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A bibliometric review on the implications of renewable offshore marine energy development on marine species

Siddharth Suhas Kulkarni [a,*], David John Edwards [b,c]

[a] School of Mechanical, Aerospace and Automotive Engineering, Coventry University, Gulson Road, Coventry, CV1 2JH, UK
[b] Department of Built Environment, Birmingham City University, UK
[c] Faculty of Engineering and the Built Environment, University of Johannesburg, South Africa

A R T I C L E I N F O

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Animals
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A B S T R A C T

The growing global demand for sustainable and environmentally friendly energy has stimulated the rapid adoption of renewable offshore energy. However, infrastructure needed for green energy production ironically impacts upon marine species and biodiversity. Consequently, this positional review paper seeks to comprehensively synthesise the prevailing body of knowledge on the impact of offshore energy development on a broad range of marine species. An interpretivist philosophical stance and inductive reasoning was adopted using scientometric analysis to conduct a rich synthesis of extant literature. From an operational perspective, the Scopus database was utilised to search for key terms on the phenomena under investigation and using the VoS Viewer software for the identification of trends using scientometric maps. The analysis reveals that research in this area of science has increased significantly over the last decade but private sector involvement is conspicuous by its absence. Primary concerns among the research community include the impact of energy development on the abundance of species, pollution and biodiversity behaviour and migration. At present, researchers have extensively focused on the impact of offshore wind farms on fish and marine mammals. However, the literature reveals no significant long-term impact upon energy development on most marine species albeit, short-term interference has raised concerns (from sound, disruption of navigation and foraging patterns, and damage of habitat). To minimise short term disruption, researchers have recommended the use of acoustic deterrence during construction, enforcement of protected areas and continued research.

1. Introduction

An insatiable public demand for sustainable energy has prompted energy generation stakeholders to explore alternative sources of green energy (Umar et al., 2021) such as harnessing offshore power within the 'blue economy' (Geerlofs, 2021). Harnessing wind and wave energy constitute the primary sources of offshore power but other sources include: tidal streams (Karama et al., 2021); thermal gradient (Chen et al., 2020); and salinity gradient (Choudhary et al., 2021). For example, the European Union (EU) has built off-shore wind power infrastructures with the capacity to generate 22,072 MW of electricity with the UK, Germany and Denmark leading in the total installed capacity (Wind Europe, 2020). Within UK waters, circa 38 operational offshore wind farms have been installed to exploit lower energy development costs on a large scale (Edelenbosch et al., 2020). The European Wind Energy Association (EWEA) estimates that 20–40 GW of offshore wind energy capability and capacity will be working in the EU by 2022 (Mahalik et al., 2021; Wang et al., 2020 b). However, offshore wind infrastructure development, is more complicated compared to onshore equivalents given inherent complexity in engineering, construction and resource consumption (Peters et al., 2020). Offshores developments also operate in a turbulent and unpredictable ocean environment and are often located along the coast line where sea water is generally shallow and suitable for biodiversity to flourish (Kelsey et al., 2018). Consequently, these projects significantly impact upon marine ecology during the construction and operational phases of the infrastructure's development (Benham, 2017).

A plethora of articles published have sought to specifically assess the effects of wind and marine energy development on marine species (Bonar et al., 2015; Hastie et al., 2015). However, hitherto scant research has been conducted to provide a holistic synthesis of the prevailing body of knowledge on the environmental impact of wind power

* Corresponding author.
E-mail addresses: drsidd10@hotmail.com, ac8061@coventry.ac.uk (S.S. Kulkarni), drdavidedwards@aol.com (D.J. Edwards).

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generation upon marine species or methods employed to mitigate this risk. Couched within this prevailing knowledge gap, this research conducts a comprehensive scientometric evaluation of the effects of renewable offshore energy development on marine species. Concomitant objectives seek to: engender wider polemic debate and discussion to stimulate further research; provide clarity on the impacts of marine energy generation on individual species; and provide recommendations for mitigating these potential impacts.

2. Global offshore wind

Globally, offshore wind farm development has increased rapidly with an annual growth of over 25% (Díaz & Guedes Soares, 2020) and similarly, the sector is expected to grow by at least 25% by the year 2030 (de Castro et al., 2019). This market growth reflects stakeholders' (i.e., government, energy producers and energy distributors) endeavours to lower industrial emissions and global warming as delineated within the United Nation's Framework Conventions on Climate Change and the Paris Agreement; where the latter strives to keep atmospheric temperature increases below 2 °C (Dasandi et al., 2021). To fulfil the Paris Agreement, the various signatories have adopted different economic and political regulations aimed at boosting the installation of off-shore wind and marine energy projects (Fitzer et al., 2019). This has seen the number of projects increase through strategies such as the zero-subsidy bid introduced in Germany and the Netherlands (MacKinnon et al., 2021).

A report by the Global Wind Energy Council (GWEC, 2020) notes that the global capacity of offshore wind energy stood at 29.1 GW after the installation of an additional 6.1 GW in 2019. At present, China is the leading developer having added 2.4 GW followed closely by the UK and Germany with an additional 1.8 GW and 1.1 GW respectively (GWEC, 2020). By the end of 2019, the capacity of installed offshore wind farms in the EU totalled 22,072 MW and is expected to rise exponentially in the coming decades (Wind Europe, 2020). Offshore wind energy, as compared to onshore wind energy, is costly in terms of planning, designing, construction, operation and maintenance (O&M) but remains economically viable over the whole life cycle of the asset. For example, Hevia-Koch and Klinge Jacobsen (2019) estimate that the current costs of investing in offshore wind energy are 1000–1950 EUR/kW but these costs are expected to continue declining in the future as technology improves. The Wind-energy-the-facts.org (2015) estimates that the investment in offshore wind is 2–2.2 million EUR/MW but O&M costs are estimated at 10–13 EUR/MWh and 15–49 EUR/MWh for onshore and offshore wind energy respectively.

2.1. Global marine energy

Conservative estimates of global marine energy indicate that there is a potential to develop 32 PWh/y within the offshore blue economy (Islam & Hasanuzzaman, 2020). However, and despite the potential, a meagre fraction of this capacity has been exploited with the global marine energy production being only 536 MW in 2016 (Chu Van et al., 2019). Of the developed marine energy, South Korea has the largest share with 254 MW from tidal energy (K. J. Kim et al., 2020). Other viable commercial plants are in Scotland, France, Sweden, China, US, Netherlands, and Ireland (Charlier & Finkl, 2009). Areas with the highest potential to generate tidal energy are the western coastlines of the Americas, Africa, Europe, New Zealand and Australia (Breeze, 2014). It is anticipated that energy generation from renewable marine resources will increase to 20–50% of the potential capacity by 2050 (Sowa et al., 2018).

