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Is OSPAR 98/3 science-based politics or politics-based science?

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Man-made structures in the marine environment such as offshore Oil & Gas infrastructure are known to provide a hard substrate that enables ecosystems to develop on and around them. Current decommissioning practices on the UK Continental Shelf are mandated by the OSPAR Decision 98/3 with the premise of a clean seabed at its core, meaning that it is the expectation that all infrastructure is completely removed at the end of its operation life, leaving a clear seabed behind. This study critically reviewed 49 peer-reviewed articles relating to the ecosystem and the impact to these ecosystems by current removal practices. The results clearly demonstrate that current science-based evidence shows that existing O&G platform substructures act as multipurpose artificial reefs upon which rich ecosystems have developed and that their removal degrades the overall North Sea marine environment. Furthermore, this study shows that clear-sea bed policies, such as OSPAR 98/3, do not reflect, nor understand the complex relationship and interdependencies between biology and man-made structures and do not reflect current scientific knowledge. It is concluded that based on current knowledge, it is no longer scientifically justifiable to mandate the removal of all O&G infrastructure during decommissioning and that applying the principle of a clean seabed according to the OSPAR Commission should be re-considered.

KEYWORDS

OSPAR 98/3, manmade structures, ecosystem, ecology, Oil & Gas, marine, environmental impact

1 Introduction

Offshore decommissioning regulations in the UK are controversial, as evidenced by a recent focus of scientific research programs investigating the impact of man-made structures (MMS) on the marine environment (Birchenough and Degraer, 2020). MMS are emplaced in the marine environment for a number of different purposes by a range of different industries and can include fixed and mobile Oil & Gas (O&G) installations and

infrastructure, offshore wind farms (OWF), pipelines and cables, shipwrecks, and fish farms.

Recent research identifying the potential ecological benefits of MMS on the marine environment (Fowler et al., 2020), highlight environmental and political challenges of both decommissioning *in situ* and full removal (Sommer et al., 2019) and list gaps in our understanding and knowledge of MMS ecology (Dannheim et al., 2020; Fortune and Paterson, 2020). It is not the intention of this study to repeat this work, instead, a synopsis of the findings of each of the reviewed articles is presented, and key ecological criteria are identified from within these articles and a qualitative analysis is presented in a ‘traffic light system’.

This study focuses on decommissioning of offshore O&G infrastructure located on the UK Continental Shelf in the North Sea where according to OGUK, 2019 36 % of it is expected to be decommissioned and removed by 2028 (OGUK, 2019).

When the operator (owner of the infrastructure) decides to decommission they must seek permission from the UK government and as a requirement of that process an Environmental Impact Assessment (EIA) is required (Department for Business, Energy & Industrial Strategy, 2018). However, because of current policy, the EIAs do not consider the full impact of the removal of MMS on the marine environment (Fortune and Paterson, 2020) and that the clean seabed policy mandated by the OSPAR Decision 98/3 results in biased comparative assessments by not considering the full impact of decommissioning on the marine environment, nor a comprehensive range of decommissioning options, including decommissioning *in situ*.

1.1 Decommissioning in the UK

In 1998 the United Kingdom and Europe introduced the most stringent regional decommissioning framework worldwide (Fam et al., 2018). After the 1995 Brent Spar incident the *OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations* (OSPAR Commission, 1998) became legally binding under the Petroleum Act 1998 as amended by the Energy Acts 2008 and 2016. It generally prohibits “dumping, and the leaving wholly or partly in place, of disused offshore installations within the maritime area” of the North Sea. Derogations, such as leaving footings or the complete installation in place, may be permitted by the competent authority of a Contracting Party only for the following types of structures:

- large steel installations weighing more than 10,000 tonnes, installed before 1999.
- gravity-based/floating concrete installations.
- damaged/deteriorated structures.

To qualify for derogation one of these cases must apply and an in-depth comparative assessment must be carried out to demonstrate that the disused O&G installation cannot be re-used, recycled or disposed on land. Currently, only 12 % of the O&G platforms located on the UKCS may qualify for derogation (Oil & Gas Authority, 2020a). All other platforms must be removed to ensure a clean seabed. It has been argued that rigs-to-reefs is a valid

method of re-using existing material and creating artificial reefs, however, the *OSPAR Guidelines on Artificial Reefs in relation to Living Marine Resources* (OSPAR Commission, 2012) demand artificial reefs to be built from inert, virgin materials. Hence, the guidelines exclude any type of rigs-to-reefs model in the North Sea. An in-depth analysis (Jørgensen, 2012) of the development process of these guidelines indicated that the Contracting Parties originally intended to find suitable ways of using O&G installations as artificial reefs. However, due to the Brent Spar controversy, many of the Contracting Parties argued that the rigs-to-reefs alternative would be mistakenly considered as dumping at sea by the general public and the environmental NGOs (Jørgensen, 2012). Without consulting the scientific community all Contracting Parties except for Norway decided to ban rigs-to-reefs in the North Sea in order to avoid any further public debates and protests.

Following the long history of decommissioning in the U.S. Gulf of Mexico (Kaiser and Pulsipher, 2005), UK was the second country to enter the decommissioning market at scale (Wood, 2018). The North Sea Transition Authority (NSTA) (previously the Oil & Gas Authority (2020b)) estimate the overall decommissioning expenditure for the UKCS will be £44.5 billion, the cost of which will be met by the operators (60%) and the UK tax payers (40%) through tax relief (National Audit Office, 2019). These figures include various decommissioning activities but are dominated by well plug and abandonment (P&A) and the complete removal of the O&G installations (subsea, floating, and fixed structures).

According to Oil & Gas UK (OGUK, 2019) £15.2 billion is forecast to be spent on decommissioning in the North Sea over the next decade. Furthermore, OGUK calculates that approximately 20 % of these decommissioning costs will be used for the removal and onshore disposal of more than 100 platforms, topsides and substructures. Depending on the region the topsides removal may be marginally more expensive than substructure removal. This equates to an estimate of £1.4 billion to be spent over the next ten years; just for substructures’ decommissioning. In total, it will cost between £4 billion and £5 billion to fully remove the 306 substructures that are currently installed UKCS platforms (steel only) (OGUK, 2019).

