishing industry into the potential socio-economic impacts of offshore wind energy developments on their work patterns and income.
Macreadie, P.I., Fowler, A.M., Booth, D.J., 2011. Rigs-to-reefs: Will the deep sea benefit from artificial habitat? Front. Ecol. Environ. 9, 455–461.
Maddock A. , 2008. UK biodiversity action plan priority habitat descriptions (updated 2011).
Mallat, C., Corbett, A., Harris, G., Lefranc, M., 2014. Marine growth on North Sea fixed steel platforms - Insights from the decommissioning industry. In: Proceedings of the ASME 2014 33rd International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers. June 8–1:1–10.
Mangi, S.C., 2013. The impact of offshore wind farms on marine ecosystems: a review taking an ecosystem services perspective. Proc. IEEE 101, 999–1009.
Marine Data Exchange , 2020. ⟨https://www.marinedataexchange.co.uk/⟩ (accessed 23 December, 2020).
Marine Ecological Surveys Ltd , 2005. Thanet Offshore Windfarm Benthic and Intertidal Resource Survey.
Marine Ecological Surveys Ltd , 2007. Thanet Offshore Windfarm Benthic and Conservation Resources Survey.
Marine Management Organisation , 2014. Review of post-consent offshore wind farm monitoring data associated with licence conditions.
Markert, A., Wehrmann, A., Kröncke, I., 2010. Recently established Crassostrea-reefs versus native Mytilus-beds: differences in ecosystem engineering affects the macrofaunal communities (Wadden Sea of Lower Saxony, southern German Bight). Biol. Invasions 12, 15–32.
Medcalf, K., Small, N., Finch, C., Parker, J., 2012. Spatial framework for assessing evidence needs for operational ecosystem approaches, JNCC Report No: 469.
Ministère de la transition écologique et solidaire , 2019. PROJET DE LOI énergie-climat.
Mueller-blenkle C., Mcgregor P.K., Gill A.B., Andersson M.H., Metcalfe J., Bendall V., Sigray P., Wood D., Thomsen F. , 2010. Effects of pile-driving noise on the behaviour of marine fish. COWRIE Ref: Fish 06–08, Technical Report 31st March 2010.
National Infrastructure Commission , 2021. Natural Capital and Environmental Net Gain.
Natural Capital Committee , 2014. The state of natural capital: restoring our natural assets.
Natural Capital Committee , 2017. How to do it: a natural capital workbook.
Nedwell J.R., Parvin S.J., Edwards B., Workman R., Brooker A.G., Kynoch J.E. , 2007. Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters.
New Zealand Government , 2019. Climate change response (Zero Carbon) Amendment Act 2019.
Nieweg, D.C., Post, J.N.J., Vink, R.J., Muricidae, G., 2005. Rapana venosa (Gastropoda: Muricidae): a new invasive species in the North Sea. DEINSEA 11, 169–174.
Office for National Statistics , 2018. UK natural capital: Ecosystem service accounts, 1997 to 2015.
Olsen O.T. , 1883. The piscatorial atlas of the North Sea, English and St. George's Channels, illustrating the fishing ports, boats, gear, species of fish (how, where, and when caught), and other information concerning fish and fisheries. Taylor and Francis, London.
Ørsted , 2019. Respecting the natural environment. ⟨https://orsted.tw/en/About-us/Environment⟩ (accessed 16 August 2019).
Palumbi, S.R., Sandifer, P.A., Allan, J.D., Beck, M.W., Fautin, D.G., Fogarty, M.J., Halpera, B.S., Incze, L.S., Leong, J.A., Norse, E., Stachowicz, J.J., Wall, D.H., 2009. Managing for ocean biodiversity to sustain marine ecosystem services. Front. Ecol. Environ. 7, 204–211.
Pearce B., Hill J., Wilson C., Griffin R., Earnshaw S., Pitts J. , 2011. Sabellaria spinulosa Reef Ecology and Ecosystem Services Marine Research Report.