The modest numbers reported are due to technological and ecological challenges associated with the exploration of marine energy (Jung & Schindler, 2020). Generally, the energy density of most marine resources is low with the highest range of tidal energy being 17m while the average wave height being 2m (Mukhopadhyay et al., 2020). In addition, the highest flow rate of currents is 2.5 m/s while the maximum temperature difference between deep seawater and surface seawater is 24 °C. There is significant conversion potential in the use of salinity differences as the osmotic pressure of 24 atm is sufficient for large scale development (Gao et al., 2021). According to Breeze (2014), it is possible to generate 2000 GW from the potential annual energy potential of 2000 TWh/y in salinity gradient. Nevertheless, tidal current has the highest potential generating capacity of 5000 GW from an annual availability of 800 TWh/y.

2.2. The UK context

The UK is a global leader in the development of renewable offshore energy, mainly via wind farms – refer to Fig. 1 (Loughney et al., 2021). The current government seeks to boost the installation of wind power towards 40 GW by 2030 – equating to sufficient energy to power every home in the country (Evans et al., 2019). The Crown Estate (2018) (which is responsible for leasing energy development land), estimate that the UK generated 26.5 TWh in 2017; sufficient to power approximately 26% of households. In 2018, offshore wind accounted for 8% of the total energy generation, which reduced the volume of carbon emissions by 12 million tonnes. Nonetheless, wind farm infrastructure development has generated significant concerns about the impact upon the marine ecology (Hooper et al., 2015).

In addition to offshore wind farms, the UK has made significant strides in harnessing renewable energy from wave power (Bonovas & Anagnostopoulos, 2020). The presence of high-speed waves, particularly in the North and West coasts of Scotland can support the generation of 45 TWh (Sowa et al., 2018). Presently, Scotland hosts one of the largest operational tidal turbines, aK1000™ developed by Atlantis Resources Corporation, at the European Marine Energy Centre in Orkney (Hollaway, 2013). According to Lamy and Azevedo (2018) there is significant potential for the UK in the generation of wave energy but significant investment cost constraints exist.

3. Methodology

The epistemological positioning of this paper adopted the interpretivist philosophical stance (Sepasgozar et al., 2020) and inductive reasoning (Chamberlain et al., 2019) to generate new theory from the ensuing discourse within the prevailing body of knowledge. Each publication constituted secondary data and a unit of analysis (Roberts et al., 2018); this approach has been adopted extensively within extant literature. For example (Akinlolu et al., 2020): examined the status and emerging trends in construction safety management technologies (Nazir et al., 2021); conducted a comparative analysis of modular and traditional housing construction; and (Darko et al., 2020) investigated applications of artificial intelligence research in the construction industry. For an operational perspective, sceintometric analysis was performed to evaluate the available literature on the phenomena under investigation using the Scopus database and the open-source software VOS Viewer (Van Eck & Waltman, 2013). Scopus was utilised because it constitutes one of the largest bibliometric databases with over 79 million records including citations and abstracts (AU - AlRyalat et al., 2019). Search terms entered into Scopus were sourced from a manual review of literature viz: ("offshore wind*" OR "marine energy" OR "offshore drill*") AND (effect* OR implication* OR consequence*) AND marine (life OR species OR animal*).

3.1. Results

The search yielded 2956 results that were manually cleansed and filtered using predefined entry criteria viz: only scientific journals published in English and post 1987. This yielded a total of 1978 research articles that were exported from Scopus to constitute the data set.

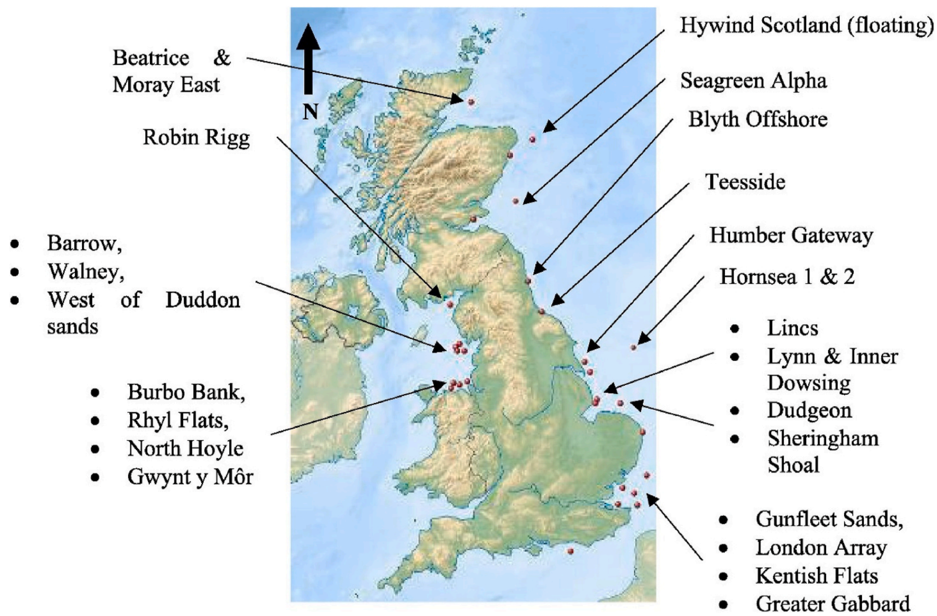

Fig. 1. Location of offshore wind farms in the UK (Loughney et al., 2021).

3.2. Stakeholders

Fig. 3 presents a network analysis of countries that are actively participating in this area; where the size of the node denotes the volume of work conducted by each country and the lines between nodes indicate interconnectivity between countries. Prominent countries in terms of volume of research published are: United States, United Kingdom, Germany, Canada, France, Netherlands, China, Denmark and Japan (May 1997). This finding is consistent with previous literature showing that these countries are leaders in the generation of offshore wind and marine energy (GWEC, 2020; OEERE, 2018).