1.2 Clean seabed or protection

The ecosystems of the North Sea have been significantly impacted by human activities such as fishing, environmental pollution, greenhouse gas (GHG) emissions, increase of sea temperature due to climate change, sand, oil and gas extraction as well as introduction of wind farms, shipwrecks and shipping (Halpern et al., 2008; Lindeboom et al., 2011). This altered ecosystem led some scientists (Schläppy and Hobbs, 2019; van Elden et al., 2019) to adopt the “novel” ecosystem approach, which acknowledges the functions and services of a new ecosystem that is formed by the presence of MMS. Some scientists argue that instead of hoping that the ecosystem will be restored to its ‘original’ environmental baseline without human intervention (Ounanian et al., 2019), we could start to accept the new state of the ecosystem and try to restore it pro-actively and appropriately (Macreadie et al., 2011; Fowler et al., 2018). Furthermore, the

evidence for this ‘original’ environmental baseline is completely absent. Decommissioning *in situ* (leaving the platform substructure in place) can be seen as active marine restoration and an investment in the future to be evaluated on an unbiased case-by-case basis (Ekins et al., 2006; Fowler et al., 2014).

In the rigs-to-reefs model used in the U.S. Gulf of Mexico for example, 50 % of the savings made by reefing rather than full removal must be paid by the O&G operators to the artificial reef fund (Scarborough Bull and Love, 2019). Liability for the structure is transferred to the state, which is then responsible for maintenance and monitoring. This model could be adapted and incorporated into the Maximise Economic Recovery (MER) strategy as a life extension option of O&G installations in the North Sea (Falcone, 2020).

From a marine spatial planning perspective, one might argue that a clean seabed is the preferred choice to reopen the sea to other users such as fisheries. However, the 500 m safety zones around the 1350 O&G installations in the North Sea (OSPAR Commission, 2017) only represents a maximum of 0.1 % of the total North Sea area (Fowler et al., 2020), in comparison, the Marine Protected Areas (MPA) cover 18.6 % (OSPAR Commission, 2019b).

1.3 Marine protected areas

The main goals of both OSPAR and the EU are protection of key threatened and/or declining species and natural habitats, conservation and restoration of natural ecosystems and enhancement of biodiversity in the maritime area (OSPAR Commission, 2019a) and EU protected Reef Habitats (European Environment Agency, 2013). To secure these goals, Marine Protected Areas were established over the last two decades. O&G installations were historically awarded licenses in MPAs and therefore MMS exit in these areas. Supplementary Figure 1 illustrates all designated OSPAR MPAs (OSPAR Commission, 2019a) and EU protected Reef Habitats (European Environment Agency, 2013) in which UKCS platforms are located. Most of these MPAs were designated after the platforms’ installation and that is why currently more than 50 % of all UKCS platforms (152 in total) are located either in designated OSPAR MPAs or 1170-Reefs Habitats. No specific guidance is provided on how to address the challenge of decommissioning platforms located in these areas. Hence, 16 out of 21 platforms located in a MPA with “not in use” status have not yet been removed.

Some researchers have developed comprehensive decision-making tools for decommissioning the infrastructure in MPAs, for example Burdon et al. (2018) but all are based on full removal and therefore do not compare the other options such as decommissioning *in situ*.

1.4 Protected marine species and MMS

The cold-water coral *Desmophyllum pertusum* (previously named *Lophelia pertusa* and named as such in the 49 articles reviewed for this study but will be referred to as *D. pertusum* from here), is a protected and endangered marine species. It is found in many locations throughout the North East Atlantic region and

although it may be a protected species, there is no legal requirement for it to be protected if it is found on an O&G MMS.

On both the Murchison (CNR International, 2013) and Ninian North (CNR International, 2016) platforms. *D. pertusum* colonies were found on the steel jackets, which was highlighted in the EIA. The Joint Nature Conservation Committee (JNCC), the public body that advises the government and is required to assess the EIAs as part of the statutory decommissioning regulations, advised that because the *D. pertusum* colonies would not have occurred without the presence of the platforms, the mortality of the protected cold-water coral because of decommissioning operations would not be considered as an issue of significant concern.

In the case of the decommissioning of the Brent Delta (Shell U.K. Limited, 2017) and Dunlin Alpha (Fairfield Energy Limited, 2019) platforms *D. pertusum* colonies were found on both and *Arctica islandica* (ocean quahog) was observed near Dunlin. The EIAs, however, concluded that it was not deemed necessary to take any measures to protect these rare and threatened species during the decommissioning.

In all these examples derogations were allowed, but the basis for these decisions were not due to species and thereby environmental protection.

1.5 Ecological benefits of MMS

According to Fabi (2015) artificial reefs are human built structures that actively enhance and/or recover natural habitats, raise productivity and manage marine resources and can serve many other purposes. In the North Sea an offshore artificial reef should achieve at least one of the following objectives: 1) provide new hard substrate for sessile invertebrates; 2) provide shelter for juvenile and mature motile invertebrates; 3) restore depleted habitats and mitigate habitat loss; 4) enable growth and reproduction of rare, threatened and commercially important species and habitats; 5) enhance biodiversity; 6) protect sensitive habitats from fishing activities; 7) create potential networks of MPAs to manage connectivity and species’ life cycle; 8) enable research and educational activities.

While demonstrating which of these objectives are generally met by an existing O&G reef, it is also important to identify any uncertainties and knowledge gaps. This will further help in concluding whether there is enough science-based evidence available to enable an unbiased comparative assessment of different options for decommissioning platform substructures. Based on Fowler et al. (2014), a distinction is made between the following *in situ* and full removal options for decommissioning:

- Full removal: transport complete substructure to shore and re-use or re-cycle.
- “Leaving intact”: remove topsides and leave complete substructure in place (add navigational aid).
- “Topping”: cut top section and either transport to shore or deploy next to structure (cutting depth requirement is the IMO free draught of minimum 25 m following the examination of Fowler, Jørgensen and Coolen et al.

(2020) or 55 m following the Department for Business, Energy & Industrial Strategy guidelines).

- “Toppling”: topple whole structure in place.

Reefing of the structure in a designated area will not be discussed further in this study as no research data are available to evaluate this option in detail for the North Sea.