Pearce, B., Farinas-Franco, J.M., Wilson, C., Pitts, J., DeBurgh, A., Somerfield, P.J., 2014. Repeated mapping of reefs constructed by Sabellaria spinulosa Leuckart 1849 at an offshore wind farm site. Cont. Shelf Res. 83, 3–13.
Perrow, M.R., Gilroy, J.J., Skeate, E.R., Tomlinson, M.L., 2011. Effects of the construction of Scroby Sands offshore wind farm on the prey base of little tern Sternula albifrons at its most important UK colony. Mar. Pollut. Bull. 62, 1661–1670.
Petersen, B., Exo, K., 1999. Predation of waders and gulls on Lanice conchilega tidal flats in the Wadden Sea. Mar. Ecol. Prog. Ser. 178, 229–240.
Picone, F., Buonocore, E., Agostaro, R.D., Donati, S., Chemello, R., 2017. Integrating natural capital assessment and marine spatial planning: a case study in the Mediterranean sea. Ecol. Model. 361, 1–13.
Presencia, C.E., Shafiee, M., 2018. Risk analysis of maintenance ship collisions with offshore wind turbines. Int. J. Sustain Energy 37, 576–596.
Rabauta, M., Calderóna, M.A., Moortel, L., Van de, Dalfsen, J., van, Vincx, M., Degraer, S., Desroy, N., 2013. The role of structuring benthos for juvenile flatfish. J. Sea Res. 84, 70–76.
Reid W.V., Mooney H.A., Cropper A., Capistrano D., Carpenter S.R., Chopra K., Dasgupta P., Dietz T., Duraiappah A.K., Hassan R., Kasperson R., Leemans R., May R.M., McMichael T.A.J., Pingali P., Samper C., Scholes R., Watson R.T., Zakri A.H., Shidong Z., Ash N.J., Bennett E., Kumar P., Lee M.J., Ciara Raudsepp-Hearne H.S., Thonell J., Zurek M.B. , 2005. Millennium ecosystem assessment, 2005. Ecosystems and human well-being: synthesis. World Resources Institute.
Reise, K., 1982. Long-term changes in the macrobenthic invertebrate fauna of the Wadden Sea: are polychaetes taking over? Netherlands. J. Sea Res. 36, 29–36.
Ricotta, C., de Bello, F., Moretti, M., Caccianiga, M., Cerabolini, B.E.L., Pavoine, S., 2016. Measuring the functional redundancy of biological communities: a quantitative guide. Methods Ecol. Evol. 7, 1386–1395.
Roach, M., Cohen, M., Forster, R., Revill, A.S., Johnson, M., 2018. The effects of temporary exclusion of activity due to wind farm construction on a lobster (Homarus gammarus) fishery suggests a potential management approach. ICES J. Mar. Sci. 75, 1416–1426.
Schmid, B., Tilman, D., Wardle, D.A., 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 294 (80-), 804–809.
Sea Impact , 2021. Sea Map. ⟨https://sea-impact.com/map/⟩ (accessed 7 April 2021).
Shiganova, T.A., Musaeva, E.I., Bulgakova, Y.V., Mirzoyan, Z.A., Martynyuk, M.L., 2003. Invaders Ctenophores Mnemiopsis leidyi (A. Agassiz) and Beroe ovata Mayer 1912,

and their influence on the pelagic ecosystem of northeastern Black Sea. Biol. Bull. 30, 225–235.
Smart, D.E., Stojanovic, T.A., Warren, C.R., 2014. Is EIA part of the wind power planning problem? Environ. Impact Assess. Rev. 49, 13–23.
Smyth, K., Christie, N., Burdon, D., Atkins, J.P., Barnes, R., Elliott, M., 2015. Renewables-to-reefs? – decommissioning options for the offshore wind power industry. Mar. Pollut. Bull. 90, 247–258.
Snelgrove, P.V.R., 1997. The importance of marine sediment biodiversity in ecosystem processes. Ambio 26, 578–583.
Swedish Environmental Protection Agency , 2020. Sweden's climate act and climate policy framework. 〈http://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedish-environmental-work/Work-areas/Climate/Climate-Act-and-Climate-policy-framework-/〉 (accessed 2 February 2021).