The second notable pattern in the data is that much of the research is affiliated to academic institutions and government research facilities – refer to Fig. 3 which includes organizations with at least three citations. Academic institutions with high co-authorship include the Alfred Wegener Institute, a government-funded non-profit research institution in Germany (Mollenhauer et al., 2021). The Plymouth Marine Laboratory and the University of Plymouth have also been key research centres

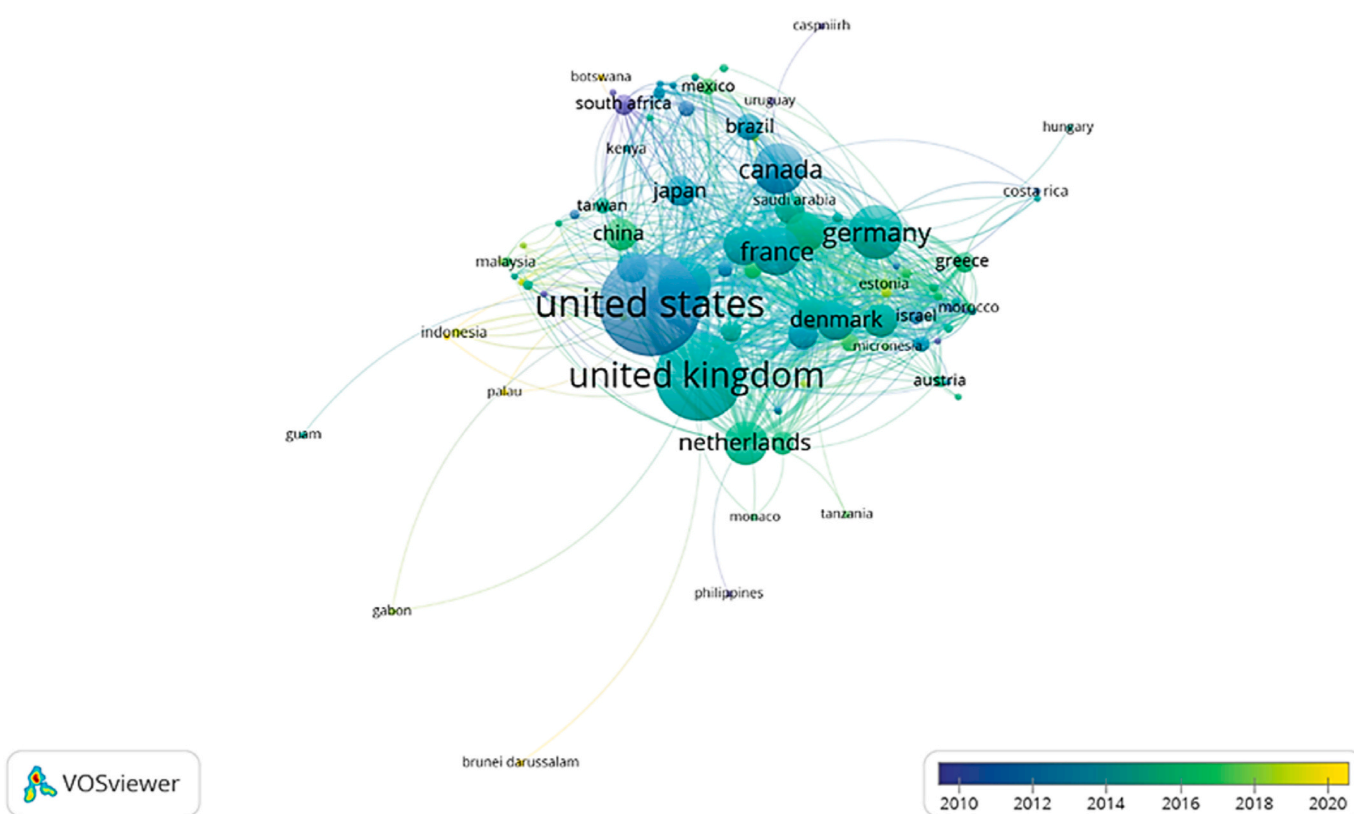

Fig. 2. Co-authorship by country.

(Schmidt et al., 2020). In other cases, public research facilities have collaborated with academic institutions and non-profit organizations focusing on conservation. For instance, the research by (Madsen et al., 2015) is affiliated to the University of the Highlands and Islands and The Royal Society for the Protection of Birds, a conservation charity. Similarly, the study by Wei et al. (2021) involved the Shanghai Ocean University, Heriot-Watt University, and the Chinese National Marine Data and Information Service. Involving these stakeholders, especially government agencies, could be an indication of growing interest in legislation, policy and investment in offshore wind and marine energy (O'Hanlon & Cummins, 2020). Notably, private organizations have not played a key role in research despite being the greatest beneficiaries from commercial offshore wind and marine energy development.

3.3. Research interests

Profiling bibliographic data by research interest is key in understanding the range of phenomena investigated by researchers. This analysis was undertaken in two ways viz: 1) evaluating the co-occurrence in all keywords (refer to Fig. 4); and 2) examining co-occurrence in author keywords (refer to Fig. 5). Only keywords with at least 15 appearances and 9 appearances in Figs. 4 and 5 were included respectively. Based on the item density map below, it is notable that most research has focused on the Atlantic and Pacific Oceans with particular interest in key habitats and breeding grounds for marine species such as: coral reefs; lagoons estuaries; and sea grass. When it comes to the type of effect, research has focused on: sea life; water pollution; noise pollution; sedimentation; organic matter; community structure; and behaviour and migration. Specific species impacted upon by offshore energy generation include: porpoise; fish; birds; and sea mammals. Interestingly, aerial survey is often utilised because the behaviour of targeted species can be observed more readily.

Fig. 5 presents a co-occurrence of keyword terminology as a thermographic image; where red represents intensive areas of research and the cooler yellow to blue colours represent more evenly dispersed co-occurrences. It is interesting to note that whilst words such as 'Atlantic Ocean' and 'animals' feature prominently, the even dispersion of words could illustrate the researchers' preference (within this community of practice) to study a whole ecosystem vis-à-vis a single constituent part of such in greater intensity.

4. Types of impact on specific species

The primary types of impact identified from the systematic review are described in the Table below:

4.1. Fish, crustaceans and mammals

The existence of infrastructure and devices used in the generation of offshore energy negatively affects marine species in terms of behaviour, migration and density of epifauna (Tiano et al., 2020). Moreover, operational wind turbines have caused zonation of habitats and subsequently a decline in the number of species. Ultimately, non-indigenous species repopulate the areas (Causon & Gill, 2018). Conversely, offshore energy development can increase sculpin biomass in and around infrastructure (Raoux et al., 2017). This behaviour was observed in the shorthorn sculpin species (*Myo-xocephalus scorpius*) whose abundance increased due to the availability of food and shelter (Taormina et al., 2018). Noise and electromagnetic fields at the base of wind turbines do not affect the behaviour of sculpin species. Other species, such as whiting (*Merlangius merlangus*) are highly attracted to the environment offered by offshore wind farms (Raoux et al., 2017). Research also reveals the depletion of whiting populations in distances of up to 6 km and a rise in abundance in wind farms (Shadman, Amiri, Silva, Estefen, & La Rovere, 2021) which replicate artificial reef (Lossent et al., 2018). The presence of tube-dwelling benthos is one of the primary attractions for whiting communities under turbines (Kim et al., 2019).