2 Evaluation methodology

In total, 49 peer-reviewed articles were examined in depth and the most important data were extracted, see [Table 1](#). More than 50% of the research articles are from 2018 to 2020. A slight bias towards the Southern North Sea can be observed. The most comprehensive research review study conducted by [Fowler et al. \(2020\)](#) was further used as guidance for the qualitative critical-analysis. The study outlines five key ecological considerations when undertaking decommissioning assessments: 1) *provision of reef habitat*; 2) *productivity of offshore ecosystems*; 3) *enhancement of biodiversity*; 4) *protection of the seabed from trawling*; 5) *enhancement of connectivity*. The main criteria related to each of the ecological considerations were then used to qualitatively evaluate the literature findings. In addition, a colour-coded traffic light system was introduced to highlight the current state of knowledge:

- Green: Mature, science-based evidence is available. The findings are statistically significant and are confirmed by other studies.
- Gray: Immature early research studies and simulation-based evidence available. The results suggest a trend, but extensive validation is lacking.
- Red: No science-based evidence available.

For the final presentation of the evaluation results the average of the knowledge status of the respective criteria related to the five key consideration was determined by reflecting this in the colour and its brightness. The stronger the green colour, the more mature, science-based evidence is available. The lighter the green colour, the less science-based evidence is available. If the criteria is marked as green, the current research knowledge status can be considered as mostly mature, science-based evidence. However, if the criteria are marked as gray, only immature research is available. If a criterion is red, then no science-based evidence is available. The red brightness scale is to be interpreted inverted to the green scale.

3 Results

More than 50 % of the research studies examined in depth were conducted between 2018 and 2020. This strong interest is due to the fact that environmental scientists identified a potential ecological value in leaving O&G structures partly or fully in place ([Fowler et al., 2018](#); [Fortune and Paterson, 2020](#)). That is why it is important to understand the current knowledge status and highlight the remaining knowledge gaps before the O&G structures are finally removed ([OGUK, 2019](#)). Time is pressing and changing regulatory frameworks and legislation takes a while as seen in the past in California ([Scarborough Bull and Love, 2019](#)). It can take 10 years until the research work is completed (see *INSITE Programme – Phase 2*), all stakeholders involved are coordinated ([Shaw et al., 2018](#); [Tung, 2020](#)) and finally the political consensus to update OSPAR Decision 98/3 was found. Past experience has shown that aligning the OSPAR Parties could be the especially difficult ([Jørgensen, 2012](#)). However, many research initiatives gained considerable momentum worldwide ([McLean et al., 2020](#)), therefore further research should be supported and access granted to the not yet freely accessible but available extensive environmental data ([Macreadie et al., 2018](#); [Murray et al., 2018](#)) in order to close the remaining knowledge gaps.

In the next sections the traffic light rating results of the current knowledge status are presented, organised by the ecological considerations identified by [Fowler et al. \(2020\)](#): 3.1) *provision of reef habitat*; 3.2) *productivity of offshore ecosystems*; 3.3) *enhancement of biodiversity*; 3.4) *protection of the seabed from trawling*; 3.5) *enhancement of connectivity*.

3.1 Provision of reef habitat

Refer to [Tables 2](#) and [3](#).

3.2 Productivity of offshore ecosystems

Refer to [Table 4](#).

3.3 Enhancement of biodiversity

Refer to [Tables 5](#) and [6](#).

TABLE 1 Summary of parameters for data extraction of the peer-reviewed articles.

Receptor	No. articles	Meta data	Community ecology	Findings/effects
Seabed	9	Key species	Abundance	Species characteristics
Benthos	12	Location	Richness	Water depth
Fish	12	Max. depth	Biodiversity	Substrate material
Mammals	6	Substrate type	Detection (first records)	Substrate type
Fisheries	3	Sampling method	Biomass	Location
		Sampling period	Recover/reproduction	Interconnectivity
		Data analysis	Dispersal	Spatio-temporal
		Food web	Disturbance	

TABLE 2 Provision of reef habitat (part 1): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
O&G reef vs. natural reef	<ul style="list-style-type: none"> O&G reefs provide the same kind of habitat as natural reefs (hard substrate). The same benthic communities are significantly abundant on both reefs except for <i>M. edulis</i> and <i>J. herdmani</i> which are not normally found far offshore on natural reefs. 	Supplementary Table 7
	<ul style="list-style-type: none"> The habitat provided by deeper sections of O&G reefs is more like the habitat of natural reefs than that of shallower O&G sections, where <i>M. edulis</i> and <i>J. herdmani</i> are abundant. 	Supplementary Table 7
	<ul style="list-style-type: none"> O&G reefs provide fish with the same good quality prey as natural reefs, as compositional analysis shows. However, the prey species may slightly differ from open water supply. 	Supplementary Table 11
O&G reef vs. other artificial reefs	<ul style="list-style-type: none"> O&G: reefs made of concrete and steel provide the same kind of habitat, as the same benthic species communities are significantly abundant on both structure materials. However, the reef habitat of mobile units differs from that of fixed structures, as different sessile invertebrate species are found there. 	Supplementary Table 7
	<ul style="list-style-type: none"> OWF: mature O&G and young OWF reefs, both located in Southern North Sea, provide the same kind of habitat, as the same benthic species and fish communities are significantly abundant on both structure types. Within the OWF reefs the edible crab prefers rocky scour protection of a monopile more than a tripod type of jacket structure. Due to the areal footprint grey and common seals prefer OWF structures and pipelines for foraging over O&G platforms. 	Supplementary Tables 7, 14
	<ul style="list-style-type: none"> Wrecks: research indicates that O&G reefs and wrecks provide different types of habitats, as not the same benthic species and fish communities are found on these reefs, e.g. <i>C. smithii</i> prefers pipelines and O&G structures, but has only been detected once at a wreck. 	Supplementary Tables 4, 5, 14
Ecologically or commercially important species	O&G reefs provide habitat for many different species:	
	<ul style="list-style-type: none"> Benthic fauna: <i>M. edulis</i>, other Mollusca, Cnidaria, Echinodermata, tube-building Amphipods and crabs showing most significant abundance on O&G/OWF. 	Supplementary Table 4 and 5
	<ul style="list-style-type: none"> Fish: Atlantic cod, Pouting, Saithe, European plaice showing most significant abundance at O&G/OWF. Flat fish species and Whiting are also regularly sighted near the structures, but their density increases with distance to the structures. 	Supplementary Table 11
	<ul style="list-style-type: none"> Mammals: Harbour porpoise showing the highest abundance of mammals at/near O&G, but also Minke, Killer, and Pilot whales are significantly abundant. 	Supplementary Table 16
Non-native or invasive species	<ul style="list-style-type: none"> O&G reefs provide habitat for a low percentage of non-native or invasive species. 	Supplementary Table 4
	<ul style="list-style-type: none"> Non-native or invasive benthic fauna are predominantly found in the intertidal zone on O&G/OWF, if abundant. 	Supplementary Table 4
	<ul style="list-style-type: none"> Non-native or invasive benthic fauna also use other reefs than O&G/OWF: <i>C. smithii</i> normally lives at O&G/pipelines using wrecks as steppingstones; <i>C. mutica</i> uses near-shore reefs as habitat while <i>C. linearis</i> prefers offshore structures (co-existing possible); <i>M. leidyi</i> only appears on O&G in summer months due to higher sea temperature. 	Supplementary Table 4

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red).