The Crown Estate , 2020. Marine Data Exchange. 〈http://www.marinedataexchange.co.uk/〉 (accessed 23 December 2020).
Tidbury, H., Taylor, N., van der Molen, J., Garcia, L., Posen, P., Gill, A., Lincoln, S., Judd, A., Hyder, K., 2020. Social network analysis as a tool for marine spatial planning: Impacts of decommissioning on connectivity in the North Sea. J. Appl. Ecol. 57, 566–577.
Troost, K., 2010. Causes and effects of a highly successful marine invasion: Case-study of the introduced Pacific oyster Crassostrea gigas in continental NW European estuaries. J. Sea Res. 64, 145–165.
UK Government , 2017. Guidance: Environmental Impact Assessment. 〈https://www.gov.uk/guidance/environmental-impact-assessment#the-purpose-of-environmental-impact-assessment〉 (accessed 3 February 2019).
UK Government , 2019. Industrial strategy-Offshore wind sector deal.
UK Government , 2020. The Ten Point Plan for a Green Industrial Revolution.
UNEP , 2006. Marine and coastal ecosystems and human well-being: A synthesis report based on the findings of the Millenium Ecosystem Assessment.
Vanhellemont, Q., Ruddick, K., 2014. Turbid wakes associated with offshore wind turbines observed with Landsat 8. Remote Sens. Environ. 145, 105–115.
Vattenfall Wind Power Ltd , 2017. Thanet extension offshore wind farm: marine geology, oceanography and physical processes technical report.
Vineyard Wind L.L.C. , 2021. Vineyard Wind 1. 〈https://www.vineyardwind.com/vineyard-wind-1〉 (accessed 16 February 2021).
Walker T. , 2001. Review of impacts of high voltage direct current sea cables and electrodes on Chondrichthyan fauna and other marine life [Basslink Supporting Study No. 29. Marine and Freshwater Resources Institute No. 20].
Watling, L., Norse, E., 1998. Disturbance of the seabed by mobile fishing gear: A comparison to forest clear cutting. Conserv Biol. 12, 1180–1197.
Weatherdon L.V., Friedrich L.A., Martin C.S., King S. , 2017. Experimental Seagrass Ecosystem Accounts: A pilot study for one component of marine ecosystem accounts.
Welsh, D.T., 2010. It's a dirty job but someone has to do it: The role of marine benthic macrofauna in organic matter turnover and nutrient recycling to the water column. Chem. Ecol. 19, 321–342.
Whitehead, H., Goodchild, H.H., 1909. Some notes on moorlog, a peaty deposit from the Dogger Bank in the North Sea. Essex Nat. 16, 51–60.
Wilhelmsson, D., Malm, T., 2008. Fouling assemblages on offshore wind power plants and adjacent substrata. Estuar. Coast. Shelf Sci. 79, 459–466.
Willsteed, E.A., Jude, S., Gill, A.B., Birchenough, S.N.R., 2018. Obligations and aspirations: a critical evaluation of offshore wind farm cumulative impact assessments. Renew. Sustain. Energy Rev. 82, 2332–2345.
Wilson, J.C., Elliott, M., Cutts, N.D., Mander, L., Mendão, V., Perez-Dominguez, R., Phelps, A., 2010. Coastal and offshore wind energy generation: Is it environmentally benign? Energies 3, 1383–1422.
Wiltschko, R., Wiltschko, W., 1995. Magnetic orientation in animals. In Gill, A.B., 2005. Offshore renewable energy: Ecological implications of generating electricity in the coastal zone. J. Appl. Ecol. 42, 605–615. https://doi.org/10.1111/j.1365-2664.2005.01060.x.
Wolfson, A., Van Blaricom, G., Davis, N., Lewbel, G., 1979. The marine life of an offshore oil platform. Mar. Ecol. Prog. Ser. 1, 81–89.
Yang, M., Yang, F., 2020. Net zero-carbon energy in rural China. Front. J. Renew. Energy 01.
Zhang, S., Li, X., 2021. Future projections of offshore wind energy resources in China using CMIP6 simulations and a deep learning-based downscaling method. Energy 217, 119321.