Akin the other species, pouting (*Trisopterus luscus*) is also drawn to the bottom of offshore energy infrastructure given the availability of food and safe shelter (Bray et al., 2016). Overall, large structures deter predators. A stomach content assessment by Reubens et al. (2011) established that pouting present in wind farms have higher protein content, indicating that development in the benthic population at the site favours their migration. Nonetheless, their presence is significantly seasonal, with less during the winter. Crabs show similar patterns in the colonisation of the bottom areas of marine energy infrastructure. Langhamer and Wilhelmsson (2009) studied manufactured holes at the bottom of the wave energy infrastructure and indicated a higher presence of crabs at the site compared to the surrounding environment. These holes served as artificial reefs and resulted in a five-fold increase in the density of the species.

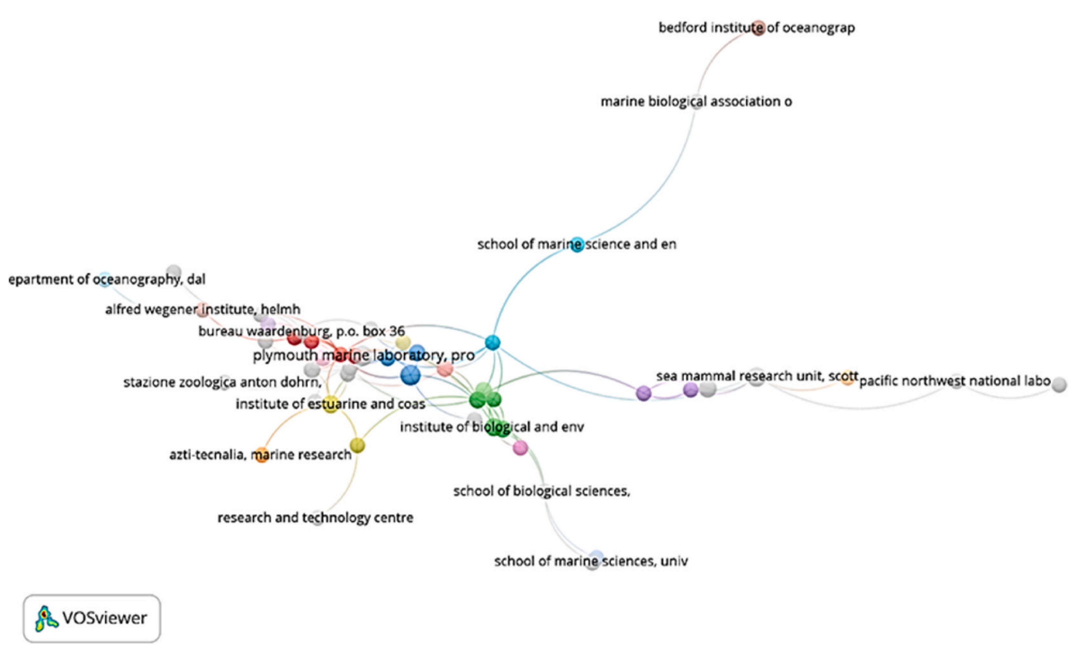

Fig. 3. Citation by organizations.

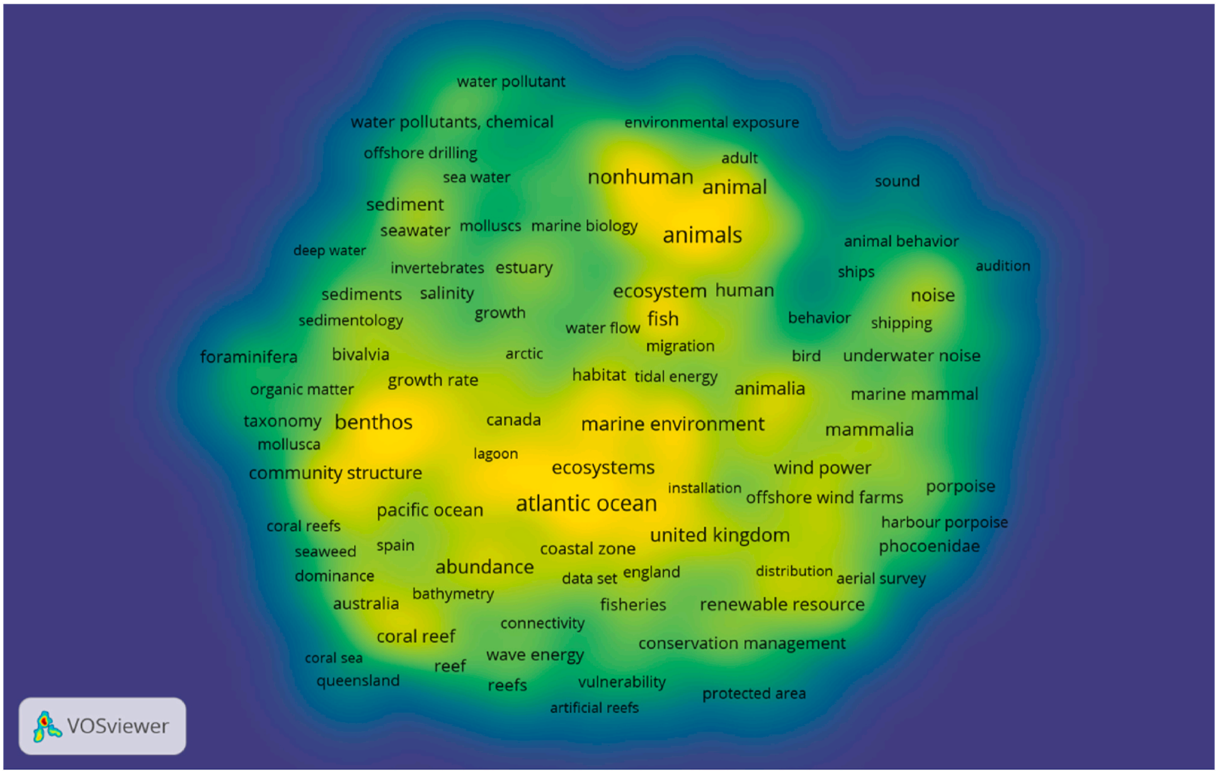

Fig. 4. Co-occurrence in all keywords.