TABLE 3 Provision of reef habitat (part 2): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
	O&G reefs not only provide habitat for rare and threatened species, but also support the self-restoration of biogenic reefs:	
Rare and/or threatened species	<ul style="list-style-type: none"> • Relict populations of <i>O. edulis</i> found on O&G/OWF showing potential to form self-sustaining reefs. 	Supplementary Table 4
	<ul style="list-style-type: none"> • Massive populations of <i>M. edulis</i> abundant on shallower parts of O&G/OWF, although not naturally found offshore. “Mytilusation”: through biomass export, shells form natural beds. 	Supplementary Table 4
	<ul style="list-style-type: none"> • Colonies of <i>L. pertusa</i> found on O&G showing strong potential to form self-sustaining reefs. 	Supplementary Table 5
	<ul style="list-style-type: none"> • Atlantic cod shows significant abundance at O&G/OWF using the reefs for foraging, e.g. <i>Jassa</i> spp. as prey. 	Supplementary Table 11
	<ul style="list-style-type: none"> • Harbour porpoise showing high abundance at/near O&G especially during night. However, it remains unclear whether they use the reef for certain activities such as foraging. 	Supplementary Table 16
Impact on soft-bottom ecosystems	<ul style="list-style-type: none"> • The installation of O&G/OWF increases the abundance of fish assemblages in the short term, but does not show any significant effects in the long term. However, the richness of benthic fauna increases with community age. 	Supplementary Tables 9, 13
	<ul style="list-style-type: none"> • Klunder et al. (2020) indicate that O&G have an impact on the local carbon cycling, while Reeds et al. (2018) observes a local ecological halo effect around the O&G. 	See research studies
Impact of decom-missioning options	<ul style="list-style-type: none"> • Full removal of O&G will clearly result in complete loss of reef habitat for benthic and fish species communities as discussed above. 	Supplementary Table 1
	<ul style="list-style-type: none"> • “Leaving intact” of O&G substructure will provide full reef habitat functions as discussed above. 	Supplementary Table 1
	Partial removal of O&G has different impacts depending on the selected option (“topping” vs. “toppling”), as the benthic and fish species are very sensitive to depth:	
	<ul style="list-style-type: none"> • Due to the buildup of vertical zonation on O&G, all partial removal options result in the loss of reef habitat in the intertidal and infralittoral zones meaning that not only the non-native and invasive species will lose their habitat, but also the Blue mussel <i>M. edulis</i> and the European Flat Oyster <i>O. edulis</i> (if abundant). 	Supplementary Tables 6, 9
	<ul style="list-style-type: none"> • Depending on the platform and cutting depth the reef habitat of the circalittoral zone including the tube-building Amphipods <i>Jassa</i> spp. may be partly or fully removed. Shallower platforms in the SNS have tight depth bands with richness peaks at intermediate depths and are therefore sensitive to the cutting depth. Toppling may be technical unfeasible in shallower water. 	Supplementary Table 6
	<ul style="list-style-type: none"> • Motile invertebrates and Cnidarians are predominantly abundant in the epi-benthic zone near the bottom. These species together with the cold-water coral <i>L. pertusa</i>, which is found in deeper waters in the NNS, may not significantly be affected by neither of the both partial removal options, only by disturbance. 	Supplementary Tables 5, 6
	<ul style="list-style-type: none"> • Pelagic fish living mid-depth to surface will certainly lose their habitat including shelter and prey. Benthopelagic fish such as Atlantic cod and Saithe, which live in the bottom zone but also look for prey in the upper zones (according to their food web), may lose interest in the remaining cut-off habitat. 	Supplementary Tables 11, 12

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red).

TABLE 4 Productivity of offshore ecosystems: Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Sessile invertebrates	<ul style="list-style-type: none"> Significant biomass of <i>M. edulis</i>, <i>M. senile</i> and other types of Mollusca and Cnidaria is produced on O&G/OWF. 	Supplementary Tables 4, 5
Motile invertebrates	<ul style="list-style-type: none"> Echinodermata, tube-building Amphipods and crabs show significant abundance and high richness on O&G. 	Supplementary Tables 4, 5
	<ul style="list-style-type: none"> <i>J. herdmani</i> develops distinct genetic populations on O&G/OWF that hardly show any inter-connectivity of structures. 	Supplementary Table 8
Behaviour of important fish species for fisheries	<ul style="list-style-type: none"> Atlantic cod shows high residency and site fidelity towards O&G/OWF. 	Supplementary Table 11
	<ul style="list-style-type: none"> Atlantic cod and Saithe use the O&G reef for foraging. Atlantic cod prefers <i>Jassa</i> spp., while Saithe prefers Euphausiacea as prey that is different from the prey available at open water. 	Supplementary Table 11
	<ul style="list-style-type: none"> Atlantic cod shows larger body size at O&G/OWF than in the surrounding soft-bottom ecosystem. 	Supplementary Table 14
Reproduction & nursery grounds	O&G reefs provide potential nursery and spawning grounds, and give coral reefs the possibility to reproduce. Observations so far include the following:	
	<ul style="list-style-type: none"> The crab <i>C. pagurus</i> use OWF as nursery grounds. Egg masses of the whelk <i>B. undatum</i> were found on O&G. 	Supplementary Table 4
	<ul style="list-style-type: none"> The Lump sucker fish broods its eggs on O&G. Juveniles of Atlantic cod were spotted at O&G. 	Supplementary Table 11
	<ul style="list-style-type: none"> Conflict of interest: Simulation models show a potential overlap between spawning grounds of flatfish species and future OWF sites. Flatfishes are not significantly attracted by OWF, hence an increase of these structures may result in a decrease in reproduction or displacement of flatfishes. 	Supplementary Table 14
	<ul style="list-style-type: none"> <i>L. pertusa</i> has strong potential to form cold-water coral reefs on O&G, particularly in the NNS. This is confirmed by various industry studies, e.g. Shell identified a total of 199 <i>L. pertusa</i> colonies on Brent D and is complemented by extensive simulation models that show the potential of highly interconnected coral ecosystem networks. 	Supplementary Tables 5, 7, 8, (Shell U.K. Limited, 2017)
Local growth rate	<ul style="list-style-type: none"> The growth rate of benthic fauna species on O&G/OWF and its biomass production and export rate are well studied and vary seasonally. 	Supplementary Tables 4, 9
	<ul style="list-style-type: none"> O&G provide fish with good quality prey and therefore larger than usual Atlantic cod fish are observed at O&G/OWF, but overall growth rates for different fish species are not available. 	Supplementary Tables 11 14
	<ul style="list-style-type: none"> There is no distinct science-based evidence of growth rates of mammals related to O&G reefs. 	n.a.
	<ul style="list-style-type: none"> Comparative data on local growth rates between O&G reefs and other artificial or natural reefs are not available. 	n.a.
Regional total productivity	<ul style="list-style-type: none"> Direct measures of ecosystem productivity are lacking for O&G/OWF, therefore no regional total productivity is available for fishery-important species. 	n.a.