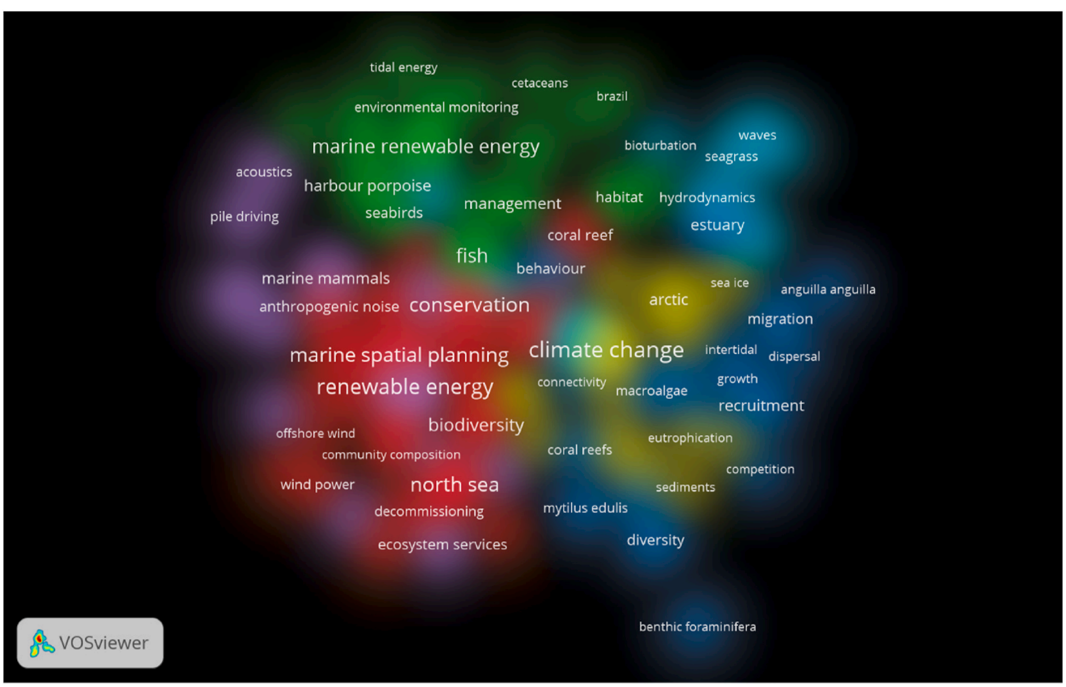

Fig. 5. Co-occurrence in author keywords.

Marine energy development results in a substantial change in the sea bottom ecology required for the survival of macrobenthos (Wright et al., 2020); marine species included in this group are generally larger than a millimetre (e.g. crustaceans, sponges, worms, ascidians). Coates et al. (2014) reported an increase in the abundance and diversity of macrobenthos at the bottom of offshore wind farms. The rise is attributed to a decline in sediment grain size and an increase in organic matter (Mo et al., 2012). A decline in wave strength at the base of turbines led to the entrapment of larvae while offering a safe habitat for species such as the sand mason worm (*Lanice conchilega*) which is especially prolific in this environment. Other macrobenthic species with high dominance at the foundation of wind turbines include *A. rubens*, *L. conchilega* and *S. bombyx*. The reduction in the population of one species tends to create more ground for the dominance of another. Some species co-exist and favour the survival of others. For instance, *L. conchilega* builds habitat tubes from coarse material, in turn resulting in finer sediment that is necessary for *S. bombyx* (Rabaut et al., 2007). However, the effect of operational wind turbines on planktonic communities is unclear. It is speculated that offshore wind farms have an effect on the surface gravity waves under the blades, which may influence the hydrographic regime on the ocean floor (Seyfried et al., 2019). It is also suspected that the hard surfaces under the turbines are ideal for the settlement of planktonic larvae.

Similar to harbour seals, Grey whales (*Eschrichtius robustus*) react to a disturbance caused by offshore energy generation. However, whales are highly susceptible to collusion and entanglement due to poor sight (Mendoza et al., 2019) and infrastructure may affect their distribution and migratory routes (Davis, 2010). Nonetheless, a study focused on the North Atlantic right whale (*Eubalaena glacialis*) established that the animals consistently used wind energy generation areas, with their presence being determined by the season (Leiter et al., 2017).

The installation of energy development infrastructure involves extremely noisy stages, such as pile-driving that affects the communication and physiological well-being of animals (Williamson et al., 2019). For instance, herring are highly sensitive to pile-driving noise at distances of up to 80 km from the source. They can also detect sounds from operational offshore wind turbines from 4 km away (Kikuchi, 2010). At close distances, the noise has the potential to cause significant auditory impairment and can result in internal or external damage or deafness. Due to its high sensitivity, energy development noise can mask interspecific communication as found in the Atlantic herring (*Clupea harengus*). According to a study by Bergström et al. (2013), the effect of marine energy generation on cod is limited to the construction period. The researchers found that there was a surge in the abundance of cod within operational offshore wind farms for three years after construction. Similarly, Reubens et al. (2014) established that cod are highly attracted to offshore wind turbines as it provides food and security from predators. However, a study (Thomsen et al., 2006), on the Atlantic cod (*Gadus morhua*) indicate that they are highly sensitive to construction sound, with signs of increased heart rate and behavioural disturbance. Conversely, studies on the Atlantic salmon (*Salmo salar*) show that they are not disturbed by the noise from operational wind turbines and can only perceive it within a kilometre. Dab (*Limanda limanda*) does not have high sensitivity to noise as it does not have a swim bladder; it is only sensitive to sounds at high frequencies of 30–250 Hz. Dab is particularly sensitive to particle motion and can only hear noise from operational wind turbines within a kilometre (as in the case of salmon). Hastie et al. (2015) found that seals are greatly affected by the noise associated with the construction of offshore wind infrastructure and can suffer permanent auditory impairment. This is because most seal species (such as the California sea lion (*Zalophus californianus*) and stellar sea lions (*Eumetopias jubatus*)) communicate at frequencies of 1–40 kHz (Davis, 2010). In effect, the sound interfered with intraspecific communication that critical in feeding and detection of predators. Similarly, Madsen et al. (2006) note that pile-driving resulted in a decrease in the number of seals hauling-out for three months within a 10 km radius. However, the effect of the infrastructure on the behaviour of seals tends to decline as they can effectively move between structures as noted by (Russell et al., 2014). Bailey et al. (2010) found that whales are also highly sensitive to pile-driving and can exhibit behavioural disturbance within a radius of 40 km from the source as observed in minke whales (*Balaenoptera acutorostrata*). Research on the impact of offshore energy development on harbour porpoises (*Phocoena phocoena*) is conflicted. However, a primary observation is that they communicate at low frequencies and hence, they are not susceptible to the masking effect. Like other marine mammals, dolphins use sound for communication and can exhibit disturbance at 50 km from an offshore construction site (Bailey et al., 2010). This is because the noise masks vocalisation as noted with bottlenose dolphins (*Tursiops truncatus*). Consequently, dolphins are likely to lose or alter their direction during migration as their sensitivity to the geomagnetic field is compromised (Normandeau et al., 2011).

Teilmann and Carstensen (2012) note that the echolocation activity in wind farms declined drastically during construction and gradually increased from a baseline after three years. Electricity generation equipment (such as motors and cables) create electromagnetic fields that can be sensed by certain marine species and influence their behaviour. Normandeau et al. (2011) note that there is a marginal to moderate impact of undersea electric cables on the feeding behaviour of sandback sharks (*Carcharhinus plumbeus*) that feed on benthic organisms inhabiting the seafloor. The electromagnetic effect of underwater power cables also impacts upon the behaviour of eels, as indicated by a decline in their swarming speed within the range of cables (Andrew B Gill & Taylor, 2001). An evaluation of European eels (*Anguilla anguilla*) shows a potential effect on migration (Bray et al., 2016). Nevertheless, cables do not seem to be an imminent threat to eel behaviour, as their abundance appears to increase over time(Bergström et al., 2013). The navigation of sockeye salmon (*Oncorhynchus nerka*) to and from their natal rivers for breeding is significantly guided by the earth's magnetic fields (Normandeau et al., 2011). This implies that the presence of high-frequency electric cables along their migration pattern could affect their breeding by hampering the number of fish moving up the river or hatchlings returning to the sea (Rossington & Benson, 2020). Lobsters primarily dwell on the seafloor and rely on the earth's magnetic field for navigation and so consequently, artificial magnetic fields caused by undersea electricity cables can impact upon their behaviour (Taormina et al., 2018). Similarly, porpoises are also extremely susceptible to magnetic fields caused by electric cables from wind farms (A B Gill et al., 2012).

4.2. Reptiles and birds

Offshore energy infrastructure and facilities are not limited to impacting marine animals. They also pose possible threats to reptiles and birds, for instance, turtles rely heavily on geomagnetic sensors for navigation (R. May et al., 2015). Implicatively, the installation of power cables in nesting beaches has been found to affect the movement of loggerhead turtle (*Caretta caretta*) hatchlings towards the beaches; they swarm randomly. This means that fewer populations of the hatchlings survive every cycle, which could have long-term effects on the survival of the species (Lovich & Ennen, 2013). Wilson (2007) speculates that the extensive installation of wind farms could raise concerns about the mortality of marine birds. Threats from in-flight collisions with rotor blades and the general avoidance of feeding grounds in feeding farms are key causes of mortality. However, the implications of these factors are dependent on the species, flight behaviour, weather conditions and flock size (Moss, 2017).

The production of offshore energy done on suitable grounds for white-winged scoters (*Melanitta fusca*) can influence their abundance by interrupting their feeding patterns. The species has a higher preference for low salinity areas with a higher presence of hard bottom substrate, chlorophyll availability and lower temperatures (Meattey et al., 2019). Nonetheless, the collision threat does not have a significant impact on the ability of the species to utilise their sites (Dhunny et al., 2019). Offshore wind turbines have the potential to affect the migratory behaviour of different bird species through obstruction and distraction (Thomas et al., 2018). This could impend their ability to move between their feeding and breeding areas. However, some species such as ducks adapt rapidly to new environments. For example, the Tufted Duck (*Aythya fuligula*) and Pochard (*Aythya ferina*) can fly greater distances and around wind farms and in poor inclement visibility conditions caused by fog and darkness (Percival, 2003). Raptors are highly dependent on marine animal resources for foraging and they are likely to be impacted by the integration of energy generation infrastructure into marine ecology (Rial-Berriel et al., 2021). Areas with high turbine densities pose a higher collision risk to raptors but the probability of collision is typically low at less than a bird annually (Sommer et al., 2019). However, the installation of infrastructure along the migratory paths of raptor species such as the Griffon Vulture (*Gyps fulvus*) and Golden Eagle (*Aquila chrysaetos*) increases the collision risk, especially when the birds fly in large numbers.

4.3. Plants

Endemic seagrass (*Posidonia oceanica*) provides a key habitats for benthic animals and implicatively, it is imperative to assess the impact of offshore energy development on the species (Oprandi et al., 2020). Seagrass is under threat from physical destruction, variance in hydrographic environment and sedimentation during the construction of marine energy infrastructure. This is because most drilling and pile driving is done in soft sediment areas that are favourable for the growth of endemic seagrass (Soukissian et al., n.d.). Nevertheless, the infrastructure reduces consequential fishing activities that cause the destruction of the seagrass. The effect of offshore wind generation has been explored extensively compared to other forms of marine energy (Sola et al., 2020). Of the selected sources, only one article focused on other forms of marine energy on ocean species. Most studied groups of marine species such as fish, mammals and invertebrates. This could be explained by their relative abundance in the ocean topography (Lin et al., 2018). Crabs and seagrass have been studied in reptile and plant categories respectively. Considering the type of effect, it is notable that sound, habitat and food have been extensively researched compared to collision and electromagnetic fields from undersea cables (Fey et al., 2019). The greatest impact arises from the noise generated during the construction phase of offshore energy projects (Scott et al., 2018). The destruction of habitat for benthic species such as seagrass could result in their decline, which lowers the supply of food for other species (Horn et al., 2021). Fortunately, these impacts are short-term as noted in studies focusing on benthic communities that tend to colonise the bottom of the infrastructure due to the availability of organic matter, safe breeding grounds and artificial reefs (Bray et al., 2016; Coates et al., 2014; Rabaut et al., 2007). Similarly, secondary predators such as Pouting are afforded protection from larger predators such as Seals that tend to avoid the energy sites. The artificial reefs created by marine infrastructure results in the colonisation of the sea bottom by a variety of benthic organisms. Consequently, it has been found that wind farms rapidly become an attraction for many species in the food chain after construction is completed (Mavraki et al., 2021). One of the most interesting observations is the five-fold increase in the abundance of harbour porpoise in operational wind farms from baseline years after the construction (Andersen & Olsen, 2010).