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red). n.a., Not available.

3.4 Enhancement of connectivity

Refer to [Table 7](#).

3.5 Protection of the seabed from trawling

Refer to [Table 8](#) and [9](#).

3.6 Traffic light rating of qualitative analysis

[Table 10](#) presents the traffic light rating results of the qualitative analysis. As the evaluation results highlight, the traffic lights for the key ecological considerations are predominantly showing green. This means that in general the current research knowledge status can be considered as mostly mature, science-based evidence. In detail, it can be seen that more mature, science-based evidence is available for proving that O&G reefs provide reef habitat and enhance biodiversity. Less mature science-based evidence is available for showing that O&G reefs protect the seabed from trawling, enhance the inter-connectivity of hard substrate for larval dispersal, and are productive offshore ecosystems.

When examining the main criteria related to the key ecological considerations, it can be seen that not all of them are highlighted in green and the knowledge gaps have been identified and are discussed as follows.

Only immature research data was available to assess the effectiveness of protecting rare and/or threatened species from trawling. It is evident that benthic fauna species and habitats such as European Flat Oyster *O. edulis* beds ([Kerckhof et al., 2018](#)), cold-water coral *D. pertusum* (*L. pertusa*) reefs ([Bergmark and Jørgensen, 2014](#); [Henry et al., 2018](#)) and deep-sea sponge *Porifera* spp. ([Gates et al., 2019](#); [Vad et al., 2020](#)) aggregations are actively protected by the O&G reef from trawling, however, it is not evident if certain fish species or marine mammals are effectively protected from trawling. Furthermore, only immature research data are available to determine the fishing results near the O&G reefs at the boundaries of the exclusion zones ([Reubens et al., 2013](#); [Rouse et al., 2020](#)).

It is evident that non-native or invasive species use hard substrate such as O&G reefs as stepping-stones ([Coolen et al., 2016, 2018, 2020](#)) to disperse. However, the exact larval dispersal mechanism and the extent to which O&G reefs contribute to their inter-connectivity has not yet been determined.

Due to the complexity, growth rates, especially of mobile species in connection with O&G reefs, are difficult to measure and are therefore lacking. For this reason, the overall productivity of O&G reefs and thus their impact cannot be determined on a regional basis.

The qualitative analysis shows that the knowledge status on the impact of MMS on the marine environment can be considered as mostly mature, science-based evidence, however, some knowledge gaps have been identified. In order to determine if the current knowledge status is sufficient to conduct an unbiased comparative assessment and decide whether to remove or not to remove the O&G structures, the main evaluation criteria need to be critically assessed ([Martins et al., 2020](#)). For example, are all criteria relevant

generally or do they need to be adapted on a case by case basis? Do all identified knowledge gaps need to be closed before conducting a comparative assessment? These questions should be answered by stakeholder collaboration ([Tung, 2020](#)) and an integrated scientific team as suggested by [Shaw et al. \(2018\)](#) in order to avoid a Brent Spar 2.0 ([Side, 1997](#)). Meanwhile, [Fowler et al. \(2020\)](#) recommend temporarily suspension of the mandatory removal of the O&G structures. The decommissioning community is currently undergoing a paradigm shift and until now, the knowledge gaps mandated the precautionary principle ([OSPAR Commission, 1992](#)) of full removal. However, scientific evidence may soon be available that will allow assessments on a case by case basis, so that the application of the precautionary principle will become obsolete.

3.7 Main features of O&G reefs

[Tables 2, 3](#) clearly demonstrate that O&G reefs provide the same excellent reef habitat for benthic fauna, fish and marine mammals as natural and other artificial reefs. However, it should be noted that they also provide habitat to species that are not normally found far offshore, such as *M. edulis* and *J. herdmani*. Furthermore, rare and/or threatened species such as the cold-water coral *D. pertusum* colonise O&G reefs and the overfished Atlantic cod resides there.

[Table 4](#) shows that O&G reefs significantly produce biomass of sessile and motile invertebrates and larger body sizes of Atlantic cods have been observed. Furthermore, O&G reefs serve as reproduction and nursery grounds especially for the edible crab, but also for rarer species such as the whelk *B. undatum* and the lump sucker fish. A total of 199 *D. pertusum* colonies have been identified on Brent D in 2008 ([Shell U.K. Limited, 2017](#)), 30 years after start-up. Only the total productivity of mobile species at a local and regional level has not yet been determined.

[Tables 5–7](#) highlight that not only is the local biodiversity significantly increased by O&G reefs, but also that regional biodiversity can be enhanced. This is achieved by inter-connectivity of hard substrates through larval dispersion. The physical parameter that most affects biodiversity is water depth. The material and type of substrate seem to play a less important role when it comes to species abundance and richness.

[Tables 8, 9](#) present that especially rare and/or threatened benthic fauna species colonising a O&G reef are actively and effectively protected from trawling. Since bottom trawling is the number one cause of physical disturbance to the seabed, it is expected that each exclusion zone, although very small compared to the entire North Sea, will help protect valuable ecosystems ([Fowler et al., 2018](#)).