5. Discussion

The analysis has uncovered research trends, the primary concerns for marine species and recommendations supported by the literature. A complex relationship between the types of impact and the way these affect marine species has established and notably, one source or type of impact could manifest in multiple ways. Fig. 6 (Farr et al., 2021)

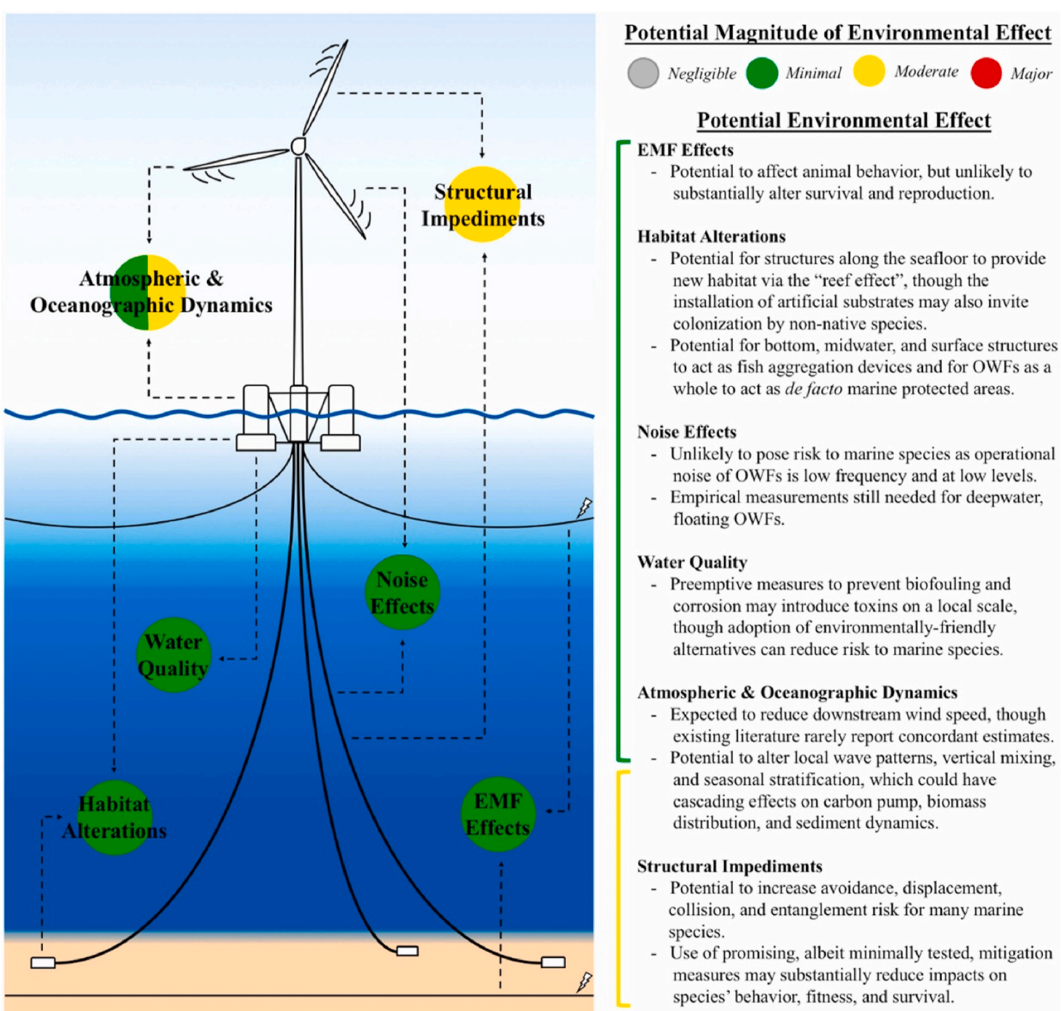

Fig. 6. Potential environmental effects of offshore wind energy development (Farr et al., 2021).

illustrates, the noise from construction processes (e.g., pile-driving) may result in the behavioural disturbance, physiological harm and subsequent disruption of habituation patterns in animals. However, these consequences will vary for different species; extreme measures may not be necessary when the habituating species are not significantly affected. Thus, it would be beneficial if projects and their corresponding precautionary measures are considered from two perspectives: specific (e.g., determining the marine species occupying the area of concern) and general (e.g., understanding the potential impact of noise). For example, professionals, mainly in engineering, undertaking future marine energy development projects and research and adopting this paper's results, must regard the findings based on their circumstances.

A single literature-based recommendation can offer several ways of curbing possible negative impacts associated with marine biology projects (e.g., offshore energy development). For instance, sound deterrence keeps vulnerable species from harmful pile-driving noise, preventing physical harm, death or associated behavioural disturbance and ensuring that the species will continue to use the site once the noise has subsided. Moreover, setting up protected areas through collaborations and involvement of stakeholders will help safeguard the habitat of endangered species and warrant continuous feeding behaviour. Similarly, ascertaining those projects will preserve migration routes or breeding grounds will result in the survival of species.

The development of renewable offshore energy is a plausible solution to meet the growing global demand for green energy and sustainable development (Yang et al., 2021). Offshore energy is also significantly reliable and available in abundance and, implicatively, can be used in the long-term (Kudelin & Kutcherov, 2021). However, offshore energy projects have tangible negative implications on marine species. As the result, it is imperative to evaluate the recommendations to solving the present challenges.

5.1. Acoustic deterrence

Acoustic deterrence includes strategies to reduce the impact of noise on marine species (Todd et al., 2021). As a result, the adoption of acoustic deterrence offers a short-term solution by keeping vulnerable species away during noisy processes such as pile driving (Chou et al., 2021). According to (P. T. Madsen et al., 2006), the use of harassment and deterrence devices such as seal-scarers and porpoise pingers (before pile driving commences) reduced the exposure of the species to harmful frequencies (Findlay et al., 2021).

5.2. Artificial reefs

Coral reefs are essential in sustaining marine species as they offer safe habitat for breeding while providing food for the extensive ocean ecology (Edmonds et al., 2021). Consequently, the treatment of energy development infrastructure as artificial reefs could help counter the formative implications associated with their construction (Ainsworth et al., 2020). The inclusion of artificial holes has been found to be highly effective in encouraging the colonisation of wind farms by benthic organisms that provide food for other species (Maurya et al., 2021). Some of the recommendations for improving feasibility of infrastructure as artificial reefs include the maximization of the bottom surface area and integration of designed materials such as reef balls (Kang et al., 2021).

5.3. Protected areas

The identification and avoidance of protected areas during the implementation of energy projects is an effective way of avoiding most of the identified negative implications on marine species (Choudhary et al., 2021). This means that the implementation of all offshore energy projects should be preceded by the performance of environmental impact assessments (Jägerbrand & Bouroussis, 2021). These assessments should focus on the cumulative effect of the project and potential collision with human activity and interests, which calls for significant participation of stakeholders (Pelucchi et al., 2020). This could avoid conflict between fishing, energy development and environmental conservation interest groups (Kabir & Khan, 2020) (Table 1).

5.4. Priority research

The identification of priority research areas can fast-track the development of solutions to mitigate the identified changes. Polagye et al. (2020) proffer that the interaction between animals and infrastructure technology should be a priority area of investigation particularly, in terms of generating innovative ways to reduce or eliminate the stress caused by the electromagnetic fields from underwater cables (Czermański et al., 2021). Continuous assessment and research on strategies to reducing the impact of noise during construction should also be prioritized (Duquette et al., 2021). The authors note that research should be both site-specific and general; it should concentrate on the immediate needs of the construction site while solving general problems. Table 2 below provides a summary by linking the recommendations to the potential technologies involved within the offshore energy development could be further researched.

5.5. Limitations of the study

The selection of sources to study the implications of renewable offshore energy development was significantly selective. Notably, the researchers only reviewed the abstracts of randomly selected articles and discarded a majority once concept saturation was achieved. This means that it is highly likely that the study did not capture all the effects on marine species, especially in cases where such information was not included in the abstract. Consequently, this research may be limited in the sense that is does not offer a complete view of the impact of offshore energy on marine species. Similarly, the research does not highlight all the recommendations available in literature. The researcher primarily focused on recommendations that have practical relevance to engineers

Table 1
General types of impact in literature.

Type of Impact	Description	Citations
Presence of devices and collusion	The presence of the infrastructure and devices used in the generation of offshore energy affects the day-to-day lives of marine species.	Tiano et al., 2020; Causon & Gill, 2018; Raoux et al., 2017; Taormina et al., 2018
Pollution	Pollution originates from matter introduced into the marine habitat during construction, operation, and decommissioning of energy infrastructure	Wright et al., 2020; Coates et al., 2014; Mo et al., 2012; Seyfried et al., 2019
Noise effects	The installation of energy development infrastructure involves very noisy stages such as pile-driving that affects the communication and physiological well-being of animals	Raoux et al., 2017; Stenberg et al., 2015; Lossent et al., 2018; H.-J. Kim et al., 2019
Electromagnetic effects	The electricity generation equipment such as motors and cables create electromagnetic fields that can be detected by some marine species and, as a result, affecting their behaviour	Teilmann & Carstensen, 2012; Normandeau et al., 2011; Bray et al., 2016; Bergström et al., (2013)
Physiological harm	The sound from the installation, operation, and decommissioning of offshore energy infrastructure, destruction of habitat, and electromagnetic fields can cause physiological harm to different species	R. May et al., 2015; Lovich & Ennen, 2013; Moss, 2017; Meattey et al., (2019)

Table 2
Relationship between Recommendation and Technologies involved and benefits.

Recommendation	Technologies involved	Citations
Acoustic Deterrence	• Offshore energy parks • Pile driving • Seal-Scarers and Porpoise Pingers	Mortensen et al., 2021; Todd et al., 2021; Chou et al., 2021; Findlay et al., 2021
Protected Areas	• Environmental performance impact assessment • Human interests in protected areas • Environment conservation interest groups • Energy implementation projects	(Choudhary et al., 2021); (Jägerbrand & Bouroussis, 2021); Pelucchi et al., 2020; Kabir & Khan, 2020
Artificial Reefs	• Energy development infrastructure • Artificial reef construction • Inclusion of reef balls	Edmonds et al., 2021; Ainsworth et al., 2020; Maurya et al., 2021; Kang et al., 2021
Priority Research	• Identification of interaction between animals and energy harnessing devices • Reduction of noise impact during construction	Polagye et al., 2020; Czermański et al., 2021; Duquette et al., 2021

who are arguably most likely to develop tangible solutions. One of the resounding discoveries made is the potential benefit of undertaking priority research aimed at mitigating the primary concerns about the impact of offshore energy development on marine biology. Future research should focus on establishing the priority areas for research and development by quantifying the negative impacts of offshore energy to identify what can be considered to be most detrimental to marine species. The process should involve performing an audit aimed at taking account of the steps that have been made and success achieved in mitigating specific challenges. Based on this output, it will be possible to determine the areas of priority where significant gain can be achieved.

6. Conclusions

The increasing demand for global energy has resulted in the development of renewable offshore energy to mitigate concerns for global warming and environmental sustainability. In addition to wind and waves, there are other sources of renewable marine energy being explored such as tidal streams, thermal gradient and salinity gradient. The goal of this study was to undertake a comprehensive scientometric evaluation of current research on the effects of renewable offshore energy development on marine species to identify trends and research focus. It has been noted that offshore wind farm energy has become the most popular source of offshore renewable energy with an annual growth of over 25%. The research adopted involved a scientometric analysis to evaluate the available literature on the topic using the Scopus database. Notably, the greatest impact arises from the noise generated during the construction phase of offshore energy projects from which, only a few sound-sensitive species are affected. Also, the risk of collision with marine energy infrastructure is considerably low (at less than a single bird fatality every year). Similarly, electromagnetic fields from power cables only affects species that can detect them but do not adversely affect their behaviour. Generally, the short-term impacts of noise and destruction of habitat is reversed in the long-term as infrastructure results in the development of benthic communities that support the food chain.

As of a broader interest the inclusion of multi-purpose platforms or MPP's which has gained interest in the last decade due to the synergy from the co-location of offshore renewable and aquaculture systems. Therefore, MPP's could provide a good opportunity for the aquaculture and offshore renewable energy sector because of the open sea which would provide enough space for fish farms, and would be safe from the human pollution sources, and this increase organic fish production and create positive impact for renewable energy and aquaculture sectors. Three primary recommendations have been identified in the literature. First, the implementation of acoustic deterrence strategies reduces the exposure of vulnerable marine species to potentially harmful noise during construction. Second, engineers should develop infrastructure to simulate coral reefs to promote the recovery of the ecology from previous damage. Finally, research should be carried out in a prioritized manner to ensure that the critical concerns about the impact of offshore energy development are addressed.

CRediT authorship contribution statement

Siddharth Suhas Kulkarni: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization, Investigation, Software. **David John Edwards:** Writing – review & editing.

Declaration of competing interests

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

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