In conclusion, the study clearly demonstrates that O&G reefs act as artificial reefs according to the definition of [Fabi \(2015\)](#).

3.8 O&G reefs to be protected?

[Tables 3, 6](#) and [9](#) highlight that different decommissioning options will have different impacts on the O&G reef habitat and fisheries.

TABLE 5 Enhancement of biodiversity (part 1): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Physical and environmental impacts	<ul style="list-style-type: none"> • Water depth: The species richness of sessile invertebrates definitely shows a buildup of vertical zonation. The distribution is non-linear with the peak at intermediate depths or in the bottom zone. Motile invertebrates show highest species richness in the bottom zone. 	Supplementary Table 6
	<ul style="list-style-type: none"> • Substrate material/type: Structures made of concrete could increase the species richness and biodiversity of benthic fauna locally. However, studies did not observe significant differentiation between rock and steel. 	Supplementary Table 7
	<ul style="list-style-type: none"> • Design: Compared to laid pipelines, trenching significantly decreases the species richness of benthic fauna and Whiting and increases other fish species' richness. 	Supplementary Tables 9, 13
	<ul style="list-style-type: none"> • Time: Species richness of benthic fauna increases with community age. 	Supplementary Table 9
Regional impacts	<ul style="list-style-type: none"> • When comparing O&G reefs located in the CNS and SNS, significant clustering in benthic communities was observed. Species abundance is higher in CNS than in SNS. 	Supplementary Table 8
	<ul style="list-style-type: none"> • More data sets are available for the SNS than for the CNS and NNS regions, therefore only indicative conclusions can be drawn. 	Supplementary Tables 2, 3
O&G reef vs. natural reef	<ul style="list-style-type: none"> • In general, no great differentiation in species richness between artificial and natural hard substrates are reported. 	Supplementary Table 7
Trade-offs: O&G reef vs. soft-bottom ecosystem	<ul style="list-style-type: none"> • O&G/OWF reefs significantly enhance the local biodiversity of benthic fauna and fish species compared to its surrounding soft-bottom ecosystem. Concrete O&G reefs can also host unique benthic communities (+ 23%) compared to natural reefs located in close proximity. 	Supplementary Tables 7, 14
	<ul style="list-style-type: none"> • First records in the SNS of obligate hard substrate fish species such as Goldsinny wrasse and Grey triggerfish underline the attractiveness and biodiversity potential of O&G/OWF reefs. 	Supplementary Table 11
O&G reef vs. other artificial reefs	<ul style="list-style-type: none"> • OWF: Neither significant differences in species richness between old O&G and young OWF nor between rock (scour protection of OWF) and O&G steel reefs are reported. 	Supplementary Table 7 and 9
	<ul style="list-style-type: none"> • Wrecks: Much more different fish species are observed at OWF than at wrecks indicating that wrecks have less biodiversity than OWF and O&G structures. 	Supplementary Table 11
Local vs. regional biodiversity	<ul style="list-style-type: none"> • Various studies clearly show that benthic fauna such as <i>M. edulis</i> use artificial structures as stepping-stones to spread out into areas that they otherwise could not reach. 	Supplementary Table 8
	<ul style="list-style-type: none"> • Simulations indicate that all different types of hard substrates (artificial and natural) are highly interconnected through larval dispersal. Especially O&G reefs contribute to the distribution of <i>L. pertusa</i>, Echinodermata and <i>Porifera</i> spp. 	Supplementary Table 8

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red).

TABLE 6 Enhancement of biodiversity (part 2): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Impact of decom-missioning options	• Full removal of O&G will clearly result in the loss of local biodiversity	Table 1
	• Full removal of O&G may also result in the decrease of regional biodiversity due to the loss of connectivity between hard substrates. Simulations predict 60% reduction in connectivity.	Supplementary Table 8
	• There is no clear evidence that the soft-bottom ecosystem in the North Sea could fully recover after full removal of O&G.	
	• If “leaving intact” the O&G substructure, neither the local nor the potential for improving regional biodiversity will change.	Tables 1, 10
	• Partial removal of O&G result in the reduction of local biodiversity. Due to the buildup of vertical zonation, both removal options “topping” vs. “toppling” result in the loss of the upper zones including <i>M. edulis</i>	Supplementary Table 6
	• Partial removal of O&G may also result in the reduction of regional biodiversity due to the loss of connectivity between hard substrates. However, simulations indicate that benthic species living in deeper sections or in the bottom zone such as <i>L. pertusa</i> , Echinodermata and <i>Porifera</i> spp. may stay connected through larval dispersal using the remaining parts of O&G as stepping-stones. Vertical extension of reef habitat by “toppling” in place or “topping and deploy top next to structure” may even enhance the epi-benthic biodiversity and connectivity.	Supplementary Table 8

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red).

TABLE 7 Enhancement of connectivity: Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Connectivity through larval dispersal	• Various studies clearly highlight that benthic fauna use different types of structures incl. O&G reefs as stepping-stones to spread out into areas that they otherwise could not reach.	Supplementary Table 8
	• Simulations show that all different types of anthropogenic (e.g. O&G, OWF, wrecks, buoys, pipelines, etc.) and natural hard substrates are interconnected.	Supplementary Table 8
	• Simulations underline that O&G reefs in the CNS and NNS contribute to the distribution of benthic fauna through larval dispersal. Note that not all of the simulations are yet validated against real data.	Supplementary Table 8
Larval dispersal mechanism	• <i>J. herdmani</i> develops distinct genetic populations on O&G/OWF that hardly show any inter-connectivity of structures. It is assumed that structures get populated by populations from the surrounding ecosystem that date back to the time of the glaciers and not from neighbouring structures.	Supplementary Table 4
	• Genetic taxa data show that <i>M. edulis</i> can spread over 181 km offshore, whereas the current models predict locations greater than 85 km offshore to be isolated from coastal communities.	Supplementary Table 8
Rare and/or threatened species	• Studies and simulations show that <i>L. pertusa</i> form highly interconnected coral ecosystem networks and that the deep-sea sponge <i>Porifera</i> spp. uses the O&G structure as stepping-stone to settle down in the surrounding seabed.	Supplementary Table 8
Non-native or invasive species	• Non-native or invasive benthic species use hard substrate as stepping-stones and are found in the intertidal zone.	Supplementary Table 4
	• No connectivity simulations of non-native or invasive benthic species are available. No studies of larval dispersal and mechanism available.	n.a.
Impact of decom-missioning options	• Full Removal: evaluation see Table 4	Supplementary Table 8
	• “Leaving intact”: evaluation see Table 4	Supplementary Table 8
	• Partial Removal: evaluation see Table 4	Supplementary Table 8

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red). n.a., Not available.

TABLE 8 Protection from trawling (part 1): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Protected vs. non-protected seabed	<ul style="list-style-type: none"> As a result of the compulsory exclusion zone of 500 m established around O&G, roughly 0.1% of the North Sea area is currently protected from fishing activities. Estimates of future OWF exclusion zones lead to a similar result as for O&G. 	Supplementary Table 17
	<ul style="list-style-type: none"> Further 18.6% of the North Sea area are covered by designated Marine Protected Areas reducing the fishing pressure. 	
	<ul style="list-style-type: none"> More than 50% of all UKCS platforms are located either in designated OSPAR MPAs or 1170-Reefs Habitats. 	Supplementary Figure 1
	<ul style="list-style-type: none"> Bottom trawling is the leading cause of physical disturbance to the seabed. Any type of disturbance has a significant impact on the benthic habitat and associated fish assemblages. 	Supplementary Table 9
	<ul style="list-style-type: none"> Due to the development of a local ecosystem around the O&G, which provides reef habitat and improves biodiversity and productivity, it is assumed that the soft-bottom ecosystem within the undisturbed exclusion zone is in equilibrium and is different from the disturbed, unprotected zone. This unprotected ecosystem has to be constantly re-established and calibrated in order to function properly 	Supplementary Tables 2–6
	<ul style="list-style-type: none"> Comparative data on the status of soft-bottom ecosystems in the exclusion zones, MPAs and other areas are not available. 	n.a.
Ecologically or commercially important species	<ul style="list-style-type: none"> Direct measures of the biomass of the benthic fauna within the protected exclusion are available. 	Supplementary Tables 4, 5
	<ul style="list-style-type: none"> Only indirect measures and estimates of the biomass of the fish assemblages within the exclusion are available. 	Supplementary Table 11
Rare and/or threatened species	<ul style="list-style-type: none"> Benthic fauna such as Oyster <i>O. edulis</i> beds, cold-water coral <i>L. pertusa</i> reefs and deep-sea sponge <i>Porifera</i> spp. Aggregations are highly sensitive to disturbance and bottom-trawling. Protected O&G reefs clearly support the reproduction and recovery of these species. 	Supplementary Tables 4, 5, 8, 9
	<ul style="list-style-type: none"> Atlantic cod is highly overfished and use O&G reefs as shelter, nursery, school and for foraging. However, overall protected fish biomass can only be estimated by observation. 	Supplementary Tables 11, 13
	<ul style="list-style-type: none"> Harbour porpoises are significantly abundant at O&G reefs and are very sensitive to any kind of disturbance. However, there is no clear evidence that these mammals use the protected O&G areas as shelter or for other relevant activities. 	Supplementary Table 16

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red). n.a., Not available.

While full removal will result in the complete loss of reef habitat, the “leaving intact” option will provide the full reef habitat. Depending on the partial removal option, cutting and platform depth, certain species communities will lose their habitat and some others may gain new extended habitat (Sammarco et al., 2014). This should be assessed on a case-by-case basis.

However, it remains unclear whether scientists would agree that O&G reefs should be protected because they provide full artificial

reef services. Ounanian et al. (2019) introduced the “human-made oasis” metaphor for O&G reefs. Hard substrate supports life, but it is also uncommon in most parts of the North Sea. Scientists from JNCC (CNR International, 2016) argue that *D. pertusum* would have not colonised the Ninian Northern Platform if the structure had not been installed and therefore, removing the structure and destroying the species would not be considered as an issue. This is partly supported by scientists interviewed by Fowler et al. (2018)

TABLE 9 Protection from trawling (part 2): Qualitative analysis of recent research findings on the impact of man-made structures against this key ecological consideration and its main criteria (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature	References
Impact of decom-missioning options	<ul style="list-style-type: none"> • Full removal of O&G will result in the loss of the exclusion zone and extend the trawling pattern again. 	Supplementary Table 17
	<ul style="list-style-type: none"> • There is no science-based evidence that reopening fishing areas will increase the fishing pressure. However, the loss of the protected area will clearly have an impact on the local ecosystem (e.g. newly introduced disturbance). 	n.a.
	<ul style="list-style-type: none"> • Compared to partial removal, full removal would reduce the risk of snagging. 	Supplementary Table 17
	<ul style="list-style-type: none"> • If “leaving intact” the O&G substructure would mean that the exclusion zone must be renewed to further protect the O&G reef. Reducing the extend of the exclusion zone may have an impact on the fishing effort near the boundaries, though. 	Supplementary Table 17
	<ul style="list-style-type: none"> • If “leaving intact” the O&G substructure would mean that neither the current snagging risk nor the remaining drill cuttings would be effected. 	Supplementary Tables 17, 1
	<ul style="list-style-type: none"> • Normally, it is preferred that drill cuttings naturally degrade. However, this may be an issue for the options “full removal”, “topping and deploy top next to structure”, and “toppling”, since any kind of disturbance (incl. shing) can lead to leaching. 	Supplementary Tables 17, 1
	<ul style="list-style-type: none"> • Partial removal of O&G, incl. both options “topping” and “toppling”, may result in a higher risk of snagging depending on the water depth. 	Supplementary Table 17
	<ul style="list-style-type: none"> • There is no science-based evidence that partial removal of O&G, incl. both options “topping” and “toppling”, would adequately protect the remaining O&G reef from trawling. 	n.a.
Ecologically or commercially important species	<ul style="list-style-type: none"> • Studies clearly highlight that 36% of all fishing trips of Scottish demersal fleet occur within 200 m of a pipeline over a 5-year period. Most vessel incidents are related to debris, wires, or pipelines and occur near pipelines or wrecks. 	Supplementary Table 17
	<ul style="list-style-type: none"> • Almost all Atlantic cod fish found at O&G/OWF have been observed within 50 m. 	Supplementary Table 11
	<ul style="list-style-type: none"> • There is no science-based evidence that the trawling effort is greater at the boundaries of O&G exclusion zones. 	n.a.
	<ul style="list-style-type: none"> • There is no science-based evidence that catches of commercially important species are greater at O&G exclusion zones. 	n.a.

Colour-code expresses knowledge status: mature science-based (green), immature (grey) and no science (red). n.a., Not available.

who stated that it is ethically acceptable to destroy such species because they say this hard substrate does not belong there. Where and how much hard substrate there was before trawling began in the NS is unknown, so there is no way to understand where hard substrate ‘should be’. On the other hand, the same scientists (Fowler et al., 2018) also argue that O&G structures should not automatically be removed; showing that some in the science community are making decisions and providing policy advice without understanding the entire picture. Many authors and

some NGOs, including van Elden et al. (2019) and Schläppy and Hobbs (2019), now argue that O&G reefs could be valued as novel ecosystems.

4 Discussion

The results show that the majority of the key ecological criteria to determine the impact of MMS on the marine environment are

TABLE 10 Colour-coded illustration of the qualitative analysis: traffic light rating of the current knowledge status – mature science-based (green), immature (grey) and no science-based (red) – with regards to the key ecological considerations (Fowler et al., 2020).

Key criteria	Evaluation of findings in literature
Provision of reef habitat	• O&G reef vs. natural reef
	• O&G reef vs. other artificial reef
	• Ecologically or commercially important species
	• Non-native or invasive species
	• Rare and/or threatened species
	• Impact on soft-bottom ecosystem
	• Impact of decommissioning options
Productivity of offshore ecosystems	• Sessile invertebrates
	• Motile invertebrates
	• Behaviour of important fish species for fisheries
	• Reproduction & nursery grounds
	• Local growth rates
	• Regional total productivity
Enhancement of biodiversity	• Physical and environmental impacts
	• Regional impact
	• O&G reef vs. natural reef
	• Trade-offs: O&G reef vs. soft-bottom ecosystem
	• O&G reef vs. other artificial reef
	• Local vs. regional biodiversity
	• Regional total productivity
Protection of the seabed from trawling	• Protected vs. non-protected seabed
	• Ecologically or commercially important species
	• Rare and/or threatened species
	• Fishing effort near O&G reef
	• Impact of decommissioning options
Enhancement of connectivity	• Connectivity through larval dispersal
	• Larval dispersal mechanism
	• Rare and/or threatened species
	• Non-native or invasive species
	• Impact of decommissioning options

The colour brightness relates to the maturity of the evidence available.

green in the traffic light system, meaning that in general the current research knowledge status can be considered as mostly mature, science-based evidence and that existing O&G platform substructures can and do act as multipurpose artificial reefs.

The results presented demonstrate that the current knowledge about the impact of manmade structures on the marine environment is mature enough to show that it is no longer justifiable to mandatory remove all O&G platform substructures without proper assessment of each of the five ecological considerations as described here and in Fowler et al. (2020).

Furthermore, to ensure that an unbiased comparative assessment is conducted, it is vital that the five key criteria are included and are critically assessed so that the results are used to determine the best decommissioning option, including the decision about whether to remove O&G structures or to leave them *in situ*.

For example, are all criteria generally relevant or do they need to be adapted on a case by case basis? Do all identified knowledge gaps need to be closed before conducting a comparative assessment? These questions can only be addressed in an iterative process and full stakeholder collaboration (Tung, 2020). The Brent Spar experience (Side, 1997) has demonstrated that only a transparent assessment method (Martins et al., 2020) and sound decision criteria (Fowler et al., 2020) can lead to success. To deal with this it is recommended to set up an integrated scientific team as suggested by Shaw et al. (2018) and a survey similar to Fowler et al. (2018) could be conducted with all stakeholders involved. This would help to find common ground and define team goals rather than individual discipline goals.

Some limitations within the study come from the limited number and type of research available, with benthic fauna dominating the research and a bias towards the Southern North Sea. The main knowledge gaps are identified (grey and red colour) in the traffic light system and are in relation to the following key criteria; 2) *protection of the seabed from trawling*, 4) *enhancement of connectivity*, and 5) *productivity of offshore ecosystems* and are in some part due to the complexities of these studies as well as a lack of available data. In future, new tools such as eDNA (Harper et al., 2020) could facilitate and improve the research work. Meanwhile, data gaps could be mitigated by granting access to the large number of not yet published industry monitoring data (Macreadie et al., 2018; Murray et al., 2018). In particular, monitoring data of the derogation cases, where the footings were left *in situ* such as the Ninian Northern platform (CNR International, 2016) and the Murchison platform (CNR International, 2013), would give some insight into the short-term and long-term effects on the habitat provision. Any changes to the benthic fauna and the behaviour of fish and marine mammals at the remaining O&G reef could be determined. This information could also be used to investigate knowledge gaps related to partial removal impacts. For example, what is the impact on the local and regional biodiversity including the surrounding soft-bottom ecosystem? How is the fishing effort near the O&G reefs? And does the remaining O&G reef provide protection from trawling?

Finally, It should be highlighted that other environmental considerations, especially GHG emissions from decommissioning operations (Davies and Hastings, 2023a, 2023) and hence compliance to net zero (Oil & Gas Authority, 2020a) need to also be evaluated when conducting a comparative assessment of various decommissioning options. In this respect, it is worth examining how other countries are dealing with this issue (Scarborough Bull and Love, 2019).

5 Conclusions and policy implications

This study demonstrates that a new clearly structured regulatory framework with clear environmental objectives based on scientific evidence is required for future decommissioning of O&G industry infrastructure in the UK North Sea. This new framework should also include specific expectations of decommissioning within MPAs and if endangered, protected or endangered species are present.

This review concludes that the current research knowledge status of the impact of MMS on the marine environment can be considered as mostly mature, science-based evidence. Evidence that shows that existing O&G platform substructures can and do act as multipurpose artificial reefs and that a clear sea-bed policy is no longer justifiable in the UK North Sea.

The results show that an unbiased comparative assessment using the five key criteria should be undertaken for each decommissioning program, on case-by-case basis, and that decommissioning *in situ* should be considered within these comparative assessments.

The study clearly shows that the precautionary principle of OSPAR 98/3 (OSPAR Commission, 1992) should be reversed.

Finally, the study postulates that adherence to the current version of the OSPAR Decision 98/3 is driven by politics and not by marine environmental sciences.

Author contributions

NP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. AD: Methodology, Project administration, Resources, Validation, Writing – review & editing. AH: Supervision, Validation, Writing – review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2024.1264892/full#supplementary-material>

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